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Assessment of a falling solid particle receiver with numerical simulation

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Abstract

An advanced computational fluid dynamics (CFD) model was developed which allows detailed analysis of a direct absorption falling particle receiver with horizontal aperture (face down) for a solar tower plant. The CFD model includes all relevant effects: movement of the particle curtain and the air, solar radiation, thermal radiation transfer, mechanical and thermal interactions between the particles, the air and the walls and conduction through the walls. These are spatially resolved in three dimensions for the complete receiver including the surrounding air. The coupled equations for thermal radiation, conduction and convective heat transfer are solved iteratively. First results are compared with previous simulations with a simple Matlab model and the differences due to the improvements in the simulations are discussed.

The receiver efficiency was determined to be 83% at the design point (400 MW solar input) using a single drop (no recirculation) to heat the particles from 300 °C to 800 °C. In contrast, by separating the circumferential particle curtain into 4 parts and recirculating the particles 3 times through all the sections in series the receiver efficiency increases to more than 92%. This is due to lower reflection losses from the higher particle mass flow and therefore higher opacity of the particle curtain.

Wind effects have been studied for the cylindrical face down receiver for the 100% load case with only one recirculation. For 15 m/s horizontal wind speed the receiver efficiency reduces from 89% to 84%.

Keywords: Concentrated solar power (CSP); Solid particle receiver; Direct absorption; Numerical fluid dynamics simulation

1. Introduction

A first campaign to develop a falling particle receiver for solar tower plants was led by Sandia in the 1980s (Falcone et al., 1982, 1985). A cavity receiver was proposed through which particles fall freely. In this conceptual design, the falling particles form a particle curtain that is irradiated directly by the concentrated solar radiation. First model prediction, a screening of particulate materials, and cost and system analyses were presented. This work already envisaged particle power plants for electricity generation, as shown in Fig. 1. Particles are lifted up to a tower receiver for solar heating and then back down to a hot storage on the ground. The hot particles can be used on demand to supply heat to a process. A cold storage completes the

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Nomenclature

A	area, m^2
E	specific emission, W/m^2
F	force, N
g	gravity, 9.81 m/s^2
h	heat transfer coefficient, W/(m^{2}K)
I	intensity, W/m^2
K	absorption coefficient
m	mass, kg 1/m
$\dot{m}$	mass flow, kg/s
p	pressure, Pa
$\dot{Q}$	energy flow, W
s, x	length, location, m
t	time, s
T	temperature, K
v	velocity, m/s
η	efficiency –
ε	emissivity –
μ	dynamic viscosity, Pa s
σ	density, kg/m^3

Dimensionless quantities

Ma	Mach-Number
Nu	Nusselt-Number
Pr	Prandtl-Number
Re	Reynolds-Number

Subscripts

a	air
DP	design point
in	incoming
n	in time step n
p	particles
rec	receiver

loop. The lift system was supposed to be based on a mine hoist with an insulated skip.

In a falling particle receiver nearly black particles are dropped inside a cavity to directly absorb the concentrated solar radiation. Sand-like ceramic particles with a diameter between 0.3 and 2 mm are considered as sufficient. Ceramic bauxite particles, usually used in fracking deep wells by the oil and gas industry, can be used up to 1000 °C, are nearly black (Griffin et al., 1986), available in large quantities and cost around the same as $NaNO_3/KNO_3$ (500–1000 €/t).

A first prototype of a falling particle receiver was tested over a range of input power levels from 1.58 to 2.51 MWth to provide experimental data for model validation (Siegel et al., 2010). A particle temperature increase up to 250 °C was demonstrated. CFD simulation and experimental results showed good agreement.

Other previous experimental and theoretical studies of particle flow (Kim et al., 2010b), wind effects (Kim et al., 2010a; Tan et al., 2009) and thermal simulation (Grena, 2009) can be found in literature.

Ceramic particles open the possibility to drive processes, which need higher temperatures than state-of-art molten salt systems can achieve, while still including an inherent storage capability. The most efficient steam turbines feature 620 °C reheated steam today. Supercritical CO_2 and gas turbine cycles as well as industrial thermal processes other than electricity production can also be considered. ALSTOM proposed a circulating moving bed combustion system. In this system high-density solid particles are heated by the combustion products while falling downward through the upper region of a combustor. The particles are transferred to a moving bed heat exchanger (MBHE). Proof of concept tests were successfully performed with 7000 μm bauxite particles at ALSTOM's 3 MWth test facility (Jukkola et al., 2003). Direct contact heat exchange with air being blown through a moving particle bed could also

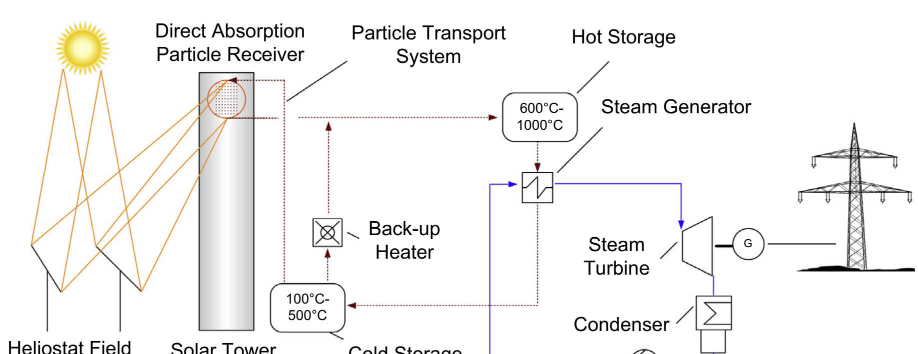

Fig. 1. Solar power plant with particle receiver, steam turbine and back-up heater.