Dense Particle Suspension as Heat Transfer Fluid: Solar Receiver, Thermal Storage, and Heat Exchanger

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Outline

Introduction

I. Dense Particle Suspension in Tubular Receiver

II. Experimental Results with Tubular Receiver

III. Thermal Storage with Particles

IV. Heat Exchanger
Literature about concentrated solar energy

SCOPUS with keywords: ▲: PCM energy storage; ◆: Solar energy applications; ▼: Solar plant design; ○: Hybrid solar power plants; ●: Thermo-chemical energy storage; ■: Powder HTFs
CSP plant layout

- Sun
- Concentrating system
- Solar receiver
- Heat exchanger
- Hot storage
- Hot HTF
- Cold HTF
- Cold storage
- Working fluid
- Power block
- Electricity grid

HTF = Heat Transfer Fluid
Introduction

Solar “flowing” heat transfer fluids

Operating temperature

High temperature (>700 °C) → High efficiency cycles ($\eta > 50 \%$)

After Benoit et al., RSER 55 298-315 (2016)
Solar “flowing” heat transfer fluids

Heat Transfer Coefficient
(0.02m diameter tube, velocity 2 m/s)

After Benoit et al., RSER 55 298-315 (2016)
Introduction

Particle receivers
Studied since the 1980’s
* PROMES-CNRS: Fluidized bed, Rotary kiln
Introduction

Particle receivers

Studied since the 1980’s

* Sandia National Laboratories: falling particles curtain
  * NREL: falling particles over hexagonal tubes
Particle receivers

Studied since the 1980’s

* DLR: Centrifugal Particle Receiver
Introduction

Particle receivers

Studied since the 1980’s

* PSI: Multi-tube rotary kiln Receiver (2006)
Introduction

Particle receivers

Studied since the 1980’s

* IRC: Compartmented Fluid Bed Receiver (2013)

Fig. 1 – Conceptual representation of the solar receiver/thermal energy storage system based on compartmented dense gas fluidized beds.
Introduction

Particle receivers
Studied since the 1980’s

* Zhejiang Univ.: Spiral Particle Receiver (2014)
Introduction

Particle receivers

Studied since the 1980’s

* CSP2 Project: Dense Particle Suspension (in tubes) Receiver (2013)
I. DPS in single-tube receiver

Experimental Pilot Rig

Schematic cross-sectional view of the lab-scale solar rig (open circuit)
I. DPS in single-tube receiver

**Highest temperature (SiC)**

- Achieved outlet temperature: 750 °C
- Temperature increase: 250 °C when irradiating 0.5 m
Heat transfer coefficient versus solid mass flux ($G_p$)

I. DPS in single-tube receiver

Heat transfer coefficient (SiC)

with 95 % confidence intervals
Solar “flowing” heat transfer fluids

Heat Transfer Coefficient
(0.02m diameter tube, velocity 2 m/s)

- Therminol VP-1
- Solar salt
- HITEC
- HITEC XL
- Na
- LBE
- Particles

Heat transfer coefficient [W/m².K]
II. Multi-tube receiver

Schematic view of the experimental setup (closed loop)

ColFB = Collector Fluidized Bed
CoolFB = Cooling Fluidized Bed
DiFB = Dispenser Fluidized Bed
①, ②: Rotary valves
Main Components

- Storage tank
- Screw conveyor
- Cooling fluidized bed
- Solar receiver
- Collector fluidized bed
- Dispenser fluidized bed

3D view of the pilot solar receiver loop (conception, manufacture: COMESSA)
II. Multi-tube receiver
II. Multi-tube receiver

Experimental results

- 100 Hours of on-sun experiments performed
- 30 Hours of steady periods
- Operating parameters ranges:
  - Inlet Power: 60-140 kW$_{th}$
  - Solid mass flow rate: 660-1750 kg/h (= 17-44 kg/m$^2$.s)
- Experimental result ranges (time averages):
  - $T_p$ increase between DiFB and ColFB: 140-340 °C
  - $T_p$ difference between tubes outlet: 130-350 °C
• DPS can work as HTF
• Particles is a high performance storage medium
• Suspension temperature up to 750 °C
  ➔ high efficiency thermodynamic cycles
• Heat transfer coefficients up to 1100 W/m².K, hopefully to be doubled
• 150 kW_{th} multi-tube pilot successfully tested
• Self-regulation with DNI variations
• Thermal yield as high as 90 %
Particle receiver / storage / exchanger

Thermal CSP plant with DPS receiver and particles as HTF
Thermal storage with particles

Thermodynamic cycle

Solar receiver with a dense particle suspension

Hot particles storage

Cold particles storage

Fluidized bed heat exchanger (steam production)
Fluid Bed Heat Exchangers

Figure 1 - Representative Configurations of Fluidized Bed Heat Exchangers

After Ramanathan et al., NASA - Lewis Research Center; Contract No. DEN 3-96 (1980)
Multistage FB Heat Exchangers

Counterflow (stacked Fluid Bed)

**Drawbacks:**
- Distributor clogging by fines
- Air bypass through downcomers
- High pressure drop
- Sensible heat loss with air

Adapted from Kunii, Levenspiel and Brenner, Fluidization Engineering (1991)
Multistage FB Heat Exchangers

Crossflow Fluid Bed

Solids from receiver and hot storage, $T_{x,in} = 800 \, ^\circ C$

Air, $T_{air, out} = \Sigma T_i/N \approx 0.6T_1$

Air, $T_{in}$

Air, $T_{out}$

Solids to cold storage and receiver, $T_{x, out} = 400 \, ^\circ C$

Fluidization air, $T_{air, in} = 20 \, ^\circ C$

**Interests:**
- Reduced pressure drop
- Reduced heat loss with air

Adapted from Kunii, Levenspiel and Brenner, Fluidization Engineering (1991)
Multistage FB Heat Exchangers

Particle Receiver and Hybrid Solar Gas turbine
Multistage FB Heat Exchangers

Particle Receiver and Hybrid Solar Steam turbine
Multistage FB Heat Exchangers

Influence of number of stages on thermal behavior (steam production)

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Table 1. Number of stages of the evaluated configurations.

IV. Heat exchanger
Multistage FB Heat Exchangers
Thermal efficiency and thermal effectiveness (steam production)

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Table 1. Number of stages of the evaluated configurations.

Efficiency = \( \frac{HF_w}{HF_s} \)

\[ \eta_{th} = \frac{\dot{Q}_w}{\dot{Q}_s} \]

Effectiveness = \( \frac{\Delta T_{out}}{\Delta T_{in}} \)

\[ \eta_{HEX} = \frac{T_{w,\text{out},n} - T_{s,\text{out},1}}{T_{s,\text{in},n} - T_{w,\text{in},1}} \]