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Particle circulation loops in solar energy capture and storage: Gas–solid flow and heat transfer considerations

Huili Zhang[a], Hadrien Benoit[b], Daniel Gauthier[b], Jan Degrève[a], Jan Baeyens[c], Inmaculada Pérez López[b], Mehrdji Hemati[d], Gilles Flamant[b,*]

[a] KU Leuven, Department of Chemical Engineering, Bio- & Chemical Systems Technology, Reactor Engineering and Safety Section, 3001 Leuven, Belgium
[b] Processes, Materials and Solar Energy Laboratory, PROMES-CNRS, 7 Rue du Four Solaire, 66120 Font Romeu, France
[c] European Powder & Process Technology, 9 Park Tremeland, 3120 Tremelo, Belgium
[d] University of Toulouse, INPT, UPS, Chemical Engineering Laboratory, 4, Allée Emile Monso, F-31030 Toulouse, France

HIGHLIGHTS

- Powder loops as heat transfer medium in a single-tube receiver unit at a 1 MW solar furnace.
- The wall-to-suspension heat transfer coefficient increases with increasing solids flux from ~430 to 1120 W/m^2 K.
- Empirical and modeling approaches were applied to compare experimental and predicted values.
- The high temperature of the circulating powder leads to significant savings in investment and operating costs.

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ABSTRACT

A novel application of powders relies on their use as heat transfer medium for heat capture, conveying and storage. The use of powders as heat transfer fluid in concentrated solar systems is discussed with respect to current technologies. The specific application reported upon is the use of powder loops in Solar Power Tower plants. In the proposed receiver technology, SiC powder is conveyed as a dense particle suspension through a multi-tube solar receiver in a bubbling fluidization mode, the upwards flow being established by pressurizing the powder feed. Tests were conducted with a single-tube receiver unit at the 1 MW solar furnace of CNRS (Odeillo Font-Romeu, F). The measured wall-to-suspension heat transfer coefficient is a function of operating temperature, applied air velocity and imposed solid circulation flux: values increased with increasing solids flux from ~430 to 1120 W/m^2 K. Empirical approaches and a heat transfer model were applied to compare experimental and predicted values of the heat transfer coefficient, with a fair agreement obtained. The research moreover provides initial data concerning the overall economy of the system. The high temperature of the circulating powder leads to an increased power cycle efficiency, an increased storage density, reduced thermal power requirements, reduced heliostat field size, reduced parasitic power consumption and increased plant capacity factor.

1. Introduction

1.1. Solar irradiance as worldwide energy source

Traditional primary sources of energy, i.e. natural gas, oil, coal and nuclear fuel, have been complemented by additional primary and secondary sources i.e. wood, biomass, vegetable oil, biodiesel, bio-ethanol, tidal power, wind, geothermal energy and the sun. Primary energy is transformed in thermal energy vectors by various technologies: combustion of fossil fuels and biomass, geothermal steam and hot water. Secondary sources need a specific energy-to-work-to-power transformation, as is the case for potential energy from water, kinetic energy of wind, and solar irradiation. The renewable energy sources only cover about 15% of the total energy demand at present; the balance is covered by mostly fossil fuels.

The hourly solar energy on earth exceeds the annual energy consumed by humans: solar energy dwarfs all other renewable and fossil-based energy resources combined [1,2]. We need energy – electrical or thermal – but commonly where and when it is not available.

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* Corresponding author.
E-mail address: gilles.flamant@promes.cnrs.fr (G. Flamant).

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Nomenclature

BFB	bubbling fluidized bed
CFB	circulating fluidized bed
CNRS	Centre National de la Recherche Scientifique
CSP	concentrated solar power
DNI	direct normal irradiance
E-PCM	encapsulated phase change material
FB-CSP	fluidized bed-concentrated solar power
FBHE	fluid bed heat exchanger
HFC	heliostat field collector
HTC	heat transfer coefficient (W/m^2 K)
HTF	heat transfer fluid
SPT	Solar Power Towers
UBFB	bubbling bed with induced pressure-driven up-flow
A	cross-sectional area of the tube receiver (m^2)
A_{ex}	internal surface area of the tube receiver (m^2)
A_{zh}	empirical coefficient of Eq. (10)
a, b	fitting coefficients of Eq. (9)
Ar	Archimedes number
C	heat capacity ratio
C_p	specific heat of heat transfer fluid (J/kg K)
$C_{p,g}$, $C_{p,s}$	specific heat of gas and solids, respectively (J/kg K)
d_B	bubble diameter (m)
d_p	average particle diameter (μm)
d_{32}, d_{sv}	Sauter mean diameter (μm)
$D_{int/ext}$	internal/external diameter of the tube (m)
F_g	gas mass-flow rate (kg/s)
F_p	solid mass-flow rate (kg/s)
G, G_p	solid circulation flux (kg/m^2 s)
g	gravitational acceleration, 9.81 m/s^2
ΔH_{loss}	heat loss by air flow (Table 9) (W)
H	separation height between 2 successive bubbles [Eq. (22)] (m)
h_t	suspension level in the tube (m)
h_b	height of the tube base (m)
h	average heat transfer coefficient from the wall to the suspension (W/m^2 K)
h_c	contact transfer resistance (W/m^2 K)
h_g, h_m	heat transfer coefficient during operation with gas "g" and solids suspension "m" (W/m^2 K)
h_{max}	maximum achievable heat transfer coefficient (W/m^2 K)
h_r	radiation component of total heat transfer coefficient (W/m^2 K)
J	circulation flux (kg/m^2 s)
k	the ratio of the radial bubble influence and the bubble diameter
$L.L_T$	effective length of the tube (m)
M	loading ratio
Nu	Nusselt number
n	frequency of bubbles passing the tip of the probe (s^{-1})
ΔP	pressure drop (Pa)
P_{atm}	atmospheric pressure (Pa)
P_b	pressure at the base of the tube (Pa)
ΔP_{bed}	hydrostatic pressure of the bed between the freeboard and the tube base (Pa)
P_{pd}	freeboard pressure of the particle suspension dispenser (Pa)
ΔP_f	flow driving pressure, defined as the difference between the pressure at the inlet and at the outlet of the tube (atmospheric) (Pa)
ΔP_t	pressure drop across the tube (Pa)
Pr	Prandtl number
Δt	time interval between two measurements varied from 20 to 66 s
ΔT_{lm}	logarithmic-mean temperature difference (K)
T	temperature, with subscripts "i/o" corresponding to inlet/outlet of the irradiated part of the tube, subscripts "w/p" corresponding to tube wall and particles, and superscript "int" corresponding to the internal side of the tube wall (K)
T_b, T_w	bed and wall temperature (K)
$T_{bed,5mm}$	bed temperature at 5 mm from the wall (K)
U, U_{mf} U_{mb}	superficial gas velocity, at minimum fluidization 'mf' and minimum bubbling 'mb' respectively (m/s)
U_B	velocity of bubbles (m/s)
U_D	velocity in the draft tube (m/s)
U_{ms}	minimum slugging velocity (m/s)
U_{pc}	minimum velocity to achieve pneumatic conveying (m/s)
U_t	terminal velocity of the particle (m/s)
U_{tf}	velocity of transition to turbulent fluidized bed (m/s)
U_{TR}	velocity of transition to circulating fluidized bed (m/s)
ρ_B	bulk bed density (kg/m^3)
ρ, ρ_g, ρ_s	density, density of gas and solids, respectively (kg/m^3)
$\alpha_p = 1 - \varepsilon$	particle volume fraction
ε	suspension voidage
ε_B	bubble fraction in the bed
ε_{mf}, ε_{mb}	suspension voidage at minimum fluidization and minimum bubbling, respectively
Φ	heat flux received by the particle suspension (W)
σ	Stefan Boltzmann constant
ε_r, ε_{app}	reduced and apparent emissivity, respectively
ε_s, ε_b	emissivity of the surface and bed, respectively
λ, λ_g, λ_p	thermal conductivity, with subscript "g" for gas and "p" for particle respectively (W/m k)
β_w, β_D	wake and drift fraction of a bubble

Most of the countries, except those above latitude 45°N or below latitude 45°S, are subject to an annual average solar irradiation flux in excess of 1.6 MW h/m^2, with peaks of solar energy recorded in some "hot" spots of the Globe, mostly in deserts [2]. The potential of applying solar energy has been studied for different countries and applications, e.g. in a peak shaving strategy [3], or for Australia [4] and India [5]. To provide a durable, widespread and global energy source, solar energy must be captured, stored and used in a cost-effective way.

1.2. Concentrated solar power plants

Concentrated solar power (CSP) is an electricity generation technology that concentrates solar heat through heliostats onto a small area, where a heat transfer fluid (HTF) is used as heat carrier. It is particularly promising in regions with high direct normal solar irradiance (DNI). CSP plants are gaining increasing interest, mostly by using Parabolic Trough Collector systems (PTC) and Solar Power Towers (SPT), the latter progressively occupying a significant market position due to their advantages of higher efficiency, lower operating costs and good scale-up potential. PTC technology is the most mature CSP design. SPT now occupies the second place and is of increasing importance as a result of its advantages and ongoing improvements. The large-scale SPT technology was successfully demonstrated e.g. by Torresol in the Spanish Gemasolar project on a 19.9 MW_{el}-scale [6] and at Ivanpah [7] at a scale of 370 MW_{el}. The Gemasolar SPT plant began production in April 2011, being the first commercially operating plant to apply molten