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Simulations of heat transfer to solid particles flowing through an array of heated tubes

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Abstract

A novel solar receiver that uses solid particles as a heat transfer fluid is being developed at the National Renewable Energy Laboratory for use in concentrating solar power plants. The prototype considered here is enclosed and contains arrays of hexagonal heat transfer tubes that particles flow between. Discrete element method (DEM) simulations were completed for a laboratory-scale solar receiver for different geometric configurations, hexagon apex angles, particle sizes, and mass flow rates. The heat transfer strongly depends on the particle size, where increased heat transfer is obtained using smaller particles. At higher solids mass flow rates, more particles contact the heat transfer surfaces and the overall heat transfer increases. When a sharper apex angle was used, the particles flow through the receiver at a faster velocity, but the heat transfer decreases because the solids concentration decreases slightly at higher velocities. The DEM simulations show that the heat transfer strongly depends on the solids concentration near the heat transfer surfaces as well as particle size. A new continuum model has recently been developed (Morris et al., 2015) that accounts for both of these effects, and it was previously tested for simple systems. In the current effort, the continuum model was applied to the complex solar receiver and validated via comparison to DEM data. The results indicate that the new continuum model accurately predicts the local heat transfer coefficient and yields an overall heat transfer coefficient with an average error less than 5%.
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1. Introduction

Concentrating solar power (CSP) plants operate by collecting heat from concentrated solar energy and then converting that thermal energy to electricity via a turbine and electrical generator (Ho and Iverson, 2014). This process is similar to conventional power plants where instead of combusting fossil fuels or using nuclear fuel rods, many mirrors covering a large area focus solar energy onto a smaller-area solar receiver. For large-scale power plants capable of producing hundreds of megawatts of electrical power, a power tower design for the solar receiver is standard. For this receiver, a field of mirrors concentrate solar radiation onto a central tower that contains a heat transfer fluid (HTF). The HTF can act directly as a working fluid to turn a turbine, i.e., steam, or indirectly to heat a working fluid.

The HTF is a critical component for the thermal and economic performance of a CSP facility (Vignarooban

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Nomenclature

Variables

A	surface area (m^2)
C_p	specific heat (J/kg K)
D_p	particle diameter (μm)
e	normal coefficient of restitution
g	gravitational acceleration (m/s^2)
H	thermal conductance (W/K)
h	heat transfer coefficient (W/m^2 K)
H_g	interphase thermal conductance (W/K)
k_n	collision spring constant (N/m)
l	gap distance between the particle surface and the wall (m)
m_p	particle mass (kg)
P	pressure (Pa)
q	heat flux (thermal or granular) (W/m^2)
Q	heat transfer rate (W)
R	radius (m)
r	radial distance (m)
s	minimum conduction distance (m)
t	time (s)
T	thermodynamic temperature (K)
v	velocity (m/s)

Dimensionless groups

Bi	Biot number, hD_p/κ_p
Nu	Nusselt number, hD_p/κ_g
Nu_g	Nusselt number for interphase transfer
Pr	Prandtl number
Re	Reynolds number
α	Hexagon apex angle
β	gas–solids drag coefficient
δ	particle–wall overlap (m)
ε	volume fraction
ϕ_g	gas–solids granular energy dissipation term
γ	dissipation term due to inelastic collisions
κ	thermal conductivity (W/m K)
Θ	granular temperature (m^2/s^2)
ρ	density (kg/m^3)
τ	shear stress tensor
μ_g	gas viscosity (Pa s)

Subscripts

c	contact
g	gas phase
$lens$	fluid lens
p	particle
pp	particle–particle
pfp	particle–fluid–particle
pw	particle–wall
pfw	particle–fluid–wall
ref	reference value
s	solids phase
w	wall
Θ	granular temperature

et al., 2015). In general, desirable characteristics of the HTF include: ability to operate at high temperatures (>650 °C), ability to flow at low temperatures, high heat capacitance for thermal storage, efficient heat transfer, low cost, and low corrosion with metal alloys containing the HTF. The ability to operate at high temperatures is critical because the thermodynamic efficiency can be increased by raising the temperature of the working fluid that enters the turbine. The ability for thermal storage significantly reduces costs associated with transient operation due to diurnal cycling or cloud cover. Solid particles (e.g., sand) are a candidate HTF that satisfies the desired characteristics and solar receivers that utilize solid particles as a HTF are under development at the National Renewable Energy Laboratory (NREL) and Sandia (Ho et al., 2009; Martinek and Ma, 2015; Siegel et al., 2010). Solid particles can improve upon existing molten salt technologies because solid particles such as sand are inert at high target temperatures (900 °C) and are inexpensive. Similarly, solid particles can improve upon HTF's such as steam or oil because solid particles have high heat capacity and perform well as a thermal storage media. There are many challenges associated with particle receivers, such as abrasion of heat transfer surfaces or attrition of particles, but the scope of this work is limited to heat transfer and hydrodynamic performance.

The prototype, solid-particle receiver designed at NREL, shown schematically in Fig. 1, is a power tower that contains many hollow heat transfer tubes. The concentrated solar radiation enters the end of each tube and is internally absorbed with near black-body efficiency. Cold particles are lifted via a bucket elevator and poured over the heat transfer tubes. These particles are heated as they

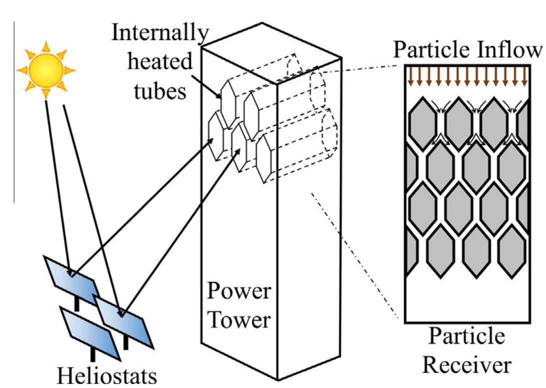

Fig. 1. A schematic showing the enclosed particle receiver with hexagonal heat transfer tubes.

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