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Bio-energy Carriers as Back-up Fuel in Hybrid Solar Power Plants

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Abstract. Electricity from concentrated solar power (CSP) plants, gains an increasing interest and importance. To fully match the supply-demand principle, CSP processes include a thermal energy storage and back-up fuel supply. Novel CSP concepts are needed with specific targets of increased efficiency and reliability, and of reduced CAPEX and OPEX. The use of particle suspensions offers significant advantages since applicable in all sub-sections of the complete CSP as heat carrier from the receiver, to the heat storage, and ultimately to the power block. The use of particles in the steam generation (power block) is a common fluidized bed boiler technology. This paper will present the entire particle-based concept, while also discussing the potential to use biomass-based energy carriers as back-up heat supply. Process data and expected effects on the process economy of the system will be discussed.

1. Introduction

In the current CSP technology, mostly Parabolic Trough Collectors (PTC) and Solar Power Towers (SPT) [1] are used, with either thermal fluids or molten salt eutectics as respective heat carriers or transfer fluids (HTF).
Operating temperatures are limited to ~390 °C (PTC) or ~565 °C (molten salt in solar power towers, SPT). SPTs mostly apply molten salts, although direct steam or hot air applications are also proposed, each technology with its advantages and drawbacks [2–5], such as difficulties in storing heat in hot air and steam systems, possible solidification of molten salts at around 220 °C, molten salt degradation when heated beyond 565 °C, heat tracing of the molten salt circuits, etc.
Particle suspension do not suffer from these limitations, and can operate at a very high and low temperature, while also facilitating hot and cold storage [2]. The upper temperature limit will be determined by the high temperature mechanical properties of the construction materials. Worldwide, the 2030 CSP potential is forecast at over 260 GW of electricity, with about 30 to 40% from SPT technology [6].

Developments of new molten salts are considered, either by using mixes of the common Na/K nitrate eutectic with $LiNO_3$ or by using other eutectic mixes (CO_3^{2-}, Cl^- or F^- salts), although such salts can corrode construction materials at high temperatures [7–10]. Using particle suspensions as heat carrier has been examined at laboratory and pilot scale since about 2010 [11, 12]. The higher operating temperatures will foster the use of advanced power cycle configurations, with combined cycles (air or CO_2 Brayton plus steam Rankine) or even supercritical cycles. The cycle efficiencies are thereby expected to increase from 35% for steam conditions at 375 °C, to 40% for high-tech molten salt SPTs with steam conditions of 535 °C, and even to 45 and ~50% for supercritical and combined power generation concepts [13-16].

2. The application of particle suspensions as heat carriers

This concept relies upon using a bubbling fluidized bed of fine Geldart A type powders [17, 18], with a forced external particle circulation. In using A-type particles, the operating superficial air velocity can be low (max. 0.15 m/s), thus limiting the air-related sensible heat losses. The system is now commonly referred to as Particle-in-Tube or as the Upflow Bubbling Fluidized Bed (UBFB). Imposed particle circulation rates, expressed per unit cross sectional area of the receiver tubes, can reach 150 kg/m²s. During the project development, the receiver internal diameter was gradually increased from 29 to 50 mm. Zhang et al. [11] reviewed previous research on similar dense up-flow systems.

The UBFB novel concept was developed through French National and European funding [19-23]. The layout of the UBFB loop involves a pressurized bottom fluidized bed (also called dispenser) and operated at a superficial air velocity close to the particle minimum fluidization velocity, a number of vertical receiver tubes that are exposed over a given height to the concentrated solar irradiation and fitted with a secondary air injection, a disengagement chamber at the receiver tube discharges, a pressurized storage hopper with downcomer and non-mechanical recycle valve (L-valve) to the dispenser [11, 24].

The heat transfer from the receiver wall to the UBFB is high, and the result of the vigorous bubbling and associated particle renewal at the wall [25] (since bubbles in A-type powders are known to reach a maximum stable bubble size and a high bubble frequency). These bubbles also induce a "gulfstream" mixing throughout the bed (and hence tube) height [26].

The integration of the particle suspension HTF, in either bubbling or moving bed [27] mode, throughout the whole power plant system, is illustrated in Figures 1 and 2 below, for different power generation concepts. The A-type particles are readily flowable, hence fostering the use of a tube bank filled with phase change materials (E-PCM) to supplement the sensible heat storage of the powders, with a latent heat storage contribution [28–30].

3. On-sun proof of concept

Single and multi-tube particle-driven receivers were assessed at the CNRS solar furnace of Font Romeu (France), with various fine A-type powders as suspension material (silicon carbide, crystobalite and olivine).

Superficial air velocities at operating bed temperature of maximum 700 °C varied from 5 to about 20 times the minimum fluidization velocity of the powders (0.5 to 0.8 cm/s). Solid circulation fluxes up to about 50 kg/m²s were imposed. The experimental set-ups and experimental procedures were previously described in detail [11, 12, 30, 31].

The heat transfer coefficient (HTC) between the wall and the UBFB were determined per total m² of the receiver tube surface area. They were found to be a nearly linear function of the imposed solid circulation flux, with a limited impact of the superficial gas velocity only. Values of ~50 kW/m² were measured at a solid circulation flux of about 10 kg/m²s, increasing steadily to ~150 kW/m² at 46 kg/m²s, and this in both the single and multi-tube testing.

With the contributions of both the particle convection and radiation heat transfer at the high wall temperatures, the overall heat transfer coefficient ranged from 430 W/m²K to 1120 W/m²K [8, 26].

4. Biomass-based Back-up Fuel Systems

Biomass is widely available, with an energy content of 15 to 23 MJ/kg. Biomass or its pyrolysis/gasification derivates can be readily applied in a hybrid CSP. A currently investigated hybrid co-generation plant is illustrated in Figure 1, where the possible application of biomass or its derived syngas as back-up fuel is indicated, and applied in various sub-sections of the overall plant layout.

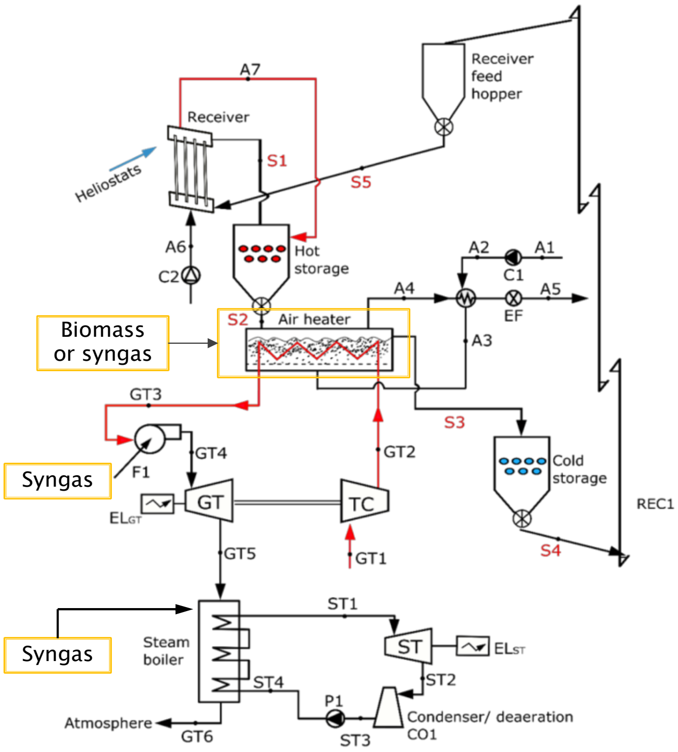
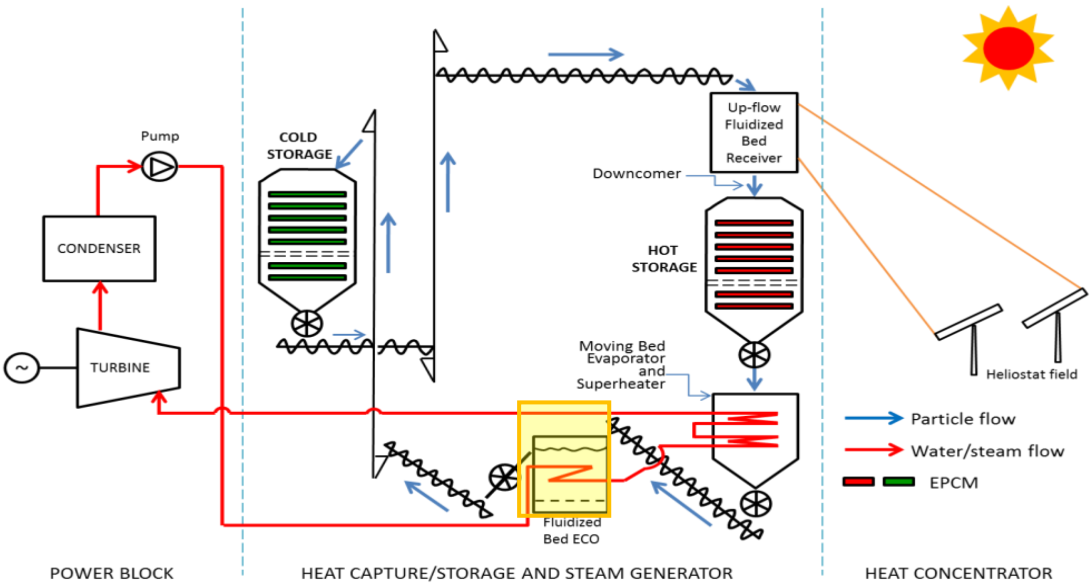


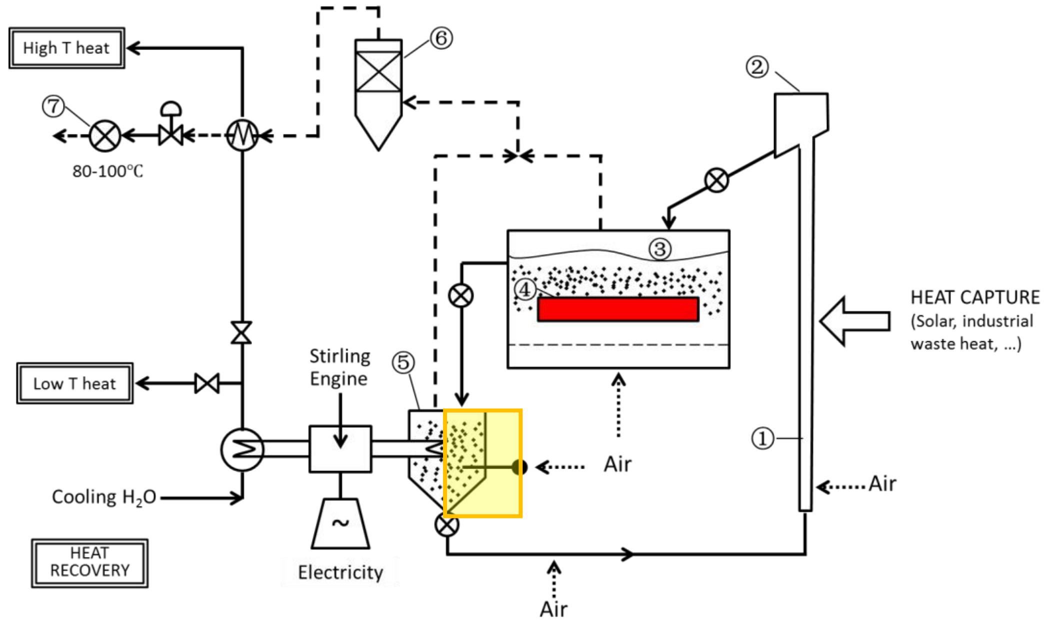
Figure 1. The CNRS hybrid co-generation project at the Themis CSP.

Several alternative applications were assessed and are represented in Figure 2.

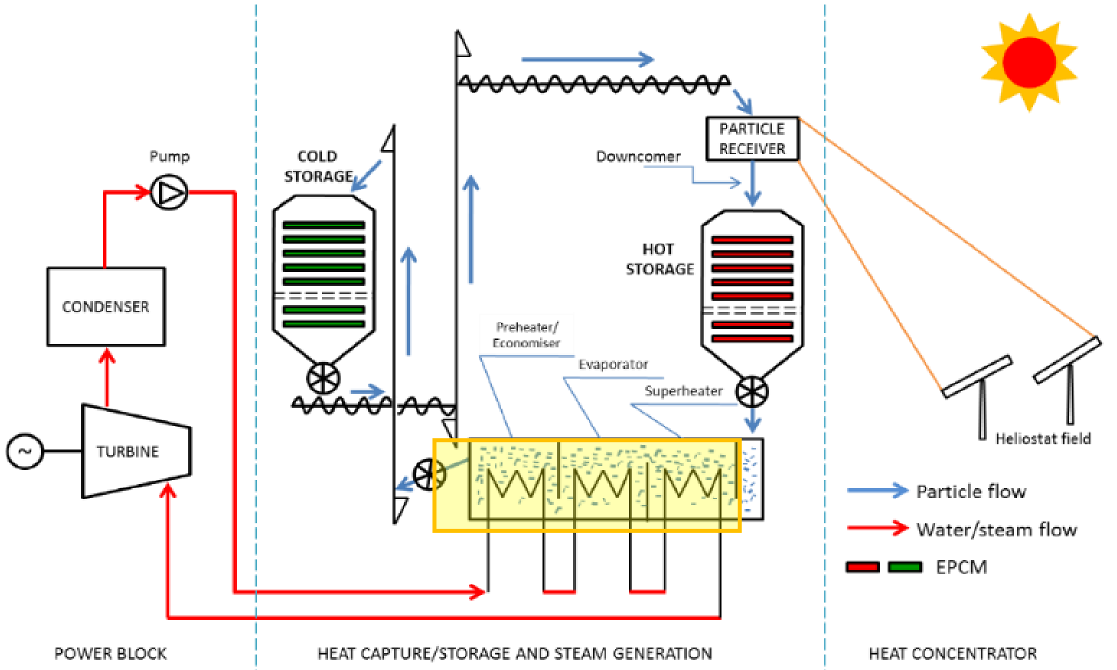
(a)



(a)



(b)



Biomass or biogas combustion

(C)

Figure 2. Different options of a hybrid biomass - CSP power plant.

5. Conclusion and recommendations

The UBFB receiver, operated with particles at high temperatures, and the subsequent application of the particle suspension in the different sub-sections of the power plant, fosters the use of high efficiency power generation cycles. It is expected that the particle loops, operating at higher temperatures throughout the process, will significantly decrease the required heat storage volumes for an equivalent capacity of the molten salt applications. Since solidification is no longer an issue of concern, circuits will not require a heat tracing. The higher cycle efficiencies achieved, will moreover allow a reduced size of the heliostat field. These SPT advantages should reduce the levelized cost of electricity (LCOE) by between 10 to 20%, with a target electricity cost of less than 100€/MWh. Since a back-up system is required for non-sun periods, the use of biomass-based energy carriers has a high potential to further reduce the back-up fuel environmental footprint.

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