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# Simulation of thermal hydraulic performance of multiple parallel micropin arrays for concentrating solar thermal applications with supercritical carbon dioxide

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ABSTRACT

Concentrated solar power (CSP) plants have the potential to provide 24 h, renewable electricity. Current CSP systems have high capital and operational costs which makes the levelized cost of electricity uncompetitive with conventional techniques. Recent experimental research has shown the potential of small unit cells (up to 2 × 2 cm) containing micropin arrays ($D_H < 1$ mm) to operate efficiently at high incident flux (> 140 W cm$^{-2}$) using supercritical carbon dioxide as the working fluid. Applying this technology to CSP systems would result in a smaller central receiver, which would reduce thermal losses, increase receiver efficiency and reduce the capital cost of the receiver component.

This study investigates and addresses the practical thermal and hydraulic issues in numbering up these small unit cells into numerous parallel cells within an integrated module design. A thermal hydraulic network model is developed to quantify the distribution and the overall receiver efficiency of an integrated module. This model is used to specify maximum allowable unit cell size and header dimensions to maintain acceptable thermal performance and pressure loss. Once a module design was finalized, parametric studies were performed to study the effects of varying incident flux on flow distribution and thermal performance of the module. The results show that an integrated module design can be achieved with less than 5% flow maldistribution and a pressure drop acceptable to the remainder of the system.

## 1. Introduction

Concentrating solar thermal power (CSP) remains an attractive complement to solar photovoltaic systems as a dispatchable source of electricity using relatively low cost thermal storage (Mehos et al., 2016). Starting in 2011, the United State Department of Energy Sun-Shot program has sought to reduce the cost of electricity generated from solar power, including CSP. The path to accomplish this has been to increase the delivery temperature of the working fluid to > 700 °C, and use the supercritical carbon dioxide ($sCO_2$) Brayton cycle as the heat engine in central tower applications. Attempts to achieve these goals has led to investigation of three receiver-to-power block pathways: (1) gas-phase receiver, (2) molten salt receiver, and (3) particle based receiver (Ho, 2017; Mehos et al., 2017). Each of these technologies have their own advantages and challenges that are the subject of active research.

Gas-phase solar thermal systems use a compressible fluid such as air, helium, or carbon dioxide as the working fluid. The circulating fluid is heated in the receiver and then is either directly utilized in a power system or to transfer energy to a thermal storage system and/or a power block. The European GAST project in the 1980s was an early example of an air based central receiver (Romero et al., 2002). The 20 MW plant used tubular panels capable of producing air at temperatures from 800 to 1000 °C at pressures of approximately 9.5 bar and incident fluxes < 20 W cm$^{-2}$ (Romero et al., 2002). Incident flux was limited by the relatively poor heat transfer coefficients of the air, which led to local overheating and high estimated capital costs (Müller-Steinhagen and Trieb, 2004; Romero et al., 2002).

These limitations spurred interest in air based volumetric receivers, where solar flux is absorbed inside a porous volume and energy is transferred volumetrically to flowing air or other gas. Ho and Iverson (2014) note numerous volumetric designs have been developed capable of producing temperatures from 800 to 1500 °C depending on the porous material. They note receiver efficiency from 50 to 60%. Prototype designs with air have shown potential for average incident fluxes of 40 W cm$^{-2}$ with peaks of 100 W cm$^{-2}$ (Romero et al., 2002). Key challenges with volumetric based designs are material durability, flow instability and the need for integrating thermal storage. Designs based

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**Nomenclature**

| | |
|---|---|
| $A$ | area ($m^2$) |
| $D_H$ | hydraulic diameter (μm) |
| $G_{max}$ | mass flux ($kg\,m^{-2}\,s^{-1}$) |
| $i$ | specific enthalpy ($J\,kg^{-1}$) |
| $K_m$ | minor loss coefficient |
| $\dot{m}$ | mass flow rate ($kg\,s^{-1}$) |
| $MD$ | maldistribution (%) |
| $N_s$ | number of segments |
| $P_D$ | pin diameter (μm) |
| $Re$ | Reynolds number |
| $S_L$ | longitudinal pitch (μm) |
| $S_T$ | transverse pitch (μm) |
| $V$ | velocity ($m\,s^{-1}$) |

*Greek*

| | |
|---|---|
| $\eta$ | efficiency (%) |
| $\mu$ | dynamic viscosity ($kg\,m^{-1}\,s^{-1}$) |
| $\rho$ | density ($kg\,m^{-3}$) |

*Subscripts*

| | |
|---|---|
| *Amin-P* | minimum transverse flow area based on segments |
| *F* | forced |
| *L* | characteristic length |
| *max* | maximum |
| *MH* | module header |
| *min* | minimum |
| *PF* | pin fins |
| *S* | segment |
| *SC* | sudden contraction |
| $sCO_2$ | supercritical carbon dioxide |
| *SE* | sudden expansion |
| *UCH* | unit cell header |

on atmospheric pressure air also require extremely high volumetric flow rates to provide meaningful thermal power input.

Lower volumetric flow rates could be obtained at higher operating pressures in tubular type receivers, but the original challenges of the 1980s remain. Gas-phase convective heat transfer coefficients are poor, leading to high surface temperature and reradiation losses. Furthermore, Ho and Iverson (2014) show that rapid thermal transients in gas-based tubular receivers can cause significant thermomechanical loads resulting in reduced fatigue life of the receiver. However, the recent interest in supercritical carbon dioxide Brayton cycles has caused gas-phase receivers to be revisited (Mehos et al., 2017). Supercritical $CO_2$ has good transport properties and relatively high volumetric heat capacity at the temperatures and pressure of interest. Prototype designs of open, "tubular" receivers using $sCO_2$ as the working fluid have been developed by industry, national labs and universities (Ho, 2017; Mehos et al., 2017).

Researchers at Oregon State University have been investigating the use of a micropin gas-phase receiver using $sCO_2$ as the working fluid. This receiver was initially conceptualized as directly supplying $sCO_2$ to the power block at high pressures and temperature (> 200 bar and 650 °C). However, the technology could also be used in an indirect gas-phase architecture where a circulating fluid is connected to thermal storage and power block through secondary heat exchangers. Initial simulations (Rymal et al., 2013) and lab-scale experiments (L'Estrange et al., 2015) of small, unit-cell devices containing arrays of micropins ($D_H \sim 300\,\mu m$) have demonstrated the potential to absorb heat fluxes > 100 W cm$^{-2}$ at the desired temperature/pressure with high receiver efficiency. By using small flow passages, the working fluid can be safely contained with minimal wall thickness, and higher gas convective heat transfer coefficients can be obtained. Both features decrease the surface temperature and reradiation losses. To minimize pressure drop, the micro-pin receiver is a modular, multi-scale design (with a conceptual schematic shown in Fig. 1). The three model scales are defined as follows:

1. **Unit cell** – The unit-cell (Fig. 2) consists of a thin flat flux plate coated with high absorptivity material. Inside the unit cell is a flow passage containing an array of micro-pin features with hydraulic diameter of approximately 300 μm. The flow length of a unit cell is determined by the maximum allowable pressure drop. Each unit cell consists of two inlet headers (from the left and right), and a central outlet header.
2. **Module** - Multiple unit cells connected in parallel in a single unit form a module. In the present study, a module will have a total heat transfer area of ~1 m$^2$ and absorb approximately 1 MW of thermal energy at 90% reciever efficiency. Thus, for 10 cm long by 1 m wide unit cells, approximately 10 unit cells must be connected in parallel to form a module. Fig. 3a shows a top view of a three-unit cell module with the flux plate removed. Fig. 3b shows the back view of this pin array with flow distribution headers. Flow enters through the module inlet header (in green[1]) from the main receiver riser. The $sCO_2$ is distributed to unit cell inlet headers (in blue), and then exits each unit cell through the unit cell outlet headers (in red). Finally, flow from each unit cell outlet header is collected in a module outlet header (in yellow), and returned to the main receiver downcomer.
3. **Central receiver** – The central receiver consists of multiple modules connected in parallel. The modular design allows for the mass flow rate of $sCO_2$ to different zones within the receiver to be controlled to maintain a specified temperature increase and enables arrangement of modules to tune the receiver surface area to a given heliostat field allowing for higher efficiency annualized performance.

Zada et al. (2016) developed a thermal model for a single unit-cell and then by solving the model multiple times at different incident fluxes, which corresponded to different positions on a full-scale receiver, were able to obtain overall system efficiency. With the multi-level model, they were able to predict thermal performance of a 250 MW receiver at an average incident flux of 110 W cm$^{-2}$ heating $sCO_2$ from 550 to 650 °C in different configurations. They concluded that an overall receiver efficiency of > 90% was possible, and that the modular nature of the design could enable the receiver to be tailored to the specific heliostat field, increasing performance for a fixed receiver area.

In the Zada et al. (2016) model, the 250 MW receiver contained 3000 unit cells. A key assumption was that $sCO_2$ flow was evenly distributed to each unit cell. However, one of the long-standing issues with multiple parallel microchannel systems is developing methods for uniform distribution of flow to the entire device. Designing the header system of a microchannel device is almost as important as the design of the device itself. Flow maldistribution is a serious issue that can have significant effects on the heat transfer performance of the device as well as the possibility of increasing pressure drop (Dharaiya et al., 2009). In the case of a solar receiver, maldistribution could lead to overheating and failure. According to Mueller and Chiou (1988) the major contributors to flow issues in microdevices are as follows:

[1] For interpretation of color in Figs. 3 and 5, the reader is referred to the web version of this article.