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# Predictive performance modeling framework for a novel enclosed particle receiver configuration and application for thermochemical energy storage

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ABSTRACT

Concentrating solar power (CSP) plants can provide dispatchable power with a thermal energy storage capability for increased renewable-energy grid penetration. Particle-based CSP systems permit higher temperatures, and thus, potentially higher solar-to-electric efficiency than state-of-the-art molten-salt heat-transfer systems. This paper describes a detailed numerical analysis framework for estimating the performance of a novel, geometrically complex, enclosed particle receiver design. The receiver configuration uses arrays of small tubular absorbers to collect and subsequently transfer solar energy to a flowing particulate medium. The enclosed nature of the receiver design renders it amenable to either an inert heat-transfer medium, or a reactive heat-transfer medium that requires a controllable ambient environment. The numerical analysis framework described in this study is demonstrated for the case of thermal reduction of $CaCr_{0.1}Mn_{0.9}O_{3-\delta}$ for thermochemical energy storage. The modeling strategy consists of Monte Carlo ray tracing for absorbed solar-energy distributions from a surround heliostat field, computational fluid dynamics modeling of small-scale local tubular arrays, surrogate response surfaces that approximately capture simulated tubular array performance, a quasi-two-dimensional reduced-order description of counter-flow reactive solids and purge gas, and a radiative exchange model applied to embedded-cavity structures at the size scale of the full receiver. In this work we apply the numerical analysis strategy to a single receiver configuration, but the framework can be generically applicable to alternative enclosed designs. We assess sensitivity of receiver performance to surface optical properties, heat-transfer coefficients, solids outlet temperature, and purge-gas feed rates, and discuss the significance of model assumptions and results for future receiver development.

## 1. Introduction

Concentrating solar power (CSP) is an effective way to convert solar energy into electricity and can be coupled with relatively low-cost thermal energy storage (TES) to offer dispatch flexibility and continuity despite solar resource variability. Current state-of-the-art commercial power tower CSP systems use a molten-salt heat-transfer fluid (HTF); thus, they are constrained to temperature limits within which the molten salt is chemically stable (< 565 °C). Next-generation CSP systems aim to increase the operating temperature to improve thermal-to-electric conversion efficiency and, correspondingly, to reduce costs and enhance economic competitiveness with alternative power-generation methods (Mehos et al., 2017). Heat-transfer fluids proposed to enable this elevated operating temperature include advanced molten salts, molten metals, gas-phase or supercritical fluids, and solid particles. Inert solids-based CSP systems with TES are promising because they can operate with currently available, low-cost particulate materials that are chemically and physically stable well above 1000 °C without the freezing-point and corrosion concerns of molten salts. Particle-based CSP systems have the potential to reduce the projected CSP system cost (Ma et al., 2015) and can theoretically be further improved by incorporating thermochemical energy storage. Thermochemical storage systems use materials that undergo endothermic chemical transformations in the solar receiver and thereby store solar energy in both sensible and chemical forms. The resulting increase in specific energy storage density has the potential to decrease solids inventory and storage containment costs—and, consequently, CSP system costs. Proposed thermochemical storage materials include metal oxides or carbonates that are endothermically reduced at high temperatures, stored, and subsequently oxidized at comparatively lower temperatures to release energy (André et al., 2016; Cot-Gores et al., 2012; Prieto et al., 2016).

Solids-based CSP systems may offer theoretical advantages over traditional molten-salt systems. However, they also introduce a unique set of challenges, including the development of a solar receiver that can effectively capture the solar heat within the particulate material with high efficiency at elevated temperature. Proposed particle-receiver

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**Nomenclature**

| | |
|---|---|
| $A_{ap,tube}$ | tube aperture area ($m^2$) |
| $A_{sh}$ | heat-shield surface area ($m^2$) |
| $C_p$ | heat capacity (J/kg/K) |
| $\overline{C}_p$ | molar heat capacity (J/mol/K) |
| $d_s$ | particle diameter (m) |
| $D_{cav}$ | embedded-cavity depth (m) |
| $D_{rec}$ | cylindrical-receiver diameter (m) |
| $D_{sh}$ | heat-shield depth (m) |
| $f_p$ | purge-gas injection height fraction |
| $F_{kj}$ | view factor from surface k to surface j |
| $h_{conv}$ | wall-to-solids convective heat-transfer coefficient ($W/m^2/K$) |
| $h_{rad}$ | wall-to-solids radiative heat-transfer coefficient ($W/m^2/K$) |
| $h_{sh}$ | heat-shield natural convection coefficient ($W/m^2/K$) |
| $H_{rec}$ | cylindrical-receiver height (m) |
| $J$ | radiosity ($W/m^2$) |
| $k$ | thermal conductivity (W/m/K) |
| $k_t$ | turbulent thermal conductivity = $C_p\mu_t/\mathrm{Pr}_t$ (W/m/K) |
| $k_0$ | pre-exponential factor (m/s) |
| $m_{s,tot}$ | solids mass flow rate per embedded cavity (kg/s) |
| $M_s$ | solids molecular weight (kg/mol) |
| $n_g$ | gas molar flow rate (mol/s) |
| $n_p$ | purge-gas molar flow rate per CSTR column (mol/s) |
| $n_{p,tot}$ | total purge-gas molar flow rate per embedded cavity (mol/s) |
| $n_s$ | solids molar flow rate per CSTR column (mol/s) |
| $n_{s,tot}$ | total solids molar flow rate (mol/s) per embedded cavity |
| $N$ | total number of embedded-cavity discretization nodes |
| $N_{cav}$ | total number of embedded cavities in full receiver |
| $N_d$ | number of embedded-cavity depth nodes |
| $N_{d,sh}$ | number of heat-shield depth nodes |
| $N_s$ | number of embedded-cavity height nodes |
| $N_{tube}$ | number of absorber tubes described by a single CSTR |
| $p$ | pressure |
| $q_{ap,tube}$ | total radiative energy flux incident on tube aperture ($W/m^2$) |
| $q_{ap,solar}$ | average solar energy flux incident on tube aperture ($W/m^2$) |
| $q_{ap,IR}$ | IR energy flux incident on tube ($W/m^2$) |
| $Q_E$ | thermal radiative (IR) energy leaving a single tube (W) |
| $Q_{E,tot}$ | thermal radiative (IR) energy loss from the embedded cavity (W) |
| $Q_C$ | average thermal energy leaving tube aperture by natural convection (W) |
| $Q_{C,tot}$ | natural convection energy loss from the embedded cavity (W) |
| $Q_{refl,tot}$ | solar reflection loss from the embedded cavity (W) |
| $Q_{source}$ | net energy source to solids per tube (W) |
| $Q_{sol,inc}$ | total solar energy incident on the embedded cavity (W) |
| $\hat{Q}_{chem}$ | chemical energy storage density (kJ/kg) |
| $\hat{Q}_{sens}$ | sensible energy storage density (kJ/kg) |
| $\hat{Q}_{tot}$ | total solids energy storage (kJ/kg) |
| $r_s$ | surface reaction rate ($mol/m^2/s$) |
| R | ideal gas constant |
| $T_{amb}$ | ambient temperature (K) |
| $T_g$ | gas temperature (K) |
| $T_p$ | purge-gas temperature (K) |
| $T_s$ | solids temperature (K) |
| $T_{s,in}$ | solids inlet temperature (K) |
| $T_{s,out}$ | average solids outlet temperature (K) |
| $T_{sh}$ | heat-shield temperature (K) |
| $T_w$ | wall temperature (K) |
| $V$ | volume ($m^3$) |
| $W_{ap}$ | embedded-cavity aperture width |
| $x$ | gas-phase oxygen mole fraction |
| $x_p$ | oxygen model fraction in purge gas |
| $\vec{v}$ | velocity (m/s) |
| $\alpha$ | embedded-cavity vertex angle |
| $\alpha_s$ | solid-volume fraction |
| $\beta$ | surrogate model adjustable coefficients |
| $\delta$ | solids oxygen vacancy |
| $\delta_{eq}$ | solids oxygen vacancy at equilibrium |
| $\Delta h_{ox}$ | oxidation reaction enthalpy (J/mol) |
| $\Delta h_{red}$ | reduction reaction enthalpy (J/mol) |
| $\Delta s_{ox}$ | oxidation reaction entropy (J/mol/K) |
| $\varepsilon_{bed}$ | effective solids bed emissivity |
| $\varepsilon_{eff}$ | effective tube emissivity |
| $\mu$ | fluid viscosity (kg/m/s) |
| $\mu_t$ | turbulent eddy viscosity (kg/m/s) |
| $\rho$ | density ($kg/m^3$) |
| $\rho_m$ | solids molar density ($mol/m^3$) |
| $\rho_{eff}$ | effective tube reflectivity |
| $\rho_{tube}$ | tube-wall surface reflectivity |
| $\eta_{cav,total}$ | embedded-cavity efficiency |
| $\eta_{cav,solids}$ | embedded-cavity efficiency-based energy stored in solids |
| $\theta$ | heat-shield vertex angle |
| $\sigma$ | Stefan-Boltzmann constant ($W/m^2/K^4$) |
| $\sigma_s$ | specularity error (mrad) |
| $\overrightarrow{\overrightarrow{\tau}}$ | viscous stress tensor ($kg/m/s^2$) |
| $\omega$ | specific dissipation rate ($s^{-1}$) |

*Subscripts*

| | |
|---|---|
| *C* | convection |
| *eff* | effective |
| *eq* | equilibrium |
| *E* | emission |
| *g* | gas phase |
| *i* | node-height position |
| *j* | node-depth position |
| *p* | purge gas |
| *s* | solids |
| *sh* | heat shield |
| *w* | wall |

*Abbreviations*

| | |
|---|---|
| CCD | central composite design |
| CFD | computational fluid dynamics |
| CSP | concentrating solar power |
| HTF | heat-transfer fluid |

configurations include open-cavity falling-particle designs (Ho, 2016; Gobereit et al., 2015; Kim et al., 2009; Siegel et al., 2010; Tan et al., 2009), open-cavity obstructed-flow designs (Ho, 2016; Lee et al., 2015), enclosed falling-particle designs (Ma et al., 2015; Martinek and Ma, 2015), rotating-cavity designs (Wu et al., 2015), and directly or indirectly irradiated fluidized-bed designs (Flamant et al., 2013). Open-cavity configurations directly illuminate the solids material and can, in theory, offer highly effective heat transfer to the solids phase. However, performance may be adversely impacted by particle loss through the open aperture, entrainment of cold ambient air within the falling-particle curtain, insufficient residence time in the heated region, and particle flow-rate constraints due to particle-curtain opacity (Ho, 2016;