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# DESING OF A UTILITY SCALE SOLAR THERMAL TOWER SYSTEM BASED ON PARTICLE RECEIVERS AND FLUIDIZED BED TECHNOLOGY

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## ABSTRACT

Particles as primary heat transfer material enable dispatch able thermal solar electricity plants with higher storage temperatures and thus higher steam temperatures/pressures of the power cycle can be reached; leading to higher plant efficiencies and lower costs.

A 136 $MW_{el}$ dispatch able solar thermal electricity plant with Silicon Carbide as primary heat transfer material and with a storage capacity of 1360 $MWh_{el}$ is presented. Fluidization technique is applied for the receiver and the heat-exchangers. The key technologies are discussed as well as the challenges in conveying/storing hot bulks and finding an efficient plant layout. The plant design is discussed showing the huge potential of this next generation STE-technology.

## INTRODUCTION

The value of dispatch able electricity conversion is more and more appreciated, as electrical grids reach their stability limits, due to an increasing portion of fluctuating renewable energy conversion and as utilities struggle to match supply by a variable demand of electrical energy. Solar thermal electricity (STE) plants are well suited for a flexible electricity conversion at utility scale via the implementation of large scale high temperature thermal energy storages (TES) in a direct storage concept. In a direct storage cycle the storage material acts as primary heat transfer fluid (HTF); thus the storage material is transported from the cold storage to the receiver, where it is heated up and stored afterwards in the hot storage. The hot storage is discharged by demand for transferring the stored heat to the working fluid of the power cycle for electricity conversion.

State of the art dispatch able STE plants use molten salt as primary HTF. A 110 $MW_{el}$/670 $MW_{th}$/10 hours of storage STE plant was commissioned in 2014 in Crescent Dunes, Tonapah, United States, showing the high potential, readiness and value of this technology [1].

To make dispatch able STE-plants more competitive, not only the SunShot-Initiative of the United States Energy Department suggests increasing temperatures and compatibility, reducing losses by higher fluxes of the receiver and thinking of alternative working fluids.

A promising next step is replacing the molten salt via particles in favor of higher temperatures, good values of thermal capacity and low cost storage materials. Bulks can be transported nearly as flexibly as liquids and thus be applied as primary heat transfer material in an active direct TES concept.

## NOMENCLATURE

| | | |
|---|---|---|
| $\alpha$ | [W/m$^2$K] | Heat transfer coefficient between a surface and a flow |
| $p$ | [Pa] | pressure |
| $\eta$ | [%] | efficiency |
| $k$ | [W/m$^2$K] | Heat transfer coefficient for a pipe or a plate |
| $P$ | [W] | Power, e.g.: blower power |
| $\dot{Q}$ | [W] | Heat flow |
| $\dot{q}$ | [W/m$^2$] | Heat flux |
| $T$ | [K] | Temperature |
| $n$ | [-] | Number, amount of |
| $\lambda$ | [W/mK] | Heat conductivity |
| $c_p$ | [J/kgK] | Isobaric heat capacity |
| $\kappa$ | [-] | Ratio of specific heats |
| $\dot{m}$ | [kg/s] | Mass flow |
| $G$ | [kg/sm$^2$] | Mass flux |
| $A$ | [m$^2$] | Area, surface |
| $\rho$ | [kg/m$^3$] | Density |
| $d$, $h$ | [m] | Diameter, Height |
| $u$ | [m/s] | Velocity |
| $t$ | [-] | Used as multiple |

**Subscripts**

| | |
|---|---|
| *fb* | Fluidized bed |
| *dist* | Distributor |
| *rad* | Radiation |
| *cond* | Conduction |
| *conv* | Convection |
| *t* | Tube |
| *i* | Inside, inner |
| *o* | Outside, outer |
| *p* | Particle |
| *rec* | Receiver |
| *mf* | Minimum fluidization |

Various particle receiver approaches are under development in the scientific community. They can be categorized in two main concepts: direct absorption particle receivers (DAR), where particles are directly beamed by solar irradiation and indirect particle receivers, where particles flow through a tube which is beamed.

As promising DAR concepts the works of the German Aerospace Centre (DLR) [2,3] and Sandia National Laboratories [4,5] have to be mentioned here. DAR are cavity receivers. Since solar irradiation enters the cavity through an aperture, only a limited sector of an elliptical field can be used. Small scale prototypes exist at the time of writing.

A promising indirect receiver concept is developed by Centre National de la Recherche Scientifique (CNRS) [6, 7], where particles are transported upwards through a vertical tubular receiver via a stationary fluidized bed. For this concept a small scale prototype exists [6], which can be easily scaled up due to its robustness.

Not only efficient particle receivers are crucial for a success of this technology, but also efficient particle heat-exchangers (HEX) transferring the heat from the particles to the working fluid of the power cycle. Moving bed [8] and fluidized bed [9, 10-13] HEX are discussed in the literature. A specialized fluidized bed HEX technology is developed by the authors, which can be operated, as flexible as, state of the art shell and tube HEX. These HEXs are operated close to the local minimum fluidization conditions keeping the auxiliary power needed for enabling the stationary fluidized bed in the range of some per mill of the electric power of the plant.

In this work a utility scale subcritical STE plant applying Silicon Carbide (SiC) as HTF is presented. SiC offers good absorption behaviour of solar irradiation, good values of thermal capacity, high hardness and low chemical reactivity guaranteeing good cycle stability. This next generation-STE-plant applies fluidization technique for the particle receiver, the concept of [7] is chosen and for the heat-exchanger, the concept developed by the authors [10-13] is embraced. In Figure 1 the basic principle of this plant is shown.

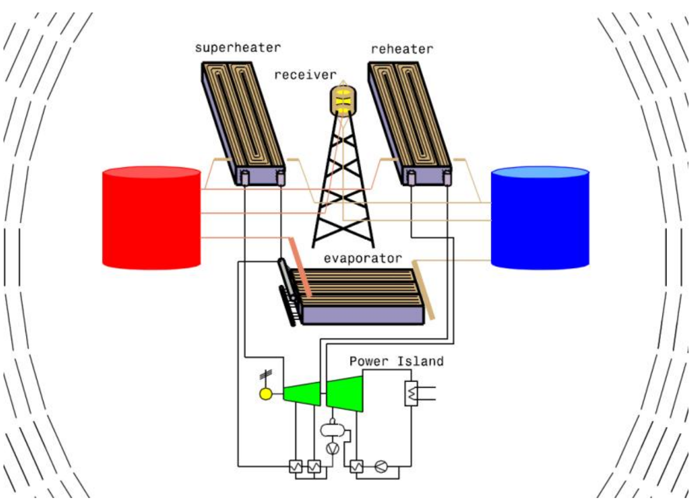


**Figure 1** basic principle of STE plant applying SiC particles as primary HTF

## METHOLOGY

As benchmark the reference plant presented in [14] is chosen. The NREL reference plant applies a central tower design and molten salt as HTF. The overall design and performance parameters of this plant are shown in Table 1.

**Table 1** overall design parameter of molten salt reference plant [14]

| | |
|---|---|
| General design parameter | |
| Thermal power receiver | 670 [$MW_{th}$] |
| Thermal storage capacity | 10 [h] |
| Solar multiple | 2.4 [-] |
| Solar field area | 1,298,000 [$m^2$] |
| Thermal power steam generator | 280 [$MW_{th}$] |
| Storage cycle | |
| Cold storage temperature | 288 [°C] |
| Hot storage temperature | 566 [°C] |
| Thermal storage volume | 13,000 [$m^3$] |
| Power cycle | |
| Power block pressure | 115 [bar] |
| Power block grass rating | 115 [$MW_{el}$] |
| Thermal efficiency power cycle | 41.1 [%] |

For designing the next-generation-STE-plant the general design parameter (thermal receiver power, solar multiple, thermal storage capacity and solar field area) from the NREL reference-plant have been taken. Instead of molten salt SiC particles are applied as HTF in favour of higher storage temperatures. The chosen storage temperatures can be found in table 2. These temperatures and the required thermal powers define all mass-/volume-flows at design point and the needed storage inventory. SiC bulks have a lower volumetric heat capacity compared to molten salt resulting in larger storage volumes. A temperature difference of 350 °C between hot and cold storage has been chosen to partly compensate the lower volumetric heat capacity of SiC.

**Table 2** overall design parameter of next generation STE-plant

| | |
|---|---|
| General design parameter | |
| as reference plant | (see Table 1) |
| Storage cycle | |
| Cold storage temperature | 400 [°C] |
| Hot storage temperature | 750 [°C] |
| Thermal storage volume | 19,600 [$m^3$] |
| Power cycle | |
| Power block pressure | 175 [bar] |
| Power block grass rating | 136.5 [$MW_{el}$] |
| Thermal efficiency power cycle | 47.6 [%] |

Finding an efficient plant layout is a challenging task, since particles cannot be transported as easily as liquids. The entire procedure for finding the layout cannot be explained in this work, but the basic idea is introduced in the following.

## FLUIDIZATION TECHNIQUE

Fluidization is a technique in which a gas flows upwards a bulk of particles at a velocity (minimum fluidization velocity) large enough to loosen the particles; a particle-gas suspension is formed, behaving like a liquid: a stationary fluidized bed.

In STE plants fluidized beds can be used efficiently for transporting particles through receiver and heat-exchangers. For fine particles minimum fluidization velocities are low, making auxiliary power for enabling the fluidization nearly negligible.

**Table 3** SiC particle properties

| SiC particles ($\rho_p$=3250 kg/m$^3$, $c_{pm}$=1140 J/kgK) | |
|---|---|
| Particle diameter | 60-80·10$^{-6}$ [m] |
| Minimum fluidization velocity | 0.006 [m/s] |

## STORAGE CYCLE

Using solid particles, such as Silicon Carbide as HTF, offers many advantages, such as no effective temperature limitations and low material prices, but faces some challenges in conveying them: Whereas liquids, such as molten salt, can be easily moved by a pump through a complex pipe system in any thinkable layout, particles have to be transported via bulk conveying systems (e.g.: screws, bucket-chain-elevators, pan-conveyors...) obligating a straight design, not allowing any curved conveying paths. In table 4 the particle flows to the receiver and steam generator are summarized at design point:

**Table 4** particle flows at design point

| SiC particles ($d_p$= 80·10$^{-6}$ m) | |
|---|---|
| To receiver | 4700 [m$^3$/h] or 1680 [kg/s] |
| To steam generator | 1950 [m$^3$/h] or 700 [kg/s] |

### Receiver

In the receiver SiC particles are heated up from the cold storage temperature to the hot storage temperature. The receiver design developed by CNRS [7] is taken due to its robustness and scalability. The principle of this indirect particle receiver concept is shown in Figure 2: A vertical tubular absorber, where particles are transported upwards via a stationary fluidized bed.

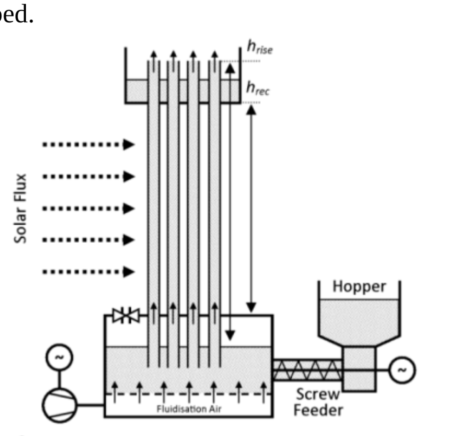


**Figure 2** principle sketch of receiver [7]

The dimensions of the receiver have been determined via a pseudo iterative procedure: the required surface area and the flow cross section for the particle suspension flow have to be estimated in a first step. Via equation (1, 2) the needed number of receiver tubes is determined.

$$\dot{Q}_{rec} = k \cdot n_t \cdot \frac{d_o \cdot \pi}{2} \cdot h_{rec} \cdot \left(T_{t,o} - T_{t,p}\right) \tag{1}$$

$$n_t = \frac{4 \cdot \dot{m}}{d_i^2 \cdot \pi \cdot G} \tag{2}$$

For dimensioning the needed flow cross section of the fluidized bed a maximum flux G of 100 kg/m$^2$ is assumed. This value is based on the authors' experience of dense particle suspension flows. The heat transfer coefficient k is about 800-900 W/m$^2$K for such an indirect particle receiver.

The receiver is aimed for a solar flux of 600 kW/m$^2$ at the cold end (bottom) and a solar flux of 300 kW/m$^2$ at the hot end (top) at design point. Ceramic tubes (e.g.: SiC) are applied, since surface temperatures of the receiver exceed 1000 °C. The temperature distribution of the receiver tubes is described via equation (3, 4):

$$\dot{q}_{solar} = \dot{q}_{cond,t} = \frac{d_o}{2 \cdot \lambda_t} \cdot \ln\left(\frac{d_o}{d_i}\right) \cdot \left(T_{t,o} - T_{t,i}\right) \tag{3}$$

$$\dot{q}_{solar} = \frac{d_i}{d_o} \cdot \dot{q}_{conv,t} = \frac{d_i}{d_o} \cdot \alpha_i \cdot \left(T_{t,i} - T_p\right) \tag{4}$$

The overall receiver efficiency is estimated via equation (5). Fluidization efforts and losses (heat transported by the fluidization gas) have been considered in equation (5), even though they are very low.

$$\eta_{rec} = \frac{\alpha_{absorpion} \cdot \dot{Q}_{in} - (\dot{Q}_{loss,rad} + \dot{Q}_{loss,con} + \dot{Q}_{loss,fb} + P_{fb})}{\dot{Q}_{in}} \tag{5}$$

During finding efficient receiver dimensions by considering equations (1-5) and the maximum capacity of appropriate commercially available conveyors (see next section), it turned out, that a single tower concept is not feasible.

For handling the required mass/volume flows of SiC particles and minimizing the conveying paths a 4 tower layout is expedient. All receivers use similar absorber tubes, although the 2 northern share 60% of the total thermal duty and the 2 southern towers 40% (location northern hemisphere).

**Table 5** design/dimension of towers/receivers

| Receiver tubes | |
|---|---|
| Tube diameter (outer) | 145 [mm] |
| Tube thickness | 2.5 [mm] |
| **2 northern towers (30% each of total thermal duty):** | |
| Tower height | 200 [m] |
| Receiver diameter | 20.5 [m] |
| Receiver section | 270 [DEG] |
| Receiver height | 6.27 [m] |
| Number of tubes | 325 [-] |

| 2 southern towers (20% each of total thermal duty): | |
|---|---|
| Tower height | 150 [m] |
| Receiver diameter | 16.5 [m] |
| Receiver section | 225 [DEG] |
| Receiver height | 6.27 [m] |
| Number of tubes | 217 [-] |
| Receiver efficiency (each) | 80.3 [%] |

The temperature and flux distribution is shown in Figure 3. Due to higher surface temperatures of the receiver, its losses are higher than those of the NREL reference plant. To compensate this higher receiver losses the field of the next-generation-STE-plant might be slightly larger. It has to be investigated, if this larger loss will be outweighed by higher efficiency of the storage and power cycle.

It can be seen in Figure 3 that an improvement of the heat transfer from the particles to the wall will increase receiver efficiency significantly; since surface temperatures will be decrease.

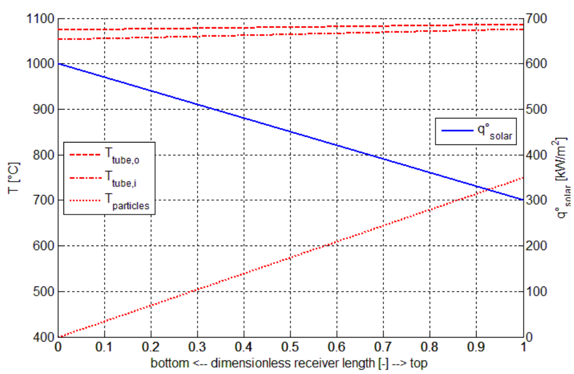


**Figure 3** Temperature and flux distribution of receiver

**Conveyors**

At temperatures above about 300 °C only pan conveyors developed for the steel industry are available on the market. These pan conveyors have a maximum inclination of 60 DEG for medium hot bulks at temperatures up to 700 °C and 45 DEG for very hot bulks at maximum temperatures of 1300 °C [15].

The conveyor, transporting the particles from the cold hopper up to the northern receiver, needs a horizontal dimension of minimum 115 m. For transporting the particles, from the receiver to the hot storage, a minimum horizontal dimension of 150 m is required. Since the hot particles are conveyed downwards, from the receiver to the hot hopper, some of the potential energy can be retrieved.

From the hot hopper, the particles are transported to the steam generators and from them back to the cold hopper.

The power consumptions of the conveyors are summarized in table 6. For all conveyors an efficiency of 50 % is assumed.

**Table 6** Power consumption of conveyors

| Charging the storage (all receivers at design point) | |
|---|---|
| Net power consumption | 2.1 [$MW_{el}$] |
| Discharging the storage (steam generators at design point) | |
| Power consumption | 0.6 [$MW_{el}$] |

**Hoppers and General Set-Up**

The logical path of the particles has been illustrated above: From the cold storage to the receivers, from the receivers to the hot storage, from the hot storage to the steam generators of the power cycle and from the steam generators back to the cold storage. In other words: four receivers and the steam generator (evaporator, superheater and reheater) have to be logically in between the cold and hot storage hopper, by considering the limitations of the space requirements of the pan-conveyors.

The plant set-up for the in this work proposed next-generation-STE-plant is sketched in figure 4. The cold storage hopper is located in the centre, the conveying paths have been minimized to all receivers and four hot storage hoppers are situated southwards of the cold hopper. The steam generators are located in between the hot and cold hoppers.

From the view point of the particle flow paths, all HEX of the steam generator are connected in parallel, so each HEX can use to full temperature difference between hot and cold storage.

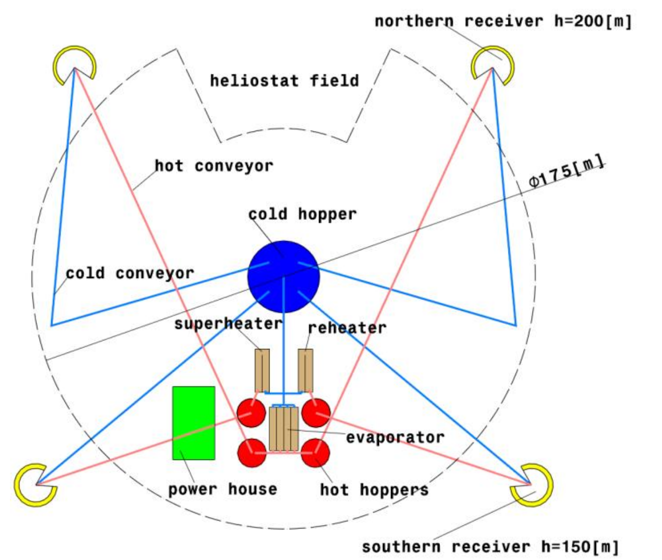


**Figure 4** simplified sketch of 4 tower plant layout

In table 7 the net storage hopper dimensions are shown. The number of hot storage hoppers is a trade off between minimum conveying lengths and maximal flexibility.

**Table 7** Dimensions storage hoppers

| 1 Cold storage hopper | |
|---|---|
| Diameter | 28 [m] |
| Height | 32 [m] |
| 4 Hot storage hoppers | |
| Diameter | 10 [m] |
| Height | 63 [m] |

Whereas a silo filled with liquids, like molten salt, can be easily discharged via a diving pump, the discharge of a large hopper storing particles is more challenging. The hopper discharge will need additional efforts and space, what is not considered in this work. Only 4 hot hoppers being rather high are chosen in favour of a more simple discharge.

## POWER CYCLE

The above presented indirect particle receiver has absorber surface temperatures around 1100 °C, resulting in slightly higher losses compared to the molten salt reference plant. The hot storage temperature of the next-generation-STE-plant is 750°C, nearly 200 °C higher than that of the molten salt reference plant, enabling higher steam pressures and temperatures of the power cycle and thus leading to higher efficiencies.

For assessing the performance of the power cycle a simplified model of the Rankine cycle, shown in Figure 5, is used, which can be flexible adjusted, quickly programmed and solved. This layout considers the needed high- and low-pressure-preheaters in a simplified, but conservative way. Calculating the regenerative preheating is crucial for correctly estimating the plant efficiency. The auxiliary power needed of a dry condenser is not yet considered in this work, but this will be included in future works.

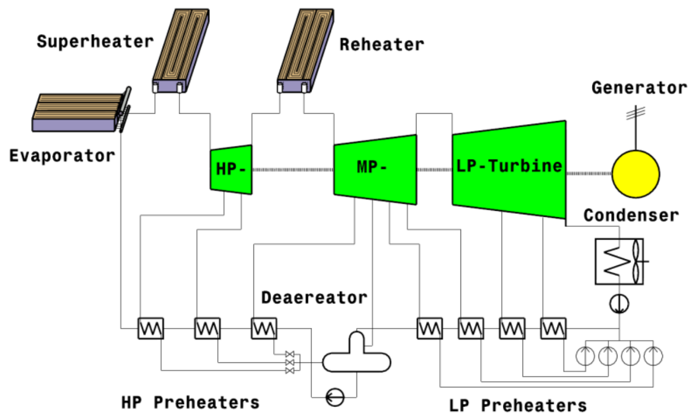


**Figure 5** model of Rankine cycle (simplified preheaters)

The overall parameters defining this cycle are presented in table 8. Three high pressure and four low pressure preheaters are applied.

**Table 8** Parameters of power cycle at design point

| | |
|---|---|
| Pressure levels | |
| High pressure | 175 [bar] |
| Medium pressure | 30 [bar] |
| Low pressure | 1.5 [bar] |
| Condenser pressure ($T_{dry,bulb}$=30°C) | 0.096 [bar] |
| Temperatures | |
| Superheater outlet temperature | 620 [°C] |
| Reheater outlet temperature | 640 [°C] |
| Subcooling evaporator | 55 [°C] |
| Duties (produced steam: 354.6 t/h) | |
| Evaporator | 118 [$MW_{th}$] |
| Superheater | 107 [$MW_{th}$] |
| Reheater | 56 [$MW_{th}$] |
| Turbines (altogether, $\eta_s$=0.90 for each) | 138.5 [$MW_{el}$] |
| Pumps (altogether, $\eta_s$=0.95 for each) | 3.1 [$MW_{el}$] |
| Generator ($\eta_{el}$=0.9856) | 136.5 [$MW_{el}$] |

### Fluidized Bed Heat exchanger

As in the receiver the fluidization technique is applied for transporting the particles efficiently through the heat-exchangers (HEX) transferring the heat from the hot particles to the working fluid of the power cycle in order to generate steam.

A fluidized-bed heat-exchanger technology has been developed by the authors [10-13] being able to transport particles horizontally at lowest realizable fluidization efforts and highest heat transfer values through a HEX. This can be achieved either in a counter-current flow or circulation evaporator design.

The well proven fluidization technique has been improved via the development of a special passive self-stabilizing nozzle-distributor-floor concept and a particle flow enhancing/controlling mechanism (two patents within filing process). This fluidized-bed heat-exchanger technology shown in figure 6 can be operated as flexibly and dynamically as state of the art shell-and-tube HEXs.

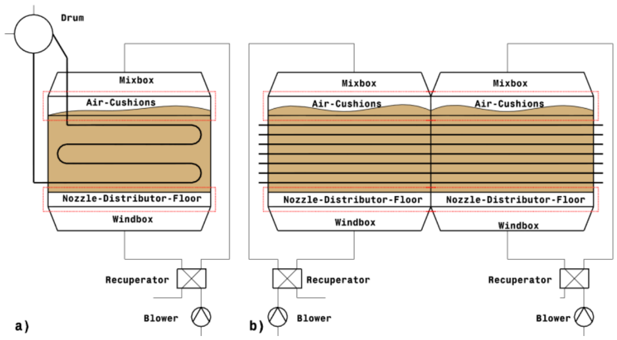


**Figure 6** sketch of fluidized-bed heat-exchangers: a) circulation evaporator, b) counter-current HEX

The overall HEX dimensions are found by determining the needed HEX surface area and flow areas, keeping in mind feasible fluxes of the working fluid and the fluidized bed.

For assessing the needed auxiliary power the required fluidization mass flow has to be determined. This is achieved via the mass balance of air over the distributor in dependence of a multiple t of the minimum fluidization velocity $u_{mf}$, see equation (6). For a stable fluidization an average multiple t of 4-5 is chosen.

$$\dot{m}_{fb} = A_{dist} \cdot \rho \cdot (u_{mf} \cdot t) \qquad (6)$$

The needed fluidization mass flow is compressed to the needed windbox pressure, which is a challenging task to determine. For enabling a particle movement through the HEX a horizontal pressure gradient has to be formed, thus being the driving force of the particle transport, whereas the pressure difference between windbox and mix box has to be equal. So the nozzle-distributor-floor and the air-cushions have to stabilize the system.

Having gained the required windbox pressure the compression power can be determined from equation (7).

$$P = \dot{m}_{fb} \cdot \eta \cdot c_p \cdot T_1 \cdot \left[ \left( \frac{p_2}{p_1} \right)^{\left(\frac{\kappa - 1}{\kappa}\right)} - 1 \right] \qquad (7)$$

**Steam generator**

As already explained above in the next-generation-STE-plant all HEXs are connected in parallel from the view point of the particles and each HEX can use the entire temperature difference between cold and hot storage. The particle mass flow rate is adjusted to deliver the required thermal duty. This connection set-up guarantees a flexible and stable control of the power cycle, especially when the hot hoppers are interconnected.

All HEXs of the steam generator are dimensioned and calculated in great detail via a specialized numerical tool, including the nozzle-distributor floor, the flow enhancing mechanism, and all auxiliary devices; such as recuperators and blowers. For this work only the overall dimensions can be presented. This is done in table 9.

**Table 9** Parameters of power cycle at design point

| | |
|---|---|
| Evaporator | |
| Basis area | 24.5 [$m^2$] |
| Heat exchanger area | 1304 [$m^2$]] |
| Tube diameter | 33.7 [mm] |
| Number of parallel tubes | 1170 [-] |
| Superheater | |
| Basis area | 94.4 [$m^2$] |
| Heat exchanger area | 1968 [$m^2$]] |
| Tube diameter | 33.7 [mm] |
| Number of parallel tubes | 312 [-] |
| Reheater | |
| Basis area | 68.1 [$m^2$] |
| Heat exchanger area | 2300 [$m^2$]] |
| Tube diameter | 42.4 [mm] |
| Number of parallel tubes | 613 [-] |

To illustrate how efficient the fluidization technique is for fine particles of SiC the needed auxiliary power for all HEX are shown in Table 10. Auxiliary power demand for the entire steam generator is in the sub per mill scale in respect to the plant capacity.

**Table 10** Auxiliary power needed for fluidized bed

| | |
|---|---|
| Blower power | |
| Evaporator | 4.3 [$kW_{el}$] |
| Superheater | 19.3 [$kW_{el}$] |
| Reheater | 11.7 [$kW_{el}$] |
| Fraction of plant capacity (all blowers) | 0.026 [%] |

## DISCUSSION

Increasing the temperature difference between cold and hot storage decreases the required particle mass flows and storage inventory. The lower the hot storage temperature, the more efficient the receiver is, but the larger the steam generator becomes.

There is room for optimization and other potential layouts should be investigated in future works. The concept is very promising and offers a wide range of different realizations.

## CONCLUSION

A potential realization of a dispatchable next-generation-STE-plant applying particles as primary heat transfer fluid has been presented. Fluidization technique can efficiently transport particles through key components: the receiver and heat-exchangers of the steam generator. Indirect particle receives have a high surface temperature resulting in higher losses, compared to state of the art plants or direct absorption receivers. To compensate these losses a slightly larger solar field is required, but this is rewarded by the application of a robust and scalable technology.

Applying particles as heat transfer materials requires a complex conveying system and plant set-up, but this is rewarded with high storage temperatures and thus high efficiencies of the power cycle.

Fluidization efforts for both receiver and steam generator are in the sub per mill range in respect to the plant capacity for the applied fine Silicon Carbide particles.

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