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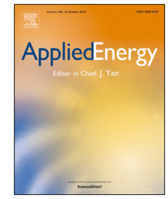

Dynamic modeling of a particle/supercritical CO_2 heat exchanger for transient analysis and control

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HIGHLIGHTS

- A dynamic model of a moving packed-bed particle-to-sCO_2 heat exchanger is presented.
- The aim of the heat exchanger is to raise the sCO_2 temperature to 700 °C at a pressure of 20 MPa.
- A control system based on adjusting both the particle and sCO_2 mass flow rates is proposed.
- The comparison between feed-forward and feedback control strategies is presented.

ARTICLE INFO

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Heat exchanger
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Feedback control
Supercritical CO_2
Falling particle receiver

ABSTRACT

A dynamic model of a moving packed-bed particle-to-sCO_2 heat exchanger and control system for concentrating solar power (CSP) applications is presented. The shell-and-plate heat-exchanger model allows for numerically investigating the transient operation and control of the heat addition to the power cycle in a particle-based CSP plant. The aim of the particle-to-sCO_2 heat exchanger is to raise the sCO_2 temperature to 700 °C at a pressure of 20 MPa. The control system adjusts both the particle and sCO_2 mass flow rates as well as an sCO_2 bypass to obtain the desired sCO_2 turbine inlet and particle outlet temperatures for a prescribed thermal duty. The control system is demonstrated for disturbances in particle and sCO_2 inlet temperatures as well as changes in thermal duty for part-load operation. A feed-forward control strategy that adjusts the sCO_2 and particle mass-flow rates as functions of measured inlet temperatures and a steady-state model solution was able to return the heat exchanger to the desired operating condition, but not without experiencing significant deviations in the sCO_2 turbine inlet and particle outlet temperature ($>$ 40 °C) during the transient. To reduce both sCO_2 and particle temperature deviations, a feedback control strategy was investigated, where sCO_2 and particle mass-flow rates based on the steady-state model solution were corrected based on measured outlet temperature deviations. The feedback control strategy maintains sCO_2 turbine inlet and particle outlet temperature to within 16 °C of the set points with a three-minute settling time for step changes in inlet conditions and thermal duty. This finding demonstrates the possibility of dynamically dispatching next-generation particle-based CSP plants driving sCO_2 power cycles.

1. Introduction and objectives

The integration of concentrating solar power (CSP) plants onto the electric grid allows for renewable solar energy to be dynamically dispatched. This is enabled by CSP's ability to provide low-cost, high-efficiency thermal energy storage, which essentially decouples the intermittent renewable resource from the thermal load of a power cycle to meet fluctuating demands of the electric grid. A recent study [1] has identified dynamic dispatch as the cost-optimal operating strategy for CSP plants. The desired future CSP plant will have fast ramping and turn-down capabilities, which only increase in importance as other renewable generators (i.e., photovoltaics and wind) increase penetration. For CSP plants to meet this need, fast ramping and turn-down capabilities as well as control must be demonstrated for next-generation CSP configurations.

The particle receiver has been identified [2] as one of the three potential pathways for the next-generation CSP plants to improve solar-to-electric efficiency through coupling to a supercritical carbon dioxide (sCO_2) Brayton cycle. According to the United States Department of Energy CSP Gen 3 Roadmap [2], the particle heat exchanger is one of

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Nomenclature

A	area (m^2)
c_p	specific heat (J/(kg K))
d_p	particle diameter (m)
GCI	grid convergence index (%)
h	heat transfer coefficient ($W/(m^2 K)$)
hc	plate spacing (mm)
H	height (m)
k	conductivity (W/(m K))
m	mass flow rate (kg/s)
p	observed order of accuracy (–)
r	refinement factor (–)
s	scaled sensitivity coefficient (°C)
t	time (s)
t_{HX}	plate thickness (mm)
T	temperature (°C)
u	velocity (m/s)
u_{num}	numerical uncertainty (%)
U	overall heat transfer coefficient ($W/(m^2 K)$)
W	width (m)

Greek letters

ΔT_{lm}	logarithm mean temperature difference (–)
ε	voidage (–)
ρ	density (kg/m^3)

Subscripts

BP	bypass
$f\text{-}b$	feedback control strategy
HX	heat exchanger
in	inlet
$f\text{-}f$	feed-forward control strategy
out	outlet
s	particulate phase
w	heat exchanger wall

the technology gaps that should be addressed to demonstrate high solar-to-electric conversion efficiencies for next-generation CSP. In the present paper, the transients and off-design operation of the particle-to-sCO_2 heat exchanger are discussed and a control system is proposed. This research issue has not been investigated in the past and it is critical to gain operational understanding of this key component of particle-based CSP plants prior to on-sun testing.

2. Prior work

Solid particle receivers have been proposed to achieve higher inlet temperatures needed for sCO_2 power cycles. In the falling particle receiver configuration, particles fall through a cavity receiver and are directly irradiated by a beam of concentrated sunlight. Direct irradiation of the heat transfer media avoids the flux limitations associated with tubular central receivers. Once heated, the particles may be stored in an insulated tank and discharged to heat the power cycle working fluid [3]. The majority of research to date has focused on the development of high-efficiency and high-temperature particle solar thermal receivers [4]. Siegel et al. [5] developed a CFD model of a falling-particle cavity receiver, which was validated against experimental measurements at power levels up to 2.5 MW_{th} at Sandia National Laboratories in Albuquerque. More recently, Ho et al. [6] presented advancements in particle receiver designs including the use of porous structures in the particle flow or particle recirculation to increase the residence time in the concentrated sunlight. Air curtains near the aperture of the receiver have also been investigated to stabilize particle flow and reduce convective heat loss by external winds. Zhang et al. [7] presented an innovative solar receiver technology in which particles move upward in tubes that constitutes the solar absorber.

Supercritical CO_2 in a closed-loop Brayton cycle offers the potential of higher cycle efficiency in comparison with superheated or supercritical steam cycles at temperatures relevant for concentrating solar power (CSP). Turchi et al. [8] studied the efficiency achieved by different sCO_2 Brayton cycle configurations, and concluded that cycle configurations such as the partial cooling cycles and recompression with main-compression intercooling together with reheat can achieve greater than 50% efficiency. However, sCO_2 Brayton cycles require higher temperature heat addition than those previously integrated with central receivers. Current central receiver technologies employ either water/steam or molten nitrate salt as the heat-transfer and/or working fluid in subcritical Rankine power cycles, with inlet temperatures lower than 600 °C.

With the advancements in high-temperature particle receiver technology approaching thermal efficiencies values of 90%, the design and analysis of a heat exchanger for extracting thermal energy from the particles and transferring it to the power-cycle working fluid is required for system realization. The design and production of particle heat exchangers for fluidized bed reactors and particle cooling for industrial applications has existed for decades. However, the unique application of a particle heat exchanger for high-temperature (≥700 °C), high-pressure (≥20 MPa) sCO_2 has not been demonstrated [2]. Gomez-Garcia et al. [9] developed a comprehensive analytical model of the heat transfer in a cross-flow multistage fluidized bed heat exchanger for particle receiver solar power plants. The model enables a parametric analysis of the heat exchanger performance to be conducted as a function of the operating conditions of the power block, the heat exchanger geometry and the fluidized bed properties. Other studies were concerned with the potential application of PCMs in high-temperature energy capture and storage, using a circulating fluidized bed (CFB) as transfer/storage mode [10]. Fornarelli et al. [11] developed a CFD model for investigating the melting process in a shell-and-tube latent heat storage with PCM for CSP applications.

Recent work has identified moving packed-bed particle heat exchangers as low-cost alternatives to fluidized beds because moving packed-beds avoid the high-cost components in fluidized beds, which include pumps to fluidize the particles and recuperators to prevent large thermal loss from the fluidization gas. Baumann et al. [12] developed a CFD multiphase model approach to describe the flow distribution and the thermal performance of a moving bed heat exchanger. They compared the numerically estimated heat transfer coefficient with the empirical penetration model, and concluded that the multiphase approach is well suited to predict the thermal behavior. Bartsch et al. [13] developed a continuous model approach, based on the theory of soil mechanics to describe the granular flow inside the heat exchanger, which was validated with particle image velocimetry (PIV) measurements of horizontal tubes. The Eulerian-Eulerian model captured the velocity profile around the tubes except for in the void region below the tube. Despite this inaccuracy, they concluded that the model is suitable for simulating moving packed beds. Isaza et al. [14] presented an analytical solution for counter-current parallel-plate moving bed heat exchangers in steady-state, applicable in sizing and thermal performance analysis. Albrecht et al. [15] developed a single-component continuum model of a moving packed-bed heat exchanger for steady state operations, capable of investigating the design trade-offs in particle size, operating temperature, and particle velocity (residence time).

For a particle-based CSP plant to be dynamically dispatched, the transient operation and control must be studied. Iverson et al. [16]