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Proposal of a Novel Gravity-Fed, Particle-Filled Solar Receiver

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Abstract. Solar Thermal Electricity power plants utilizing solid particles as heat transfer and storage media have been proposed by several research groups, with studies citing benefits of increased thermal efficiency and lower cost. Several types of solid particle receivers have been proposed, with leading designs consisting of particles falling or suspended in air. A new solid particle receiver is proposed here, consisting of a receiver fully packed with particles flowing downward with gravity. Particle flow rate is regulated with an outlet valve. This Particle-Filled receiver concept is compared to other receiver designs, and initial cold and hot experiments are conducted. Mass flux values of up to 379 kg m^{-2} s^{-1} are demonstrated, and heat transfer coefficients between 136 and 251 W m^{-2} K^{-1} are found.

INTRODUCTION

State of the art central receiver type Solar Thermal Electricity power plants often use molten salts as both heat transfer fluids and heat storage media. The concept of using solid particles, as opposed to a fluid, has been proposed and studied by numerous researchers. Cited benefits include a higher thermal efficiency of the power cycle due to the higher working temperature range of particles and elimination of the problems associated with the freezing of molten salt at temperatures below 220 ˚C [1]. Additionally, with temperatures nearing 1000 ˚C, particles could work with various power cycles such as an air Brayton cycle or supercritical CO_2 Brayton cycle [1]. Several solid particles have been suggested including ceramics and sintered bauxite [2][3], but the option of using sand holds promise due to its extremely low cost and abundance in desert regions. With sand, thermal energy storage cost could be reduced by up to 75% over molten salt systems [1].

Most components of a solid particle based power plant have mature designs, but the solid particle receiver is one exception [1]. The proposed systems fall generally into four categories, each having their own benefits and drawbacks. Direct Falling Particle Receivers feature a curtain of particles dropped from the top of the receiver which are directly irradiated through an open window as they fall [3]. In contrast, Indirect Falling Particle Receivers have also been proposed where falling particles are enclosed behind an absorber surface [4]. In Particle Suspension Receivers, particles are fluidized with air jetted in at the bottom of a riser tube. Air carries the particles upward, maintaining the particle flow rate and a solid volume fraction of up to 30-40% [2][5]. Centrifugal Receivers use particles dropped into a rotating drum and forced to the wall due to rotational forces. Radiation enters through the bottom of the drum and strikes particles directly while they are forced to the wall [6][7]. Each of these designs has several distinct drawbacks, and researchers are currently trying to overcome these challenges [8].

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THE PARTICLE-FILLED RECEIVER

A completely separate category of solid particle receiver is being proposed here, with flow and heat transfer mechanisms different from those previously studied and discussed above. This is an initial look into the conceptual design of this receiver as well as the practical benefits it could bring, and experiments are run at laboratory scale to demonstrate the fundamental trends in flow and heat transfer.

Starting with the desired criteria of high mass flux, high heat transfer, easy flow control, and minimal parasitic power use, a receiver design can be envisioned where particles flow downward through a vertical absorber tube in a fully-packed manner, similar to a fluid draining from a funnel through a vertical pipe. Here, unlike Falling Particle Receivers, particles would *not* be in free fall; the downward flow rate of particles would be regulated by a valve at the outlet. A single absorber tube is shown in Fig. 1(a) for simplicity, but a full receiver could have many such absorber tubes, as seen in Fig. 1(b). In fact, various geometries are possible, such as a finned annulus in Fig. 1(c) or the enhanced light trapping design in Fig. 1(d). While this sounds like a simple solution, to our knowledge, any proposal or analysis of such a receiver is not present in the literature. The characteristics of the conceptual "Particle-Filled Receiver" are discussed below by comparing it to the four previously studied designs.

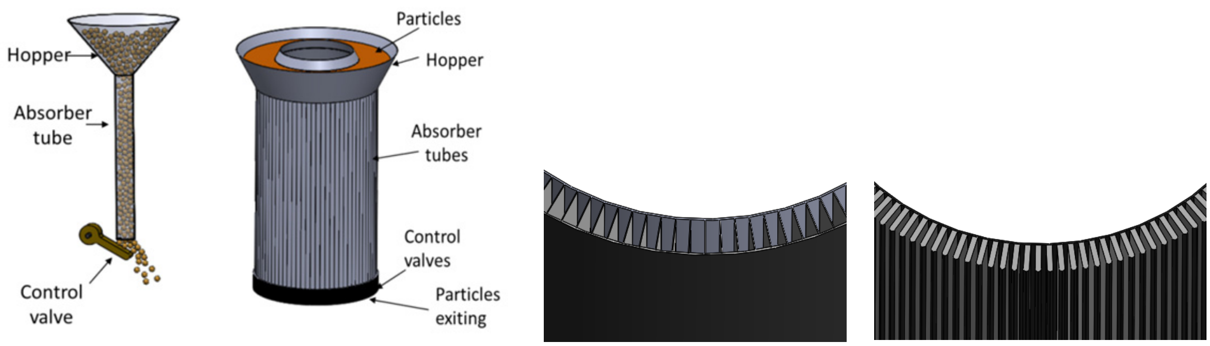

FIGURE 1. Single absorber tube as studied at lab scale (a), and full receiver (b). (c) shows a finned annular receiver, and (d) shows an enhanced light trapping geometry.

Flow Control

In any receiver design, it is important to be able to achieve a constant output temperature, even with varying environmental conditions such as radiation intensity, sun position, wind, and ambient temperature. Furthermore, radiation is typically highest in the center of the receiver, so increasing the residence time of particles on the periphery is necessary to achieve a uniform output temperature across the receiver [9]. For each of the current receiver designs, flow control is one of the main challenges [8], and researchers are adding schemes and complexity to achieve some control over the flow rate.

In contrast, a Particle-Filled Receiver could simply use outlet valves to provide a full range of flow rate adjustment from stationary up to the maximum mass flux. With temperature measurements at the receiver outlet, valves could be automatically adjusted to maintain output temperatures which are constant over time and uniform over the length of the receiver, even in varying environmental conditions.

Particle Selection

Most studies on Particle Suspension Receivers have used very small "Geldart's Group A" particles of silicon carbide, such as the 63.9 µm diameter particles studied in [5] and [10]. Sand found in deserts, probably the lowest-cost particle widely available, is much larger in dimeter, such as the 164 to 202 µm diameter particles sampled in the UAE [11] which would be more difficult to fluidize.

In Direct Falling Particle and Centrifugal Receivers, particles must have a high absorptivity, as they directly absorb radiation. Sintered bauxite particles have been considered due to their high absorptivity [3], and for these systems, sand would not be a good choice due to its low absorptivity of around 0.55.

The Particle-Filled Receiver would not impose fluidization or absorptivity requirements on the particle choice, leaving more options open to address other requirements, such as low cost.

Achievable Mass Flux

Particle Suspension Receivers must maintain the proper fluidization regime, which only occurs at certain combinations of air and particle flow rates [2]. Due to these fluidization requirements, the maximum allowable mass flux has been considered as 40 kg m^{-2} s^{-1}[5] and 45.1 kg m^{-2} s^{-1} [10], which is much lower than Falling Particle Receivers. In a Particle-Filled Receiver, because the particles are in a dense, fully-packed flow, a high mass flux is achievable, demonstrated up to 379 kg m^{-2} s^{-1} in the experiments detailed below. Falling Particle Receivers can achieve a very high mass flux as particles fall quickly with gravity, so it is not a limiting factor. Centrifugal Receivers have different challenges, but they may have difficulty maintaining a high mass flow rate once scaled up [8].

When scaling up to a large power plant, a low mass flux (as seen with Particle Suspension Receivers) will require a large cross sectional area for the flowing particle mixture. In practice, such a receiver would be very long or deep, making heat transfer difficult or inefficient. The high mass flux of the Particle-Filled Receiver could keep the receiver size small, which would be valuable when scaling up to the 100 MW range.

Parasitic Power and Losses

The air jets used by Particle Suspension Receivers require blowers which consume a considerable amount of electricity, and heat lost to the jetted air represents a thermal loss as well [5]. Centrifugal Receivers also have parasitic electric loads due to the spinning of the drum. While these are relatively small electric loads, they effectively represent a penalty to the thermal efficiency of the receiver. The Particle-Filled Receiver, which is gravity-fed, has no such parasitic losses.

Receiver Erosion

One practical concern in fluidized bed designs is the fact that particles constantly colliding with walls can erode the interior of the cavity, and Particle Suspension Receivers may face similar problems. The low velocity of sand in a Particle-Filled Receiver is expected to cause less erosion problems than in fluidized designs.

Allowable Heat Flux

Direct Falling Particle and Centrifugal Receivers feature particles that are directly irradiated. The other designs (including the Particle-Filled design) use an absorber surface that will overheat if the incident radiation is too high. Thus, the directly-irradiated receivers have the advantage of withstanding a very high heat flux (on the order of 1 MW m^{-2}) compared to designs using an absorber, which may have a limit of around 200-400 kW m^{-2} [2]. However, without an absorber surface, problems arise in practice due to wind, which can cause particle loss and disturbances to the particle flow. The Particle-Filled Receiver, like other designs with an absorber surface, will need to be designed to effectively transfer heat from the absorber to the particles, which will both raise the heat flux it can tolerate and increase the thermal efficiency.

EXPERIMENTS ON PARTICLE FLOW

Initial experiments were conducted to answer fundamental questions about dense particle flows in thin tubes, such as if there are various flow regimes, if there is a range of mass flux that can be achieved, or if excessive friction causes any blockages. Initial non-heated experiments were run with glass tubes with inner diameters of 7.75, 9.75, and 15.25 mm, each tube having length of 1.2 m. Three different types of sand with different mean diameters were used in these experiments. The sizes were measured using a set of sieves to have Sauter Mean Diameters of 99, 346, and 559 µm. These sands will be referred to as Fine, Medium and Coarse. The laboratory setup shown in Fig. 2 was built which uses a large hopper to feed the tube, and mass flow is measured using a scale placed below the collecting container. Unlike fluid flow, particle flow rate through an orifice does *not* depend on the head height above the orifice, due to the high friction forces of particles [12].

Initial testing showed that with a valve, orifice plate, or any restriction over the outlet, sand can flow downward without developing visible air pockets or becoming stuck in any way due to friction. However, if the restriction or valve is removed, sand enters a different flow regime where it is in a state of free fall through air, and the tube becomes no longer fully packed. As seen in Fig. 2, the two flow regimes are easily distinguishable. Since free-fall flow is not desired, there exists a certain maximum flow rate to maintain a packed flow regime. To find this point, a fitting with an adjustment screw was attached to the tube outlet (Fig. 2, center) and adjusted until the flow was just under the transition point. This maximum flow rate, expressed as a mass flux, was determined for each sand and tube size, and the results are plotted in Fig. 3.

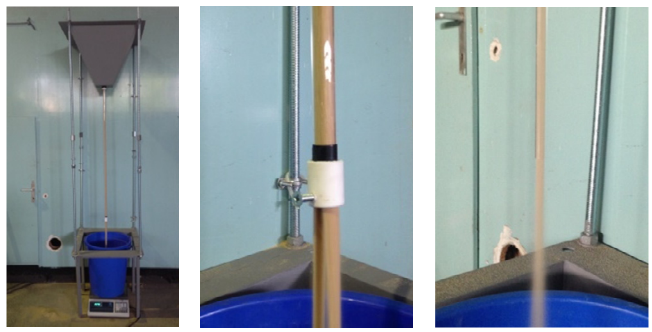

FIGURE 2. Laboratory setup (left), packed flow regime (center), and free fall flow regime (right).

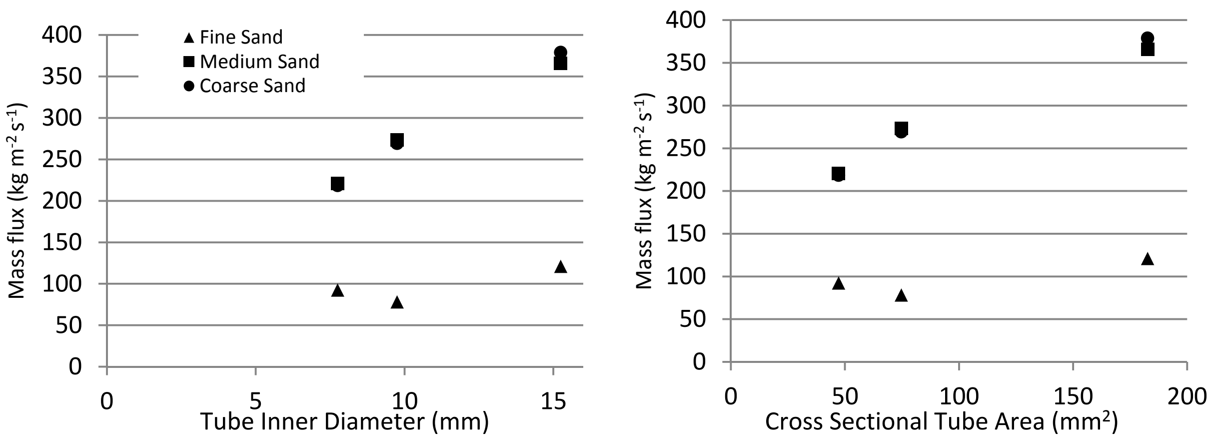

FIGURE 3. Maximum mass flux for three tube sizes and three sand grain sizes, plotted with respect to diameter and cross-sectional area.

A few observations can be made from the flow rate experiments. First, these mass fluxes are very high, roughly an order of magnitude higher than the mass flux studied with Particle Suspension Receivers [5][10]. Second, the Medium and Coarse sands are nearly identical in their maximum flux, whereas the Fine sand has a much lower mass flux. While not proven, this may be due to the higher friction in the Fine sand. Third, mass flux not only increases with the diameter of the tube, it also increases with the cross sectional area. Last, the one data point that does not follow the trend is the fine sand in the 9.75 mm tube. Upon close inspection, a slight narrowing of this glass tube can be measured at the outlet, clearly from the glass manufacturing, which would logically result in a lowered mass flux measurement for this point alone.

It was important to establish these maximum flow rates before moving on to heated tests, where an opaque copper tube rather than a transparent glass tube is used, so as to not exceed these flow rates and accidentally switch over to the free-fall flow regime.

EXPERIMENTS ON HEAT TRANSFER

Heated tests were performed with the goals of determining heat transfer coefficients and collecting data to validate future CFD modeling. The previous setup was modified to accommodate a 14 mm ID, 1.2 m long copper tube wrapped with eight heating elements, as shown in Fig 4. Four different orifice plates were used to achieve various mass flow rates. Seven K-type thermocouples, placed along the tube in between each of the heating elements, were firmly attached and insulated so as to accurately measure the outside surface temperature of the copper tube. Thermocouples were also used to measure the inlet and outlet sand temperatures.

Nominally, 2300 Watts were input to the heating elements, but a large fraction is lost to the surroundings because they are uninsulated. The inlet and outlet temperatures, along with the mass flow rate and sand heat capacity, were used to calculate the heat actually transferred to the sand. Upon starting each test, the setup was allowed to reach steady state before all temperatures were recorded.

Figure 5 shows the steady state temperatures for each sand type, using each of the four orifice plate sizes. Flow rate through the orifice is different for each sand type, so the measured flow rate is noted in the legend. The largest two orifice plates were not tested with the fine sand, as they lead to the free-fall flow regime.

With a uniform heat flux, the bulk sand temperature should increase linearly along the path. As expected, the surface temperature of the tube increases almost linearly from inlet to exit as well. The relationship is not quite linear, likely because the last heating elements are at higher temperature and have a higher loss to ambient than the first elements.

FIGURE 4. Heated laboratory setup with 8 heating elements.

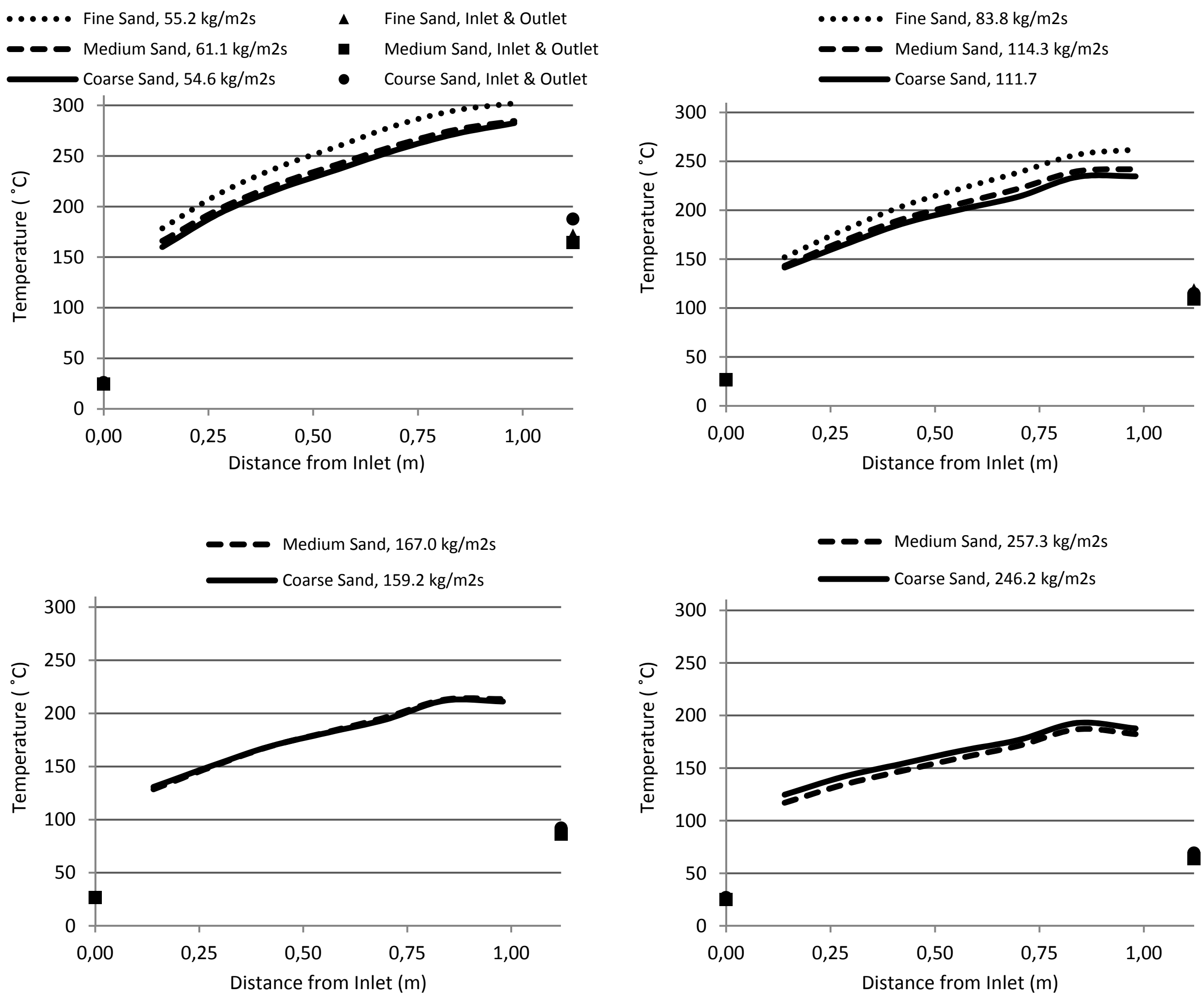

FIGURE 5. Steady state tube surface temperatures and sand inlet and outlet temperatures with four 4.75 mm orifice holes (upper left), one 9.4 mm orifice (upper right), one 11.0 mm orifice (lower left), and one 12.4 mm orifice (lower right).

For each of the 10 test runs, the heat transfer coefficient was calculated using Equation 1 [13], where the heat transfer rate Q is calculated with Equation 2, A is the interior surface area of the tube, the surface temperature is measured, and the bulk temperature is interpolated based on the overall temperature rise. An accurate method of experimentally determining the specific heat of sand was not available, so a value of 776 J kg^{-1} K^{-1} was chosen as the middle of the range for dry sand [14]. This analysis was performed near the end of the tube, where the flow can be assumed to be thermally fully developed based on the linearity of the surface temperature plots. For more accurate results, heat capacity will be measured in the future. Overall heat transfer coefficient results are plotted in Fig. 6.

$$h = \frac{\dot{Q}}{A\left(T_{surface} - T_{bulk}\right)} \tag{1}$$

$$\dot{Q} = \dot{\mathrm{m}}\, \mathrm{c_p}\left(T_{outlet} - T_{inlet}\right) \tag{2}$$

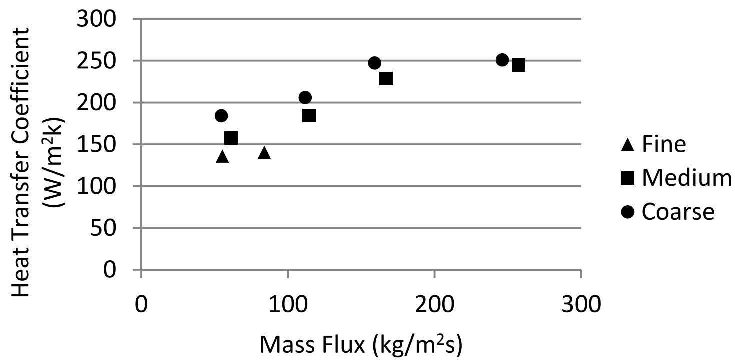

FIGURE 6. Heat transfer coefficient at various mass flux values.

Similar to Particle Suspension Receivers, the heat transfer coefficient increases with mass flux. The heat transfer coefficients found, in the range of 136 to 251 W m^{-2} K^{-1}, are much lower than those presented for a Particle Suspension Receiver, which are in the range of 400-1100 W m^{-2} K^{-1} [10]. Heat transfer coefficients are expected to increase significantly at higher temperatures, as the thermal conductivity of air increases with temperature, and radiation effects begin to play a larger role in the bulk conductivity of the particle-air mixture. The heat transfer coefficient of a Particle Suspension Receiver was shown to increase 30% due to elevated working temperatures [10]. While the heat transfer coefficient is an important parameter to classify and understand the flow, the thermal efficiency of a full receiver will depend on many factors including the surface area contacting particles, size of receiver, particle properties, and materials used.

CONCLUSIONS

The Particle-Filled Receiver proposed here may offer several advantages in real-world operation of a solid particle power plant, such as complete flow control, a high mass flux possible, no parasitic loads, and mechanical simplicity. Without the fluidization or absorptivity constraints of competing designs, an economical particle such as sand could be used.

Experiments demonstrated a high mass flux, up to 379 kg m^{-2} s^{-1} shown using a 15.25 mm ID tube, and the flow rate was demonstrated to be easily adjusted using a valve. Tests showed overall heat transfer coefficients between 136 and 251 W m^{-2} K^{-1} and increasing with flow rate.

While the heat transfer coefficients found here are lower than some competing designs [10][4], the Particle-Filled Receiver will be investigated further given its many operational and practical benefits. With a low heat transfer coefficient, the same thermal efficiency could be achieved by increasing the surface area contacting the particles. Many different geometries, such as the finned annular receiver shown above, could be considered to enhance heat transfer. If a similar thermal efficiency to other designs can be achieved while still capturing the practical benefits described, the Particle-Filled Receiver may be a very advantageous design. Thermal efficiency will be studied through modeling and experimentation in future work.

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