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Heat transfer in counterflow fluidized bed of oxide particles for thermal energy storage

Daniel C. Miller, Christopher J. Pfutzner, Gregory S. Jackson *

Department of Mechanical Engineering, Colorado School of Mines, Golden, CO, United States

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The potential for inert oxide particles as a heat transfer and thermal energy storage (TES) media in concentrating solar power (CSP) depends in part on particle receiver designs that provide high wall-to-particle heat transfer rates. This paper presents a novel continuous-flow approach to achieve high heat transfer coefficients h_w for particle receivers by fluidizing net-downward-flowing particles in a narrow vertical channel bounded by an external irradiated/heated wall and a parallel interior wall with a metal mesh opening that allows the upward-flowing fluidizing gas to exit at the top of the channel. To demonstrate the high h_w of this flow configuration, a fluidized bed in a 10 cm × 10 cm × 0.64 cm deep channel was heated through an external aluminosilicate wall with mid-IR quartz lamps that provided external wall heat fluxes up to 20 W cm^{-2}. Extensive heat transfer measurements with fluidized Carbo Accucast ID50 particles (diameters between 150 and 350 μm) in steady-state continuous downward flow and in transient batch mode assessed total h_w as functions of particle bed temperatures T_b, bed solids volume fractions α_b, and superficial gas velocities U_g. Results showed that the narrow-channel fluidized bed can achieve overall h_w as high as 1000 W m^{-2} K^{-1}. The highest h_w were measured at upward U_g between 2 and 4 times the minimum bed fluidization velocities, U_{mf}, which decreased to 0.12 m s^{-1} for the mean particle diameter at $T_b = 600\,^\circ\mathrm{C}$. Increasing U_g further above U_{mf} decreased h_w due to an associated decrease in α_b. h_w increased strongly with T_b in part, because gas-phase conductivity and the radiative heat transfer contribution increased with T_b. The extensive measurements were fit to a modified version of the Nusselt number correlation by Molerus (1992). For $\alpha_b \geqslant 0.1$, the Molerus correlation with adjusted dependence on excess fluidization velocity $(U_g - U_{mf})$ provided an excellent fit to the measured convective fraction of h_w (with $< 10\%$ error). Adding the radiation component with the Molerus correlation provides an effective tool for calculating h_w for this counterflow fluidized bed configuration. A simple analysis explored the impact of such high h_w for an indirect receiver design with angled external walls to spread solar aperture fluxes. Results from the analysis indicated that total $h_w = 1000$ W m^{-2} K^{-1} can enable solar collection efficiencies approaching 90% with external wall temperatures $T_{w,ext} \approx 1020\,^\circ\mathrm{C}$. This potential performance motivates further exploration of this fluidized bed configuration for particle receivers for CSP applications.

1. Introduction and background

Concentrating solar power (CSP), as a non-CO$_2$-emitting renewable energy resource, has unique potential in combination with low-cost, large-scale thermal energy storage (TES) to provide dispatchable renewable electricity and thereby to enable higher grid penetration of other intermittent renewable energy resources such as wind and solar photovoltaics [3,4]. Much of recent CSP technology development has focused on central receivers with solar concentrations of 1000 suns (1 sun = 1000 W m^{-2}) or more to achieve high temperatures in heat transfer fluids (HTFs) for coupling to high-temperature TES and power cycles with better electrical conversion efficiencies than typical steam Rankine power cycles [5–7]. Central-tower CSP plants have a solar collector field with heliostat mirrors that concentrate the solar flux onto a central receiver where the solar energy is absorbed and transferred to the HTF. A recovery heat exchanger extracts stored solar thermal energy from the HTF into a power cycle that generates electricity. New central-receiver CSP installations have incorporated TES subsystems based on molten nitrate salts, which also serve as the HTF, to enable temporal shifting of electricity generation to make the solar energy resource more dispatchable [8,9]. The nitrate salts

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* Corresponding author.
E-mail address: gsjackso@mines.edu (G.S. Jackson).

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have temperature stability limits below 600 °C, and thus, can only be integrated with lower-temperature power cycles such as Rankine cycles with electric conversion efficiencies well under 40%. To overcome these limitations of current molten salts, many researchers and developers are exploring HTFs that provide the potential for higher-temperature TES to allow for CSP to couple with higher efficiency power cycles, such as supercritical-CO_2 cycles [10–12] or recuperative air-Brayton cycles.

Alternative HTFs with higher temperature limits that are being explored include molten carbonate salts [13,14], molten chloride salts [15,16], liquid metals [7], inert solid oxide particles [17–20], and redox-active oxide particles for thermochemical energy storage [21–24]. Molten carbonate and chloride salt mixtures have the promise of operating temperatures as high as 850 and 900 °C respectively, but the carbonates have stability issues at high temperatures [14]. Furthermore, identifying cost-effective, corrosion-resistant structural materials for containment of these molten salts and liquid metal remains a significant challenge for operation above 700 °C [7,15]. Thermochemical energy storage (TCES) systems based on reducible oxides redox cycles have the potential to provide very high storage temperatures and specific TES capacity, but at the expense of system complexity that remains an issue for substantially more research and development [23,25]. Inert oxide particles also offer the potential for extremely high temperatures above 1000 °C, but they only provide sensible energy storage and as such lower specific TES ($\mathrm{kJ\ kg^{-1}}$) for a given temperature difference between the hot (T_H) and cold (T_C) storage [17]. Nonetheless, low-cost, inert oxide materials such as Al_2O_3 [26], bauxite [27], or quartz sand [28] have the potential to provide cost-effective energy storage at very high T_H and any range of T_C without concerns related to high-temperature corrosion or lower temperature freezing. The material stability and operational flexibility of inert oxide materials for high-temperature TES motivates the significant research on various particulate materials for heat transfer media as summarized in recent reviews [20,29].

Particulate oxide materials as the HTF and TES storage media in CSP plants require design and implementation of effective particle transport systems and robust flow control for both the solar receiver and the recovery heat exchanger to transfer the thermal energy to the power cycle. Unlike high-temperature liquid HTFs such as molten salts, particulate solids present unique challenges in terms of flow distribution and effective heat transfer. Research on particulate HTFs has led to development of two different categories of solar particle receivers, direct and indirect absorption receivers [20,30]. Direct particle receivers allow solar radiation from a heliostat field to irradiate the particles directly either in an open environment or through a transparent window, often proposed as quartz. Sandia National Laboratories in the U.S. has been leading significant efforts on developing direct absorption particle receivers utilizing a falling-particle curtain [27,31,32]. Open direct-receiver concepts rely on gravity-driven flows with or without obstructions to slow the particle fall and increase the residence time within the receiver. Other gravity-driven direct particle receivers have been demonstrated [33,34] including designs with quartz tubes to confine the directly irradiated particles [35]. With open direct receivers, high efficiency solar energy capture is possible, but convective losses and particle containment remain challenges, and it can be difficult to balance the need for high solar absorption efficiency and uniform particle heating in curtain-based designs [20]. The concerns motivate designs with transparent windows like quartz, but the structural integrity at large scales of such transparent window materials under the cyclic non-isothermal conditions presents an unresolved challenge.

Concerns with direct receiver designs motivate research and development on indirect particle receivers, where the particles are confined within opaque wall materials that provide better structural integrity under the cyclic high-temperature operation of a central solar receiver [20]. One indirect particle receiver concept uses a unique fluidized upward flowing suspension of particles to provide high heat transfer rates and particle flow control [18,36,37]. Other gravity-driven indirect receivers have employed granular flow over solar radiation-trapping cavities to increase particle residence times and surface area to spread solar fluxes and lower requirements for h_w [38,39]. Such designs with more complex geometries increase risk for mechanical failure due to thermal stresses and/or cyclic fatigue and as such designs that rely on simpler configurations and rely on flows that promote higher h_w between confinement walls and the particles. Higher h_w for external receiver walls that absorb concentrating solar fluxes reduces the necessary wall temperatures T_w to capture a specific wall heat flux $\dot{q}''_w$. Lower T_w for a given $\dot{q}''_w$ decreases re-radiation losses from the receiver to the environment (that scale with T_w^4) and thus increase receiver efficiency. To meet solar receiver efficiency goals of 90% as set by the U.S. Department of Energy [11], particle receivers with external walls will need to sustain very high h_w as discussed below in the current study.

Bubbling fluidized beds offer an approach to high h_w in indirect particle receivers and other particle heat exchanger applications. Many studies on heat transfer with fluidized particle flows have focused on horizontal tubes or tube bundles inside the bed as might be relevant in a recovery heat exchanger for CSP [40–45]. Other studies have addressed heat transfer between circulating fluidized beds and vertical surfaces [46–48], but the void volume fractions and gas velocities for those studies were much higher than typical for bubbling fluidized beds. Research groups in Europe [18,36,30,49] have experimentally assessed heat transfer between fluidized beds and vertical walls for central receiver applications. Table 1 highlights those and a few other investigations and shows significant variation in measured h_w. The large variation in h_w measurements may be due in part, to variations in particle properties, particle diameter d_p, superficial gas velocity U_g, and average bed temperature T_b. Nonetheless, these studies do indicate that some conditions can provide very high $h_w \geqslant 1000\ \mathrm{W\ m^{-2}\ K^{-1}}$, and if such h_w can be sustained in a receiver design, fluidized bed configurations may achieve receiver efficiency targets $> 90\%$.

Efforts in multi-phase flow CFD have explored the wall-to-particle heat transfer in fluidized beds [35,53,54], but conventional two-fluid CFD methods of modeling particle-laden flows have shown limited success in predicting wall-to-bed heat transfer [55,56]. Recent advances combining CFD with discrete element methods (DEM) using high-performance computing have shown promise in improving predictions of computational multi-phase modeling of particulate flows [57,58]. Computational demands for these approaches do not facilitate extensive parametric design studies, and this has encouraged research into more efficient simulation approaches such as recurrence-CFD [59]. While advances in fluidized bed modeling present opportunities for numerical design of some aspects of fluidized-bed heat exchangers and solar particle receivers, the complexities and computational costs of particle-flow modeling at necessary length and time scales support further careful experimental studies to measure h_w for a wide range of conditions and develop reliable correlations that support model calibration as well as design of particle receivers and fluidized bed heat exchangers for CSP and other thermal energy storage applications.

The heat transfer studies for fluidized beds interacting with vertical walls have generally explored particle flow regimes where the net particle flow is in co-flow upward with the gas in a large flow path. An alternative novel approach presented in this study involves net-downward, continuous particle flow in counterflow to the fluidizing gas in a narrow vertical channel. In this approach,