Applied Energy 190 (2017) 510–523

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

# Design and performance of a multistage fluidised bed heat exchanger for particle-receiver solar power plants with storage

Fabrisio Gomez-Garcia, Daniel Gauthier, Gilles Flamant *

*Processes, Materials and Solar Energy Laboratory (PROMES-CNRS, UPR CNRS 8521), 7 rue du four solaire, 66120 Font-Romeu Odeillo, France*

## HIGHLIGHTS

- A general method for designing a multistage FB HEX for hot particles heat recovery is presented.
- Temperature difference 100 °C higher than current molten salt storage technology can be achieved.
- A particle HEX for a 50 $MW_e$ solar plant with a two-stage Rankine cycle operating at 535 °C is designed.
- Thermal efficiency of 99.3% and a global heat exchange efficiency of 49.7% can be achieved.
- It is a design tool applicable for similar devices.

## ARTICLE INFO

*Article history:*
Received 22 September 2016
Received in revised form 4 December 2016
Accepted 27 December 2016
Available online 7 January 2017

*Keywords:*
Heat exchanger
Fluidised bed
Multistage
Solar power plant
Storage

## ABSTRACT

This paper presents an analytical model of a multistage fluidised bed heat exchanger for particle-based solar power plants. This model was developed as an applicable design tool for similar devices. It enables a parametric analysis of the heat exchanger performance to be conducted as a function of the operating specifications of the plant power block, the heat exchanger geometry and the fluidised bed properties, among other parameters. A 50 $MW_e$ solar plant with a two-stage Rankine cycle operating at 535 °C was used to analyse the heat exchanger design. The results indicate that for the proposed application, improvements in the thermal behaviour mostly depend on the addition of preheating and superheating stages. The most efficient configuration includes seven fluid bed stages with a thermal efficiency of 99.3% and a global heat exchange efficiency of 49.7%. With such a configuration, a maximum solid temperature difference of 387 °C may be achieved between the heat exchanger entrance and its exit for particle inlet temperature of 650 °C, thus enabling the best utilization of the thermal energy stored in the solid particles.

## 1. Introduction

A solar tower with a molten salt central receiver is the state-of-the-art concentrated solar thermal power (CSTP) technology that is used to supply electricity on demand due to its direct thermal energy storage. Although some improvements that will result in cost reduction are expected, this technology primarily suffers from three drawbacks: (1) the high cost, since the cost of binary molten salts ($KNO_3$-$NaNO_3$) is not expected to decrease in the near future; (2) the upper working limit of 565 °C, which does not enable the driving of advanced thermodynamic cycles; and (3) the low working temperature of 220 °C (the solidification temperature), which is a strong operation constraint. Particle solar receivers have been proposed to overcome these issues. In this concept, cold particles that emerge from the cold storage are heated in the solar receiver and then stored in the hot storage. A heat exchanger is located between the hot and cold storages to power a thermodynamic cycle (either a Rankine or a Brayton cycle). This key component of the application is studied in detail in this paper for a Rankine cycle after the state-of-the-art technology for particle solar receivers and multistage fluidised beds is presented.

### 1.1. Particle solar receiver

A discussion focused on recent state-of-the-art developments on particle solar receivers was provided by Flamant et al. [1]. The first prototypes were proposed in the 1980s in the SANDIA lab and in CNRS Odeillo, who developed the free-falling particle receiver, Falcone et al. [2], and the fluidised bed receiver, Flamant [3]. A review of high-temperature central receiver designs, including

---

* Corresponding author.
*E-mail addresses:* fabrisio.gomez@promes.cnrs.fr (F. Gomez-Garcia), daniel.gauthier@promes.cnrs.fr (D. Gauthier), gilles.flamant@promes.cnrs.fr (G. Flamant).

http://dx.doi.org/10.1016/j.apenergy.2016.12.140
0306-2619/© 2016 Elsevier Ltd. All rights reserved.

## Nomenclature

*Latin characters*

| | |
|---|---|
| $A$ | Surface area ($m^2$) |
| $Ar$ | Archimedes number (dimensionless) |
| $Bo$ | Boiling number (dimensionless) |
| $c$ | heat capacity ($J\,kg^{-1}\,K^{-1}$) |
| $d_p$ | particle diameter (m) |
| $D$ | diameter (m) |
| $e$ | thickness (m) |
| $f$ | friction factor of tubes (dimensionless) |
| $F_{fl}$ | fluid parameter (dimensionless) |
| $Fr$ | Froude number (dimensionless) |
| $g$ | gravity acceleration ($m\,s^{-2}$) |
| $h$ | heat transfer coefficient ($W\,m^{-2}\,K^{-1}$) or specific enthalpy ($J\,kg^{-1}$) |
| $h_{lg}$ | enthalpy of vaporization ($J\,kg^{-1}$) |
| $H$ | height (m) |
| $k$ | thermal conductivity ($W\,m^{-1}\,K^{-1}$) |
| $l$ | width (m) |
| $l_{bot}$ | distance between tubes in the lower row and the container bottom (m) |
| $l_h$ | horizontal gap between tube centres (m) |
| $l_{top}$ | distance between tubes in the upper row and the FB top surface (m) |
| $l_v$ | vertical gap between tube centres (m) |
| $l_{wall}$ | minimum horizontal gap between container walls and closer tubes (m) |
| $L$ | length (m) |
| $L_b$ | length of a single tube bundle (m) |
| $LMTD$ | logarithmic mean temperature difference (K) |
| $\dot{m}$ | mass flow rate ($kg\,s^{-1}$) |
| $\dot{m}_{wb}$ | WF mass flow rate in a tube bundle ($kg\,s^{-1}$) |
| $n$ | overall number of stages (dimensionless) |
| $n_b$ | tube number per bundle (dimensionless) |
| $n_{max}$ | maximum tube number (dimensionless) |
| $n_{tube}$ | tube number (dimensionless) |
| $n_x$ | maximum tube number in a single row (dimensionless) |
| $n_y$ | number of tube rows (dimensionless) |
| $N$ | number of tube bundles (dimensionless) |
| $N_f$ | fluidisation number (dimensionless) |
| $Nu$ | Nusselt number (dimensionless) |
| $p$ | pressure (Pa) |
| $Pr$ | Prandtl number (dimensionless) |
| $\dot{Q}$ | heat flux (W) |
| $Re$ | Reynolds number (dimensionless) |
| $S$ | cross section ($m^2$) |
| $t_e$ | square-root-average contacting time of the fluidised bed with tubes (s) |
| $T$ | temperature (K) |
| $U$ | velocity (m/s) |
| $UA$ | thermal resistance ($W\,K^{-1}$) |
| $w$ | work per unit mass ($J\,kg^{-1}$) |
| $\dot{W}$ | power (W) |
| $x$ | steam quality of water (dimensionless) |

*Greek symbols*

| | |
|---|---|
| $\delta_b$ | bubble fraction in the fluidised bed (dimensionless) |
| $\Delta p$ | pressure drop (Pa) |
| $\varepsilon$ | fluidised bed voidage (dimensionless) |
| $\eta_{HEX}$ | global efficiency (dimensionless) |
| $\eta_{th}$ | thermal efficiency (dimensionless) |
| $\mu$ | viscosity (Pa s) |
| $\xi$ | tube inside wall roughness (m) |
| $\rho$ | density ($kg\,m^{-3}$) |
| $\phi_s$ | particle sphericity (dimensionless) |

*Subscripts*

| | |
|---|---|
| *act* | FB active region |
| *amb* | ambient conditions |
| *bot* | tube bottom section |
| *cont* | container |
| *dis* | disengaging space over the FB |
| *dist* | distributor |
| *e* | emulsion in the fluidised bed (fluidised bed = emulsion + bubbles) |
| *ex* | exchange |
| *g* | gas |
| *hp* | high pressure |
| *i* | number of the $i^{th}$ stage |
| *in* | inlet or inside |
| *ins* | thermal insulation |
| *lp* | low pressure |
| *mf* | minimum fluidisation conditions |
| *n* | *n*th stage |
| *out* | outlet or outside |
| *s* | solid particles |
| *sat* | saturated vapour state |
| *sh* | shell |
| *t* | terminal |
| *top* | tube top section |
| *tube* | tube |
| *turb* | turbine or power block |
| *w* | WF |
| 1 | first stage of the heating process |

*Other symbols*

| | |
|---|---|
| $\bar{\ }$ | mean value |

*Abbreviations*

| | |
|---|---|
| CFB | circulating fluidised bed |
| CSTP | concentrated solar thermal power |
| FB | fluidised bed |
| HEX | heat exchanger |
| HTC | heat transfer coefficient |
| HP | high pressure |
| LP | low pressure |
| TES | thermal energy storage |
| WF | working fluid |

particle receivers, was presented in Ho and Iverson [4]. Alonso and Romero [5] reviewed experiments in which directly irradiated particle solar reactors were used to perform gas-solid thermochemical reactions. The falling-particle cavity receiver prototype design that was developed at Sandia National Laboratories, Albuquerque, NM for the SunShot DOE Initiative was described and modelled in Christian et al. [6]. Gobereit et al. [7] proposed a CFD simulation of a facedown falling-particle receiver that showed that efficiencies of more than 90% could be reached. Moving particles in cavity receivers present various options for the design of solar receivers. For example, a solar rotary kiln was modelled by Tescari et al. [8] for the reduction of $Co_3O_4$, which resulted in particle temperatures in the range of 900 °C-1000 °C at the reactor exit. The same laboratory (DLR, Germany) also proposed the direct irradia-