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Thermal energy storage with supercritical carbon dioxide in a packed bed: Modeling charge-discharge cycles

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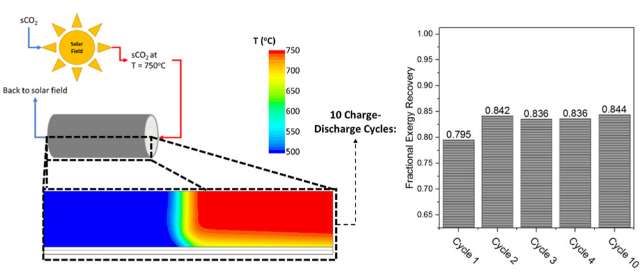
GRAPHICAL ABSTRACT



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ABSTRACT

Thermal energy storage in concentrated solar power systems extends the duration of power production. Packed bed thermal energy storage is studied in this work with supercritical carbon dioxide as the working fluid and α-alumina as the storage material. The operating conditions are appropriate for use in a supercritical Brayton cycle. An axisymmetric model produces temperature profiles in the bed, insulation, and pressure vessel in the axial and radial directions over time. The packed bed system has a mass flow rate of 8.17 kg s^{-1} at 275 bar. The inlet temperature is 750 °C for storage. In discharge, gas at 500 °C enters the bed to recover the stored energy. Discharge continues until the outlet temperature drops below 700 °C, the minimum temperature required for the turbine inlet. Ten charge-discharge cycles are considered and thermal exergetic efficiency is calculated. Due to thermal dispersion and heat losses, the exergetic efficiency varies from 0.795 to 0.844.

1. Introduction

Concentrated solar power (CSP) is an appealing renewable source of energy. Distinct from solar photovoltaics, CSP systems concentrate solar energy by reflecting sunlight to a receiver with an array of specialized mirrors. At the receiver, a thermal energy carrier is heated, and the heat is used to generate power [1]. In 2016, global CSP systems accounted for 4805 MW with the U.S. and Spain at 1745 MW and 2304 MW, respectively. Current state-of-the-art systems utilized molten salts at temperatures of 565 °C with a steam-Rankine power cycle with estimated costs in the 10–14 ¢/kWh range [2]. However, this cost remains higher than the goal of 6¢/kWh_e by 2020 under the SunShot Initiative of the US Department of Energy (DOE) [3,4]. One limiting factor in CSP applications that increases cost is that solar energy is variable and intermittent, such as from summer to winter or day to night [1], necessitating some type of thermal energy storage (TES) system [4,5].

Various pathways are being considered including improvements to molten salt technology, falling particle systems, and gas phase systems

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Nomenclature

Bi	Biot number
d_p	Particle diameter (m)
d_{bed}	Bed diameter (m)
c_p	Heat capacity ($J\,kg^{-1}\,K^{-1}$)
c_F	Dimensionless drag constant
$h_{f,s}$	Fluid-solid heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
$h_{f,s\|V}$	Fluid-solid volumetric heat transfer coefficient ($W\,m^{-3}\,K^{-1}$)
k	Thermal conductivity ($W\,m^{-1}\,K^{-1}$)
L_{bed}	Bed length (m)
$\dot{m}$	Mass flow rate ($kg\,s^{-1}$)
P	Pressure (Pa)
P_{exit}	Exit pressure (Pa)
Q_{loss}	Heat loss from vessel (W)
t	Time (s)
$t_{final,r}$	Time recovery cycle ends (s)
$t_{start,r}$	Time recovery cycle starts (s)
T	Temperature (K)
$T_{cold\text{-}recovery}$	Discharge inlet temperature (K)
$T_{initial}$	Initial temperature (K)
T_0	Ambient temperature (K)
$T_{r,out}$	Recovery outlet temperature (K)
T_s	Storage inlet temperature (K)
$U_{loss\|V}$	Overall volumetric heat transfer coefficient from vessel ($W\,m^{-3}\,K^{-1}$)
$\vec{v}_f$	Velocity ($m\,s^{-1}$)
x	Axial bed position [m]
ε	Porosity of packed bed
ρ	Density ($kg\,m^{-3}$)
η_{th}	Fractional thermal exergetic efficiency
μ	Viscosity (Pa s)
eq	Equivalent
f	Fluid
s	Solid

Dimensionless variables

$\theta = \frac{T - T_0}{T_s - T_0}$	Dimensionless temperature
$\tau = \frac{t\bar{v}_f^*}{L_{bed}}$	Dimensionless time
$X = \frac{x}{L_{bed}}$	Dimensionless position
$\bar{v}_f^* = \frac{\bar{v}_f}{\varepsilon}$	Average pore-scale velocity
$St_{f,s} = \frac{h_{f,s\|V}L_{bed}}{\rho_f c_{p,f}\bar{v}_f^*}$	Stanton number, fluid-solid
$St_w = \frac{U_{loss\|V}L_{bed}}{\rho_s c_{p,s}\bar{v}_f^*}$	Stanton number, wall losses
$\frac{1}{Pe_{af}} = \frac{k_f}{\rho_f c_{p,f} L_{bed}\bar{v}_f^*}$	Inverse fluid Péclet number
$\frac{1}{Pe_{as}} = \frac{k_s}{\rho_s c_{p,s} L_{bed}\bar{v}_f^*}$	Inverse solid Péclet number
$\kappa = \frac{\rho_f c_{p,f}}{\rho_s c_{p,s}}\left(\frac{\varepsilon}{1-\varepsilon}\right)$	Kappa number

[2]. An emerging working fluid in the gas phase systems is supercritical carbon dioxide (sCO_2) [6–9] for use in Brayton cycles [10–15]. sCO2 could work in various roles for molten salt, falling particle, and gas phase systems. Several recent studies have specifically looked at these sCO_2 systems from a holistic view of system efficiency, including the receiver, power cycle, and heat exchangers [7,16]. In the majority of these holistic analyses, a thermodynamic model is used to complete an energy balance around the storage unit, but this does not provide additional insight into the operation of the energy storage unit itself. For instance, Osorio et al. [16] considered a sCO_2 system where the hot thermal energy storage system was a molten salt. In another system, the hot thermal energy storage was a packed bed of spherical granite [7]. In their packed bed system, the average temperature difference of their heat storage system was assumed as either 5 K or 0 K for an ideal case. It did not model flow through the bed to determine the storage recovery temperature. Further, Zhang et al. [8] treated the thermal energy storage as a simplified direct heat exchanger and assumed the energy stored was fully recovered. Unlike this previous work, this paper analyzes the thermocline behavior of packed bed thermal energy storage with sCO_2 as the working fluid, which is critical to understand and optimize any TES design.

Thermal energy storage and subsequent recovery must be performed efficiently to allow for power production when sunlight is not available [7,9,16]. Three types of TES systems are available: sensible, latent, and chemical [17,18]. Sensible heat storage systems can store the fluid at high temperature or deposit the energy content of the working fluid, or a separate heat transfer fluid [19], onto a storage medium. The storage arrangement studied here is based on sensible heat storage in a packed bed [20–25]. Latent heat systems typically use encapsulated phase change materials and store/release heat via the melting/solidification process [26]. Though the energy density can be higher due to the latent heat, the operating temperatures are limited to the melting/freezing temperature of the PCM. In chemical storage, an endothermic reaction stores energy, while the reverse exothermic reaction releases the energy during recovery [27]. A current issue with these systems is heat and mass transfer within the reactor [27].

In packed bed TES (PBTES) systems, solid particles are stored in a vessel with sufficient insulation between the packing material and the pressure vessel walls. Heat from a hot fluid is deposited onto beads as it flows through the bed. To recover the heat, the flow direction is reversed; cool gas enters the packed bed and exits at a temperature close to the initial storage temperature. To better optimize the process within a packed bed, other studies have investigated the effects of void fraction, flow rate, bead material/size, and operating temperature [20,24,28,29]. More broadly, the packed bed arrangement can be utilized in a number of concentrated solar thermal (CST) technologies in addition to the CSP plants, including low temperature power cycles, desalination, enhanced oil recovery, and chemical processing [30]. In general, these design parameters must be optimized for a given system. For instance, smaller diameter packing materials can ensure no intraparticle temperature gradients exist, which is advantageous for operation. However, the small particle diameter can increase the pressure drop in the system, which represents a parasitic power loss requiring additional pumping power. Similarly, a higher flow rate of fluid may charge the bed faster, but this can increase both thermal dispersion and pressure drop, thus reducing the overall efficiency. For packed beds to be efficient in thermal cycling, they must maintain a high degree of thermal stratification [23,31]. The exergy efficiency approaches 100% when the temperature progression in the bed mimics a perfect step function, where zones of the bed are either at the maximum or minimum temperature during charge and discharge. However, thermal dispersion causes mixing and thus a thermocline develops in the bed. This effect, along with heat losses to the environment, lead to exergetic efficiencies below 100% [9,23]. Exergy is important to consider as it quantifies irreversibilities that decrease efficiency [9] and determines the amount of useful work that can be extracted from the system [23]. A detailed description of exergy calculations is provided in Section 3.4.

While TES systems in general have been studied in the technical literature, this study provides a unique analysis of sCO_2 as the working fluid in the context of a recuperated Brayton cycle with α-alumina beads as storage material. The conditions here are based on Brayton cycle operating conditions implemented at Southwest Research