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A numerical investigation of gas-particle suspensions as heat transfer media for high-temperature concentrated solar power

Jan Marti, Andreas Haselbacher *, Aldo Steinfeld

Department of Mechanical and Process Engineering, ETH Zurich, 8092 Zurich, Switzerland

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ABSTRACT

This paper investigates the detailed heat-transfer mechanisms in dense gas-particle suspensions used as heat transfer media for high-temperature concentrated solar power applications. A two-phase Euler–Euler model for dense gas-particle systems is built on the open-source code OpenFOAM. The model is capable of predicting the complex hydrodynamic behavior of bubble formation, coalescence, and breakup together with conduction, convection, and radiation heat transfer. At each time step, the model calculates the effective radiative properties as a function of the local solid volume fraction. Therefore, the model captures radiation penetrating through gas bubbles near the riser wall and radiation being absorbed within a few millimeters by the dense gas-particle suspension. Comparisons with on-sun experimental results indicate that the model accurately predicts coupled hydrodynamics and heat transfer in dense gas-particle systems. The model is used to investigate the heat-transfer mechanisms in a slowly rising, dense gas-particle suspension located in a directly irradiated riser tube. The majority of the heat transfer takes place within a distance of a few particle diameters from the heated riser wall. In this region, the particles are heated by solid conduction and heat is then transferred by solid convection to the colder flow in the center of the riser. It is shown that with a moderate riser wall temperature of 581 K and a particle diameter of 64 μm, solid conduction accounts for about 97% of the wall-to-suspension heat flux. Increasing the wall temperature to 981 K together with a particle diameter of 400 μm leads to an increase of the radiation heat-flux contribution up to about 10% of the total wall-to-suspension heat flux.

1. Introduction

Concentrated solar power (CSP) plants are typically based on subcritical Rankine cycles with a working-fluid temperature below 500 °C and a thermal-to-electricity efficiency in the range of 30–40% [1]. An increase of the working-fluid temperature above 600 °C enables the use of more efficient supercritical Rankine cycles. As a consequence, the thermal-to-electricity efficiency increases about 10% compared to a subcritical Rankine cycle [2,3]. Furthermore, to allow cost-effective and round-the-clock dispatchable electricity generation using CSP, such plants must incorporate thermal storage systems. Several types of storage concepts have been developed, but their widespread adoption is at present limited by high costs [2].

For large-scale high-temperature CSP plants, solar power towers are particularly suitable due to their maturity, high solar concentration ratio, and favorable design for thermal storage [4]. A solar power tower contains a receiver unit into which tracking heliostats reflect the incident sunlight. Inside the receiver unit, the solar energy heats either a working fluid (e.g., steam) or a heat transfer medium (HTM). The working fluid can be used directly in a heat engine whereas the HTM acts as intermediate storage of thermal energy in an indirect cycle. After passing through the receiver unit, the HTM can be either stored for later use or routed through a heat exchanger. In the latter case, the thermal energy of the HTM is transferred to a working fluid that is subsequently used in the heat engine [5,6]. Existing CSP plants based on solar power towers typically use either molten nitrate salts as HTM in an indirect cycle or water/steam as a working fluid in a direct cycle [7].

For temperatures above 600 °C, molten nitrate salts become unstable and decompose [8]. Direct steam production is impractical for thermal storage due to very high pressures at critical conditions and low volumetric heat capacities [9]. Alternative HTM are required for operation at high temperatures. This has motivated the investigation of liquid metals as high-temperature HTM [10]. However, their use entails substantial safety risks due to their reactivity with oxygen and, similar to molten nitrate salts, the problem of solidification at low temperatures [1,10]. Using particles to absorb and store solar energy can avoid the aforementioned

* Corresponding author. Tel.: +41 44 632 69 05.
E-mail address: haselbac@ethz.ch (A. Haselbacher).

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Nomenclature

Abbreviations
CFD computational fluid dynamics
CSP concentrated solar power
HTM heat transfer medium

Greek characters
α phase fraction, –
β extinction coefficient, m^{-1}
Δ difference, –
ϵ emissivity, –
γ particle collision dissipation coefficient, kg/m^3 s
κ absorption coefficient, m^{-1}
μ dynamic viscosity, kg/m s
∇ nabla operator, m^{-1}
ν kinematic viscosity, m^2/s
Ω solid angle, sr
ω scattering albedo, –
$\bar{\bar{\tau}}$ viscous stress tensor, Pa
ψ particle shape factor, –
ρ density, kg/m^3
σ Stefan–Boltzmann constant, 5.6704e−8, $W/m^2\,K^4$
σ_s scattering coefficient, m^{-1}
τ optical thickness, –
Θ granular temperature, m^2/s^2
ξ solid- or gas-phase property, units depend on context

Latin characters
$\bar{\bar{\mathbf{I}}}$ identity tensor, –
$\mathbf{g}$ gravitational acceleration vector, m/s^2
$\mathbf{n}$ unit normal vector, –
$\mathbf{q}$ heat-flux vector, W/m^2
$\mathbf{r}$ position vector, m
$\mathbf{s}$ unit vector, –
$\mathbf{U}$ interstitial velocity vector, m/s
A area, m^2
a, b coefficients, –
A_1 linear-anisotropic scattering coefficient, –
C_D drag coefficient, –
c_p specific heat capacity, J/kg K
d diameter, m
E incoming irradiation, W/m^2
e specific internal energy, J/kg^3
e_r restitution coefficient, –
f frequency, s^{-1}
G incident radiation, W/m^2
H height, m
h surface, volumetric heat transfer coefficient, W/m^2 K, W/m^3 K
I radiation intensity, W/m^2 sr
J_1 granular temperature dissipation term, kg/m^3 s
J_2 granular temperature source term, kg/m s^3
k heat conductivity, W/m K
k_Θ granular temperature conductivity, kg/s m
K_D interphase drag coefficient, kg/m^3 s
L length, m
m mass, kg
N_i number of cells, –
N_t number of time steps, –
P pressure coefficient, kg/m^3
p pressure, Pa
Q power, W
q heat flux, W/m^2
q_v volumetric flux, m^3/m^2 s
S energy source term, W/m^3
T temperature, K
t time, s
v_r dimensionless terminal velocity, –
W width, m
x radial coordinate, m
y axial coordinate, m
Bi Biot number, –
Nu Nusselt number, –
Pr Prandtl number, –
Re Reynolds number, –

Subscripts
Θ granular temperature
g gas
i cell number
p particle
r relative
s solid
0 initial
aer aeration
atm atmosphere
ave averaging
cold cold surface
conv convection
eff effective
heated heated riser section
hot hot surface
in inlet
int interval or internal
kin kinetic
leak leakage
LMTD logarithmic mean temperature difference
max maximum
norm normalized
out outlet
rad radiation
sg solid–gas interphase
sus suspension

Superscripts
n time step

problems. The potential of dilute gas-particle suspensions as working fluids for solar applications without intermediate storage was studied independently by [11–13] in the late 1970s. The use of particles as an intermediate HTM was experimentally studied in a fluidized bed [14] and in a freely falling, directly irradiated curtain [15]. Due to their stability at temperatures up to 1000 °C, particles made of alumina, silica, silicon carbide (SiC), or zircon, are especially attractive [16]. Because typical specific heat capacities of these materials are comparable to those of molten nitrate salts, particles are suitable as thermal storage media [17]. Particles made of SiC are of particular interest because they are inexpensive and widely available [6].

A recent experimental on-sun study demonstrated a new CSP concept based on dense gas-particle suspensions of air and SiC particles to store and transport thermal energy [6]. Fig. 1 shows a schematic of the concept using a slowly upward-moving, dense gas-particle suspension as HTM. Directly irradiated riser tubes heat up the particles by combined conduction, convection, and