Proceedings of the ASME 2015 Power Conference
POWER2015
June 28-July 2, 2015, San Diego, California

POWER2015-49504

DESIGN OF A 100 kW CONCENTRATED SOLAR POWER ON DEMAND VOLUMETRIC RECEIVER WITH INTEGRAL THERMAL ENERGY STORAGE PROTOTYPE

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ABSTRACT

A new concept of Thermal Energy Storage (TES) system based on current available technologies is being developed under the framework of the Masdar Institute (MI) and Massachusetts Institute of Technology (MIT) collaborative Flagship Program. The key feature of this concept lies on concentrating sun light directly on the molten salt storage tank, avoiding the necessity of pumping the salts to the top of a tower thereby avoiding thermal losses and pumping and electric tracing needs inherent in most conventional CSP plants.

This Concentrated Solar Power on Demand (CSPonD) volumetric receiver/TES unit prototype will be tested in the existing MI heliostat field and beam down tower in Abu Dhabi (UAE) which will collect and redirect solar energy to an upwards-facing final optical element (FOE). These energy will be concentrated on the aperture of the prototype designed to store 400 kWh of energy allowing 16 hours of continuous production after sunset using Solar Salt (60%$NaNO_3$ + 40%KNO_3) as storage material.

The tank is divided in two volumes: one cold in the bottom region, where Solar Salt is at 250 ºC and another hot on the upper region, at 550 ºC. A moving divider plate with active control separates both volumes. The plate includes mixing enhancement features to help with convection on the hot volume of salts.

It's expected that results will demonstrate the technical feasibility and economic viability of this concept allowing its scale up at commercial size.

NOMENCLATURE

Abbreviations

TES	Thermal Energy Storage
CSP	Concentrated Solar Power
DoE	Department of Energy
CPC	Compound Parabolic Collector
OD	Outside Diameter
FOE	Final Optical Element
BDOE	Beam Down Optical Experiment
HTF	Heat Transfer Fluid
CSPonD	Concentrated Solar Power on Demand
HX	Heat eXchanger

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INTRODUCTION

Thermal energy storage (TES) is a key aspect for development and implementation of concentrated solar power (CSP) plants in order to accommodate matching energy production with demand [1,2]. Nonetheless, the cost of electricity produced by solar thermal technologies is still an issue on the path to achieving a 100% sustainable energy system for the planet.

Presently technologies based on Solar Salt (60%$NaNO_3$ + 40%KN_3) as a storage material using two tanks have largely been developed [3]. However, to reduce costs, researchers have been developing concepts using only one TES tank, some of them as a result of the SunShot Initiative.

The US Department of Energy's (DOE) SunShot Initiative, is focused on the reduction of the cost of solar energy from 21c/kWh in 2010 to 6c/kWh by 2020 [4]. This ambitious objective is to be achieved thanks to the efforts on research of companies, universities and laboratories, promoting the solar deployment and reducing grid integration costs as well as solar technology costs. In this direction, concentrating solar power presents 4 main topics to work in, among them, TES systems.

A direct absorption Solar Salt CSP receiver to deliver baseload or variable electricity on demand to the grid 24/7 was presented by Slocum et al. [5] and Codd et al. [6]. Because of its versatility the system was called Concentrated Solar Power on Demand (CSPonD).

This new system is well suited for beam-down systems, with a compound parabolic collector (CPC) on top of a TES tank. The CPC further concentrates the sunlight coming from the beam down tower directly into the TES tank where it is absorbed and stored as sensible heat by the storage material (in this case Solar Salt). Hence, the tank simultaneously acts as a volumetric receiver and storage system.

The main advantages of this concept are: (1) it eliminates the need for a second storage tank, thereby decreasing the cost of the entire installation by up to 35% compared with conventional two tank technology [7]; (2) an increasing of the global plant efficiency due to the elimination of inefficiencies of transferring heat to separate storage systems such as low capture efficiencies, parasitic fluid pumping and piping heat tracing losses among others [8].

On the other hand, the proposal presents its own challenges: 1) The use of the same tank to store the hot and cold salt (at 550 ºC and 250 ºC respectively), 2) the need to keep the two regions thermally and physically isolated, 3) the open CPC concept, which simplifies the design and helps to increase the efficiency, leads to an increase in radiative losses and exposes the salt to the unknown effect of sand or dust particles on the salt's behaviour.

SYSTEM DESCRIPTION

The CSPonD volumetric receiver/TES unit prototype will be tested on the existing MI heliostat field and beam down tower in Abu Dhabi (UAE). The beam down will collect and redirect solar energy to an upwards-facing final optical element (FOE) which will be used to further concentrate the energy of the sun on the aperture of the tank prototype.

As it may be seen in Figure 1, the system also integrates the necessary equipment to move the salt from/to a heat exchanger (piping, electric heating, valves, molten salts pump, sensors, etc) where the hot salt heats up the heat transfer fluid (HTF).

The main functional requirements for the system were (i) a nominal thermal power of 25 kW, which can be increased up to 100 kW; (ii) a continuous energy production during 24 hours per day; (iii) low ratio of thermal losses (fixed on a 3% of the total energy stored). The nitrate salt nominal working temperature range is fixed from 250 ºC to 550 ºC to maximize the storage energy capacity of the tank avoiding freeze point in the cold side of the tank and salt degradation due to hot spots in the hot side.

In the upper region of the tank, Solar Salt is heated by the sunlight, as it penetrates the salt, to 550 °C and flows as needed to a heat exchanger (HX). The salt coming from the HX is pumped to the bottom of the tank at 250 °C. The nominal heat extraction rate in the salts-to-air heat exchanger is 25 kW.

Because of the minimum working temperature was fixed on 250 ºC (in order to maximize the tank energy storage capacity) the bottom part of the tank presents a real risk of solidification (solidification point of Solar Salt is 220 ºC). In order to overcome undesired freezing points a by-pass will be installed to heat up the cold salt volume without any use of auxiliary heating systems (Fig. 1).

In addition, solidification of salt inside the circuit may lead to heavy pressure points when the system is heated again before the start up [9]. To avoid this drawback a drain pipe is placed on the lower part of the circuit (Fig. 1) in order to empty it in case of system unexpected shut down, failure or even maintenance.

A moving divider plate with active control separates the hot salts at 550 °C from the cold salts at 250 °C.

Unique to this system is its open-to-air aperture in order to avoid high-flux reflection losses and durability concerns associated with transparent aperture windows [10]. This does lead to the possibility of contamination of the Solar Salts with external particles; hence an important part of the research is an exhaustive study of the salt composition before the testing campaign to evaluate their suitability in this application, and then periodic testing of the salts during use to understand the effects of accumulated contaminants. Experience in the heat treatment industry indicates that there should not be a problem, but in this application the salt must be pumped through a heat exchanger and hence long-term durability must be assessed.

The prototype will be located on a moving platform in order to facilitate the maintenance operations out of the beam-down installation and allow the use of existing immobile experiments.

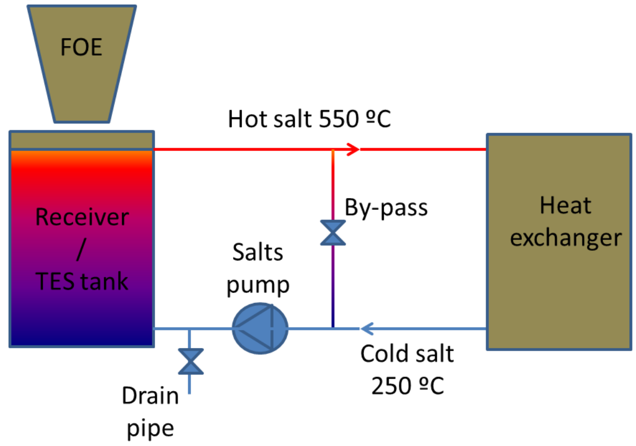

Figure 1. CSPonD system with CPC, storage tank/receiver, heat exchanger and salt flow loop.

FINAL OPTICAL ELEMENT (FOE) DESIGN

A final optical element (FOE) is designed to reduce the aperture of the tank, hence decreasing the convective and radiative losses, while minimizing the spillage losses. A first analysis [10,11] evaluated the optical performance of a Compound Parabolic Concentrator (CPC) and a cone using TracePro software. This study revealed that despite a larger aperture, a simple to manufacture cone offers a more uniform flux distribution, avoiding possible degradation of the salt. Moreover better absorption in the salt pond was predicted. Nevertheless the salt emissivity, which will be measured in the near future, is a key parameter to optimize the outlet dimension of the cone corresponding to the aperture of the tank.

Experiments on the first system will be carried out at the Beam Down Optical Experiment (BDOE) facility of Masdar Institute. To ease the manufacture of the final optical element, a true cone and a 6-facet cone (hexagonal inlet/outlet) with similar dimensions are compared. Table 1 shows that both have comparable performance. The faceted cone, however, would be easier to manufacture on a larger scale and could potentially be more easily have its surfaces lined with reflective ceramic materials.

	Cone		*6-facet cone*	
Time	12 pm	10 pm	12 pm	10 pm
FOE input (kW)	142.6	103.1	142.6	103.0
FOE output (kW)	95.9	95.4	95.4	94.9
Salt input (kW)	96.4	96.0	96.4	96.1

Table 1. Performance comparison between cone and 6-facet cone.

By assuming a high reflectance of 95% of the FOE, the transmission efficiency (ratio of FOE output to FOE input) is around 95%, corresponding to an average amount of 1 impact on the FOE. The absorption efficiency on the salt pond (ratio of salt input to FOE output) depends on the incident angle of the ray on the salt surface and is around 96%.

A 6-facet cone made of polished aluminium sheets with a 4 mm thickness will be set up at the BDOE and the simulated results will be compared to the experimental ones. Reflectance of the polished aluminium sheets will be measured and modified in the ray tracing software. The experimental measurement devices consist of a CCD camera located at the top of the tower, lambertian tiles at the inlet and the outlet of the cone and heat flux sensors to calibrate the intensity distribution provided by the CCD camera. The temperature of each aluminium sheet will be monitored by several thermocouples installed at the back of the sheets. In addition, on the cone facets' inner surfaces, reflective ceramic sheets will be attached and the experiments repeated to understand the potential for more diffuse reflectors to be used.

For future experiments, if cooling the FOE proves to be needed (depends on the reflectance and the material of the FOE), a cooling system consisting of a salt film on the FOE is under design. Salt will be driven from the cold part of the circuit at 250 ºC. The salt flow will be controlled in order to fulfill the cooling necessity depending on the time. The salt flow would be applied to the bare aluminium surfaces, and also to the reflective ceramic sheet configuration. Optical as well as thermal simulations are required to design this system.

THERMAL ENERGY STORAGE (TES) TANK DESIGN

In order to satisfy the requirement of 24 hours of energy production under a nominal power of 25 kW for 400 kWh, the TES tank was designed for a total salt inventory of 3180 kg (considering an average specific heat of 1.51 kJ/kg·K [12]). The main characteristics of the tank are listed on Table 2. Geometrical dimensions are based on the aspect ratio (height/diameter) used as design criterion on thermoclines (between 1.2 and 2). Figure 2 shows the design of the 6-facet cone and TES/receiver tank

Parameter	*Storage tank geometry*
Material	SS304L
Internal diameter (m)	1.25
Height (m)	1.94
Wall thickness (mm)	3

Table 2. Characteristics of the TES tank.

TES tank wall thermal shorts. Thermal short-circuits along the tank wall from the hot to cold regions of the tank were reduced by keeping the wall thickness to a minimum. A 3 mm thickness was selected as compromise between the corrosion rate estimated [13,14], the result of a parametric study of energy leakages through the wall and a concern for manufacturability and handling.

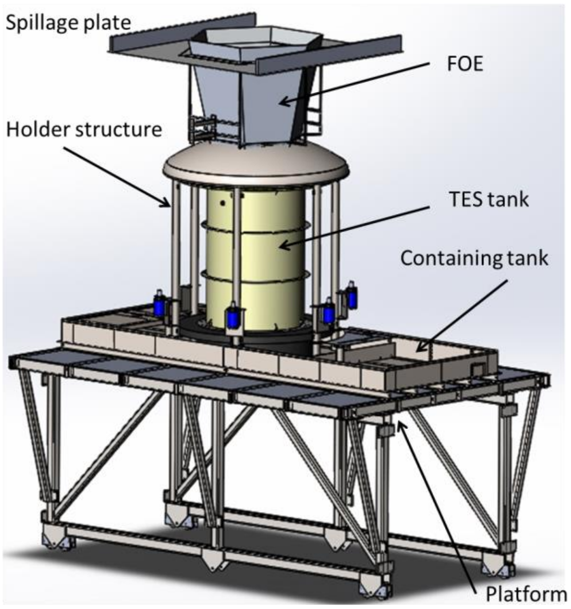

Figure 2. 3D view of system and its components (wall insulation is not represented).

A parametric study of the thermal short effect was performed for 3, 6 and 12 mm thickness and results may be seen in Fig. 3.

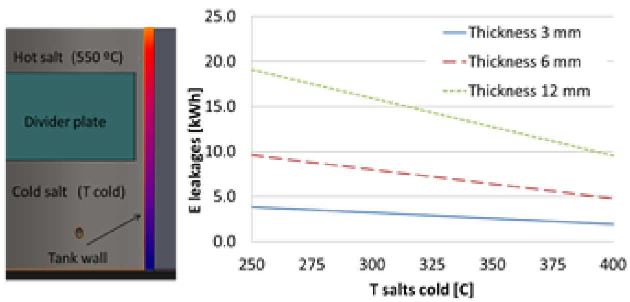

Figure 3. Energy leaks from the hot to cold salt volumes in the tank as function of TES tank wall thickness.

Fourier's law was used to calculate the heat flux along the wall. It was considered for the SS304L a thermal conductivity of 21.5 W/m·K; cross-section of the shell wall $A = \pi D \delta_{\text{wall}}$, (where D = 1.25 m); and path length e = 0.4 m. The total energy leakage was calculated for 24 hours.

$$q = -k \cdot A \cdot \frac{\Delta T}{e} \qquad \text{Eq. 1}$$

Divider plate. A divider plate is placed within the TES tank to keep thermally separated the hot salt volume from the cold one and also block the mixing of the two regions. This component, key item for the success of this system, has a diameter of 1.2 m and a total thickness of 0.24 m. In its preliminary design the divider plate is a vacuum sealed stainless vessel to reach good thermal performance, and a layer of mind steal is included in the plate to add weight. The net axial heat transfer rate for this configuration is about 0.38 kW, which represents 1.5% of the nominal thermal power.

The actuation method for the divider plate is shown in Figure 4. In the design of the CSPonD, stainless chain hoists will be used to actuate the divider plate due to its good corrosion resistivity. Three electric motors are used to drive the chains for lifting the plate, and the downward movement of the divider plate is driven by the difference of is gravity and buoyancy.

Since the CSPonD is operating close to the decomposition and the freezing temperature of the binary nitrate salt, the temperature mixing and control in the storage tank is essential for the safety operation. Natural convection within the salts was considered as one potential solution to obtain a uniform temperature in both sides of the divider plate. However, this will not be sufficient for temperature mixing in the system, especially when the divider plate is near the tank bottom. To address this problem, a second metal meshed plate constantly moving up and down, as is shown in Fig. 4, is added to enhance temperature uniformity in the hot salt volume, where the temperature control is most critical and challenging. Besides, local temperature control at the tank outlet enables simpler control design, which is introduced in detail in a separate paper.

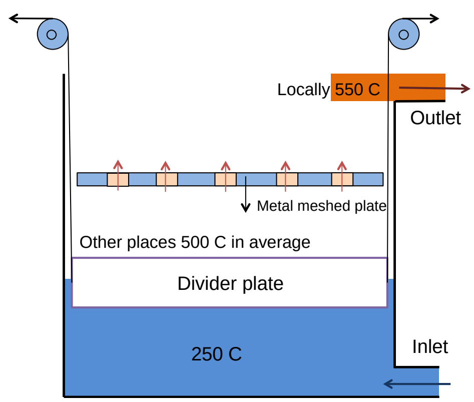

Figure 4. Divider plate and mixing plate Diagram.

TES tank thermal losses. A functional requirement for thermal losses is they should be less than 3%. The characteristics of tank wall and bottom insulation materials are shown in Table 3. Considering the insulation configuration proposed in Table 3 and neglecting tank exterior radiative losses, the average thermal losses through the wall and bottom are 15.1 kWh per day, which results in a loss of 2.5% of the total energy stored. The TES tank temperature measurement system needed to verify this performance is still under design.

For the risk of salt freezing in the bottom of the tank while the divider plate is place, a countermeasure anti-freezing control system was designed that is composed of 10 thermocouples placed in the bottom of the tank to detect cold spots and an auxiliary heater system of 8.5 kW to melt a total amount of salt of 0.026 m^3 in 15 minutes. This system will be installed in the external lower part of the tank wall.

Material	*Thermal conductivity ($W/m^2 \cdot K$)*	*Insulation thickness (mm)*	
		Wall & top	Bottom
Pyrogel® XT-E	0.07	25	--
Spintex 342G	0.20	400	--
Foamglas®	0.13	--	250
BTU Block	0.03	--	150

Table 3. Insulation material characteristics

Tank structure loading. Six round columns placed around the TES tank (Fig. 4), at 60 º between them will support the storage tank cover and the divider plate actuators (and hence the divider plate weight) and measuring and control systems. In this manner the tank wall will be loaded primarily by hydrostatic salt pressure.

TES tank lid. A tank lid was designed to accomplish a double function: minimize radiative and convective thermal losses during night period and protect the tank from possible water entrance in the rare event of a rainstorm. Rain on the hot salt could result in a steam explosion.

Containing tank. The outer component of the TES system is a safety container tank (Fig. 2). This tank of 2.3 m of wide, 6.0 m length and 0.45 m height is constructed on mild steel in order to reduce cost. Its main objective is to contain all the hot salt in the event of a rupture or leak of the salt tank or even from some other of the installation components (salts pump, heat exchanger, etc).

HEAT EXCHANGER

A direct contact salt-air counterflow heat exchanger with raschig rings is proposed in CSPonD project. The design developed is intended as a low-cost, safe, controllable way to reject heat at atmospheric pressure. A pressurized version could be used to heat air or other Brayton cycle gas. An entirely different sort of HX, with separate water, boiler and superheating sections and associated control, materials and safety challenges, would be needed for a steam Rankine cycle.

Control Requirements. We will control the salt flow rate according to a thermal discharge schedule. Approximately balanced thermal capacitance rates can be maintained by modulating both air and salt thermal capacitance rates. This can be accomplished by open-loop control of fan and pump speeds accounting for air and salt densities, both simple functions of T, at fan and pump. The heat exchanger air inlet temperature may be controlled to maintain a desired cold-salt outlet temperature, e.g. 280 ºC, by a feedback loop that modulates the ambient air damper linked, if necessary, to a recirculation damper. Moderate recirculation damper leakage should not be an issue but the ambient air damper should seal well to prevent buoyancy driven flow which would tend to cool the HX when the fan and pump are off leading to excessive electric trace heater power consumption. A similarly tight and linked discharge damper or thermosyphon trap will also likely be used as a backup system.

Design temperatures and flow rates. Balanced flow is desired to simplify control (constant gain). In addition, high heat-exchanger effectiveness is desired in order to keep air inlet temperature above the salt melting point at all times—i.e. air temperature should not drop below 250°C. The design temperatures with balanced flow and 30K air-salt temperature difference are

T_{hi}=550°C T_{co}=520°C

T_{ho}=280°C T_{ci}=250°C

For a design heat rate of Q_r = 130kW we need salt and air thermal capacitance rates equal to

$$\dot{m}c_p = \frac{Q_r}{T_{hi}-T_{ho}} = \frac{Q_r}{T_{co}-T_{ci}} = \frac{130000}{270} \cong 481.5\,\frac{W}{K} \quad \text{Eq. 2}$$

For air at 250°C the corresponding volumetric flowrate is 0.705 m^3/s. For solar salt at 280°C the corresponding volumetric flowrate is $1.72\cdot10^{-4}$ m^3/s. Design flowrates can be reduced to half or 1/3 the above if discharge is at night or continuous.

NTU-Effectiveness. For balanced counterflow operation at the HX design temperatures, the efficiency and the Number of Transfer Units (NTU) are 90% and 9, respectively.

It's assumed that the overall resistance is dominated by the air-side resistance; therefore the air-side heat transfer coefficient can be estimated from Whitaker's [15] general approximate correlation for packed columns as reported in Kreith [16]

$$\frac{h_c d}{k} = \frac{1-\epsilon}{\epsilon}\left(0.5Re^{\frac{1}{2}} + 0.2Re^{\frac{2}{3}}\right)Pr^{\frac{1}{3}} \quad \text{Eq. 3}$$

for $20 < Re < 10^4$ and $0.34 < \varepsilon < 0.78$, where ε is void fraction, Re the Reynolds number based on the bed face velocity and the effective diameter of the packing element.

Pressure drop. The friction factor correlation of Beek [17] is:

$$f = \frac{d}{L}\frac{\Delta p}{\rho V^2} = \frac{1-\epsilon}{\epsilon^3}\left(1.75 + 150\frac{1-\epsilon}{Re}\right) \quad \text{Eq. 4}$$

for $40 < Re < 2000$.

Entrainment and Flooding. Under normal operation the packing is fully wetted by a smooth film of molten salt falling at uniform velocity. Large-scale flooding can occur only at a very high air-side pressure gradient. The usual entrainment criterion is Weber number, becoming a concern at $We > 2\pi$. In our case raschig rings with an outside diameter of 9.5 mm are chosen, leading to a surface area of 528 m^2/m^3 and a bed void fraction of 0.75 [18]. With V=3 m/s and the surface tension of the salt σ_l=0.1 N/m, the Weber number is equal to 0.81 which is well below the entertainment threshold.

Dry out and entrainment of droplets are promoted by low surface tension. Particle flooding, on the other hand, is promoted by high surface tension together with small packing diameter (d) and small contact angle θ. Capillary lift is given, in our case for 8 mm packing, by

$$L_{cap} = \frac{\sigma_l \cos\theta}{\rho_l g d} = \frac{0.1}{1800 \times 9.8 \times 0.0095} \ll 0.010m \quad \text{Eq. 5}$$

indicating that formation of a stable meniscus in this size or larger packing is unlikely.

A plot of bed height, pressure drop vs bed diameter (Fig. 5) for 9.5 mm packing shows that a good compromise between pressure drop (fan power) and column surface area (tracing heat loss when HX is off duty) is for a diameter of 0.7 m, corresponding to a 1.2 m height and a 150 Pa pressure drop.

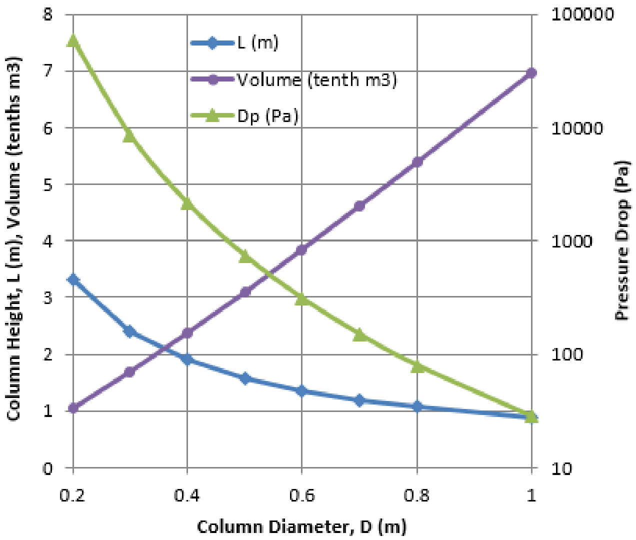

Figure 5. Column height and pressure drop as a function of the column diameter

SYSTEM OPERATION

The system operation consists of a charging process of 8 hours, corresponding to the day time. During this period 25 kW of power will be produced at same time that 400 kW of energy is accumulated from the sun and then stored as heat in the molten salt.

The charging process starts at the beginning of the day. At this moment the divider plate is near on the top level of the salt in the tank and most of the salt is at 250 ºC. Then the concentrated sunlight coming from the CPC starts to heat the upper salt layer to 550 ºC and the divider plate starts moving down at a velocity of about 0.3 mm/s. The velocity of the divider plate starts slow and as the sunlight intensity increases the velocity of the plate will increase in order to maintain the temperature of the hot salt region at 550 ºC. This displacement allows the increasing of hot volume occupied by the hot salt (and consequently increasing the net stored energy). At same time cold salt is passing from the bottom region of the tank below the divider plate to top the upper region through the gap between the tank wall and the divider plate. A constant salt flow rate of 0.01 m^3/s is sent to the HX (ideally in a full scale system for producing electricity) and cold salt are coming from the power block HX back to the tank through the lower part thereby completing the circuit.

In the sunset, after 8 hours of charging, all the salt will have reached 550 ºC and the divider plate will have arrived at the bottom of the tank. In order to reduce radiative losses, the tank aperture is closed with the insulated cover. The discharge process to the HX continues, but now the divider plate starts moving upwards increasing the cold salt volume. The salt flow rate is kept constant during charging and discharging processes allowing a 24/7 power of 25 kW.

ONGOING WORK AND EXPERIMENTAL PLAN

Currently key equipment such as molten salt pumps, valves, and electric tracing are under study and design as well as the detailed definition of the TES tank. Initially however, just the TES and safety container tanks will be installed so time-under-the-sun can be obtained for the salts to study effects of blown-in contaminants from the environment.

In addition, CFD models of the TES tank are being developed for analysis by ANSYS' Fluent program. The results of simulations should provide insight as to the salt natural convection coefficient in both upper and lower volumes and help decide if additional devices are needed to help with mixing.

The experiment plan will be divided into three main campaigns: 6-facet cone testing, TES tank testing and overall system testing.

During the 6-facet cone testing the efficiency of the cone will be evaluated. The results will be used to optimize the cone design as well as the TES tank aperture.

During the second experimental campaign the TES tank behavior will be evaluated. In this phase of experimentation the TES tank will be coupled to the 6-facet cone but not assembled to the rest of the installation. The results will be compared with simulations in order to validate the natural convection model. In addition, analysis of cone heating power, TES tank thermal losses and behavior during transients (startup/shut down) will be carried out.

The divider plate will be not installed until last experimental campaign. The last experimental campaign will consist on repeating the same experiments of the second one but in this case having the divider plate in the TES tank. An evaluation of the efficiency and performance of other system components and the system as a whole will also be completed. Furthermore, periodic analysis and characterization of the molten salts will be performed in order to evaluate the effect of sand and dust on the thermophysical properties of the salt.

CONCLUSIONS

The preliminary design of a 25 kW continuous operating TES tank with 400 kWh of energy stored in molten nitrate salt, known as the CSPonD, has been developed. The single TES tank with vertical open-top to direct absorption 6-facet cone CPC (Final Optical Element, FOE) is powered by the Masdar Institute's Beam Down Optical Experiment. The volumetric light absorption system (6-facet cone) linked to the receiver/TES tank allows a gradual absorption of energy by the salt and helps to make the system tolerant of much higher heat fluxes.

A CPC FOE is essential to minimize the spillage losses coming from the tower while maximizing the thermal performance of the tank. First experiments at the BDOE will provide valuable information to enhance the optical simulation tool and optimize the FOE design. Moreover the temperature monitoring will inform if a flowing cold salt film, coming from the heat exchanger outlet, cooling down the FOE surface is required.

Thermal losses are predicted to be 2.5% of the total energy production. Thermal shorts through the tank wall from the upper hot volume to the lower cold volume are kept low by keeping the tank wall thickness minimal. In addition, a lid will cover the TES tank aperture in order to minimize radiative losses during the night time.

A moving divider plate is a key item in this design in order to maximize the temperature gradient between the hot and cold salt volumes.

A low-cost, safe, atmospheric pressure and counterflow heat exchanger with direct contact between salt and air will be used to thermally load the system. This design can help to decrease the pressure drop in the circuit and, consequently, the pump power requirements.

Once this size unit has been developed and proven, the next step will be to design, build and test a much larger unit that is coupled to an electricity generating power system.

ACKNOWLEDGMENTS

This work is part of the CSPonD project ongoing at Masdar Institute of Science & Technology in partnership with Massachusetts Institute of Technology. This research is supported by the Government of Abu Dhabi to help fulfill the vision of the late President Sheikh Zayed bin Sultan Al Nahyan for sustainable development and empowerment of the UAE and humankind.

Initial work on the CSPonD concept was made possible by an interdisciplinary collaboration between the Cyprus Institute, the University of Illinois at Urbana Champaign, the Electricity Authority of Cyprus, and the MIT Energy Initiative. Generous graduate student fellowships were provided by the Chesonis Family Foundation, and the Bill and Melinda Gates Foundation.

Transfer of the BDOE by the Abu Dhabi Future Energy Company to Masdar Institute is gratefully acknowledged.

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