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LATEST WORLDWIDE DEVELOPMENTS IN MOLTEN SALT TECHNOLOGY AND APPLICATIONS

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Molten salt (MS) storage systems in the 565°C range can store green solar energy from thermal solar power station, such as the Crescent Dunes solar plant in Nevada. Large containers can be used to store energy and generate electricity for eight hours or more to be used at night or during peak demand hours, depending on the container size. Energy storage can reduce the fluctuation due to weather conditions experienced at thermal solar power stations because stable diurnal energy supply is made available by MS energy storage. Supported by the Office of Naval Research (ONR), the research presented discusses the recent technological developments associated with the use of molten salts for energy storage. In addition to their use for storing excess solar energy, molten salts are starting to be used in nuclear or hybrid power production. One particular aspect of interest is the focus using higher temperature salts to provide even more energy storage than conventional molten salts. One such salt, SaltStream700, allows for the use of molten salts at temperatures of 700˚C. A summary of worldwide examples of concentrating solar power (CSP) plants is presented. Commercial solar power stations have been constructed in the United States and overseas, particularly in Spain, with molten salt being considered for use in these facilities.

Keywords: Commercial electric station, Energy storage, Energy production, Solar salts, Thermal solar power.

1 INTRODUCTION

Molten solar salts are known for their ability to store large amounts of heat, and as such, this allows them store excess generated energy for later use when contained in large tanks. This paper presents catalogue of worldwide Molten Salt (MS) storage for electric power production and discusses a few real life examples showing the evolution of MS energy storage systems (MS-ESS). In addition, this paper also discusses the latest developments in technological advances involving MS storage.

2 WORLDWIDE MOLTEN SALT INSTALLATIONS

After the development of Solar Two in 1993, MS-ESS technology has evolved and accelerated worldwide, with 44 MS-ESS plants either currently operational or under construction, as well as 24 more plants in the planning stages (CSP Today 2020, NREL 2020). The success of Solar Two led to two development paths: power towers based directly on the Solar Two design and the addition of MS-based storage to commercially proven parabolic trough plants. Over 3 GW of MS plants are in operation or under construction around the world, compared to a total 5.6 GW for all

CSP plants. Table 1 lists all MS concentrating solar power (CSP) plants worldwide that are currently in use or under construction. Based on the information in Table 1, MS plants that are in operation or under construction around the world account for over 3 GW of energy, compared to a total 5.6 GW for all CSP plants.

Table 1. Current worldwide molten salt CSP Plants and their capacities (CSP Today 2020, NREL 2020).

			Size		MS storage	
Project	Technology	Country	(MW)	Status	Hours	MWh
Atacama-1	Tower	Chile	110	Construction	17.5	1,925
Golmud	Tower	China	200	Construction	15.0	3,000
Hami	Tower	China	50	Construction	8.0	400
Huanghe Qinghai Delingha	Tower	China	135	Construction	3.7	500
Qinghai Delingha	Trough	China	50	Construction	9.0	450
Rayspower Yumen	Trough	China	50	Construction	7.0	350
SunCan Dunhuang Phase I	Tower	China	10	Operational	15.0	150
SunCan Dunhuang Phase II	Tower	China	100	Construction	11.0	1,100
Supcon	Tower	China	50	Construction	2.5	125
Urat Middle Banner	Trough	China	100	Construction	4.0	400
Yumen 50 MW Tower	Tower	China	50	Construction	9.0	450
Archimede	Trough	Italy	5	Operational	8.0	40
ASE Demo Plant	Trough	Italy	2	Operational	1.0	2
Noor I	Trough	Morocco	160	Operational	3.0	480
Noor II	Trough	Morocco	200	Operational	7.0	1,400
Noor III	Trough	Morocco	150	Construction	7.0	1,050
Bokpoort	Trough	South Africa	50	Operational	9.3	465
Kathu Solar Park	Trough	South Africa	100	Operational	4.5	450
KaXu Solar One	Trough	South Africa	100	Operational	2.5	250
Xina Solar One	Trough	South Africa	100	Operational	5.5	550
Andasol 1	Trough	Spain	50	Operational	7.5	375
Andasol 2	Trough	Spain	50	Operational	7.5	375
Andasol 3	Trough	Spain	50	Operational	7.5	375
ASTE - 1A	Trough	Spain	50	Operational	8.0	400
ASTE - 1B	Trough	Spain	50	Operational	8.0	400
Arenales	Trough	Spain	50	Operational	7.0	350
Astexol-2	Trough	Spain	50	Operational	7.5	375
Casablanca	Trough	Spain	50	Operational	7.5	375
Extresol 1	Trough	Spain	50	Operational	7.5	375
Extresol 2	Trough	Spain	50	Operational	7.5	375
Extresol 3	Trough	Spain	50	Operational	7.5	375
Gemasolar	Tower	Spain	20	Operational	15.0	300
La Africana	Trough	Spain	50	Operational	7.5	375
La Dehesa	Trough	Spain	50	Operational	7.5	375
La Florida	Trough	Spain	50	Operational	7.5	375
Manchasol 1	Trough	Spain	50	Operational	7.5	375
Manchasol 2	Trough	Spain	50	Operational	7.5	375
Termosol 1	Trough	Spain	50	Operational	9.0	450
Termosol 2	Trough	Spain	50	Operational	9.0	450
Valle 1	Trough	Spain	50	Operational	7.5	375
Valle 2	Trough	Spain	50	Operational	7.5	375
Greenway CSP	Tower	Turkey	5	Operational	1.0	5
AREVA demonstration plant	Fresnel	USA	1	Decommissioned	1	1
Crescent Dunes	Tower	USA	110	Operational	10.0	1,100
Solar Two	Tower	USA	10	Decommissioned	3.0	30
Solana	Trough	USA	280	Operational	6.0	1,680
Total			**3,198**			**24 GWh**

Compared to the world, the United States is falling behind in MS energy storage, as the U.S. currently has two CSP plants that use MS energy storage to store excess energy, combining to store 2.8 GWh of energy. Spain is the leading user of MS energy storage, utilizing 8.0 GWh of storage across 21 CSP plants. China is a close second to Spain with 6.9 GWh of storage across 10 CSP plants (Ladkany *et al.* 2018).

However, when considering future development, China is planning on developing 10 more CSP plants that are capable of storing 6.1 GWh, which would allow them to pass Spain's MS energy storage total. However, Chile, which currently has one CSP plant that stores 1.9 GWh of energy, is planning to develop three more CSP plants capable of storing 14.6 GWh of energy. If completed, this would make Chile the world leader in MS energy storage (SolarReserve 2014, Tyner and Wasyluk 2013).

The first near-commercial power tower plant utilizing MS storage was the 20-MWe Gemasolar plant developed by Sener/Torresol in Andalucía, Spain, dubbed Solar Tres. This concept involved participation of U.S. companies which had been suppliers for Solar Two such as Boeing/Rocketdyne (receiver supplier) and Bechtel/Nexant (EPC), although Gemasolar was ultimately built without any U.S. involvement. Gemasolar is roughly a scale-up of Solar Two by a factor of three (120 MW_t vs. 43 MW_t for Solar Two) and a much larger storage system (300 MWh vs. 30 MWh for Solar Two). Gemasolar has operated successfully since 2011, demonstrating continuous operation at full power during good summer solar conditions (Burgaleta *et al.* 2011, Torresol Energy 2011).

The first and currently only large, truly commercial scale power tower plant based on Solar Two technology, the 110-MW_e Crescent Dunes plant, was built by SolarReserve in Tonopah, Nevada (SolarReserve 2013, SolarReserve 2014). Cresent Dunes was completed in 2015, and as was the case with Gemasolar, it is very closely based on the Solar Two design, only scaled up by a factor of 10. With 10 hours of storage, it can deliver continuous power in the summer to the Nevada grid.

3 STORAGE DESIGN EXPERIMENTATION

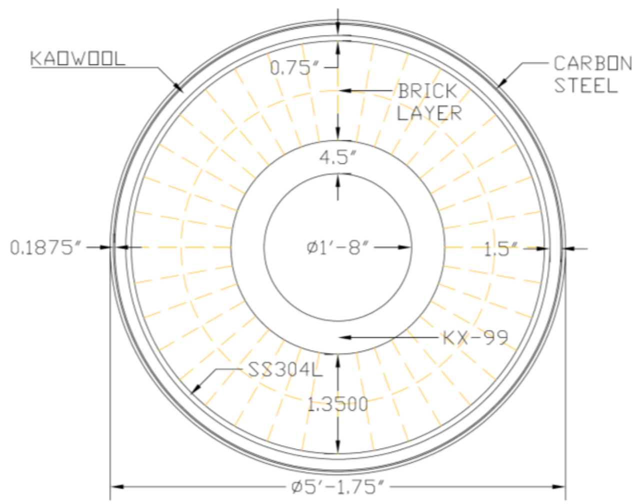

Figure 1. Cross section of the Halotechnics test hot tank (Jonemann 2013).

The National Renewable Energy Laboratory (NREL) and Halotechnics constructed an experimental molten salt storage system for testing purposes (Jonemann 2013). The height of the hot tank was 80 inches (2.032 m) and the diameter was 61.75 inches (1.568 m). The storage cavity has a 20 inch (508 mm) of this tank and a depth of 45 inches (1.143 m). Figure 1 shows the cross section of the tank, which includes the storage cavity followed by a 4.5 inch (114 mm) thick layer of KX-99 insulation, then a 13.5 inch (343 mm) thick layer of firebrick insulation, a ¾ inch (19.1 mm) thick layer of 304L stainless steel, a 1.5 inch (38.1 mm) thick layer of Kaowool insulation, and finally a 3/16 inch (4.8 mm) thick layer of carbon steel to encase the tank (Jonemann 2013).

The biggest issue experienced by the experimental tank during testing was that the molten salt seeped into the insulating firebrick. The initial design anticipated that the tank would use 400 kilograms of Halotechnics Saltstream700 (SS700) molten salt, but instead the tank needed an additional 2,000 kilograms due to this seepage. Based the porosity of the firebrick insulation, the resulting empty volume 2,200 kilograms of SS700 salts is consistent with the seepage. This caused the firebrick thermal conductivity to increase from 0.35 Watts per meter-Kelvin (W/m-K) to 0.73 W/m-K at 500°C and 0.77 W/m-K at 650°C. This points to the need of an inner stainless steel liner in the tank.

Overall, this experiment showed how a molten salt tank can operate at 700°C using SS700 salts. The tank did not have to use a nickel alloy liner in order to protect structural elements because of the firebrick insulation. Also, the estimated cost of a larger scale tank, with a 38 meter diameter and 14 meter height, is about $60 million to construct.

4 HYBRID STORAGE SYSTEM

A study by Popov and Borissova (2018) simulated and analyzed the viability of a hybrid parabolic trough and nuclear reactor power for energy production, referred to as the Solar Assisted Nuclear Power Plant (SANPP). The energy collected by the parabolic troughs would be stored in a Solar Salt Mixture (60:40 Na:K nitrate by weight) that are also used in the nuclear reactor.

Thermoflex 25.0 was used to simulate and analyze the performance of the SANPP system against the performance of a power tower. In order to produce the same amount of power from solar heat, which was 25,390 kilowatts (kW), as well as 15 hours of thermal storage, it was determined that the SANPP system produced a solar heat to an electrical efficiency of 51.9%, requiring 48,924 kW of solar heat input to achieve the specified electrical demand. The power tower operated at a 35.9% efficiency and required 70,727 kW of solar heat input. These simulations also result in the SANPP system having a lower levelized cost of energy (LCOE), which is an average cost of power production over the life of facility, of 13.45 cents per kilowatt-hour, while the power tower costs 17.74 cents per kilowatt-hour.

Simulations were also performed to see how the SANPP system compared to a tradition nuclear power plant. Both systems were set to intake 160,000 kW of nuclear heat for energy production, along with the SANPP system inputting 48,924 kW of solar heat from the earlier simulation. The nuclear power plant produced 43,911 kW of electricity, resulting in an efficiency of 27.44%. The SANPP system produced 69,302 kW of electricity, resulting in an efficiency of 33.17% (Popov and Borissova 2018).

Based on these simulations, the SANPP system is viable when compared to more conventional power systems like the nuclear power plant or the power tower. The last important consideration from these simulations is the insulation costs of these systems. It costs $154,577,000 to install a solar field for a SANPP system while installation for a power tower costs $204,690,000, which can be attributed to smaller solar field required by the SANPP system. It costs $21,197,000 to install a steam turbine for a SANPP system while it costs $14,057,000 to install a steam turbine for a nuclear reactor, which can be attributed to the larger energy input in the SANPP system (Popov and Borissova 2018).

5 SOLAR SALT THERMAL STABILITY

It is important that the high temperature stability of a molten salt be compatible with the power cycle used. Traditionally, 565ºC bulk temperature limit on solar salt has limited the use of molten salts with steam turbines, although the newest 585ºC steam turbines allow for the use of molten salts up to 600-620ºC. However, with the development of SaltStream700 by Halotechnics, it would be possible to use a Brayton cycle for energy production (Ladkany *et al.* 2018).

In order to make the Brayton cycle more efficient than the steam Rankine cycle, the use of supercritical CO_2 as an operating fluid is being explored by various laboratories, including the Korean Atomic Energy Research Institute, the Korean Advanced Institute of Science and Technology, and Sandia National Laboratory. With this development, the technology is also being studied for use in solar thermal energy production. Using supercritical CO_2 just above its critical temperature and pressure can significantly reduce the pumping power, while also increasing the efficiency of thermal-to-electric energy conversion and also reducing corrosion by eliminating the need to cycle between steam and water in a Rankine cycle (Ahn *et al.* 2015).

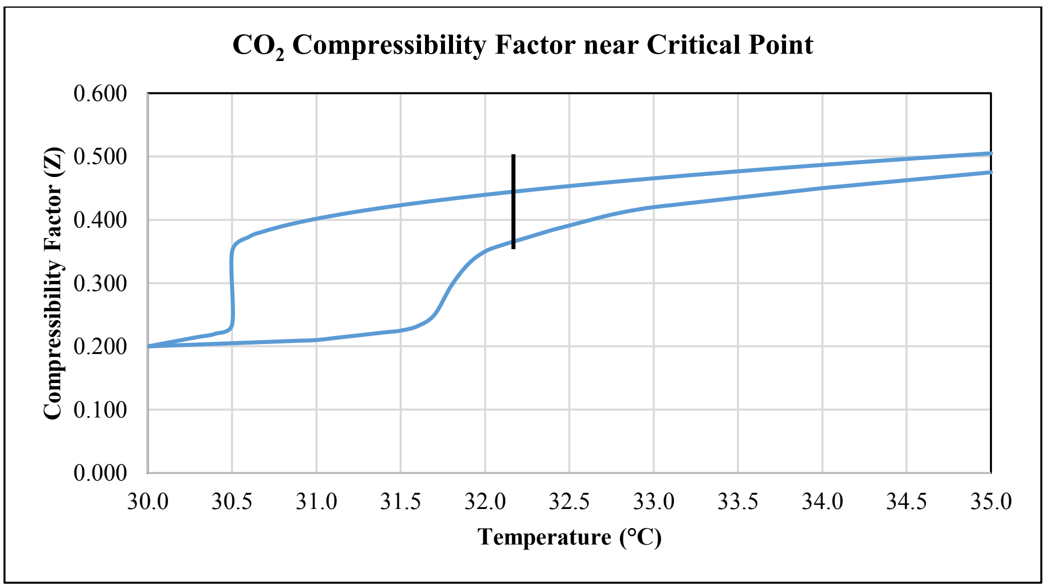

Figure 2. Compressibility factor envelopes for CO_2 near the critical point (Ahn *et al.* 2015).

Figure 2 shows the range for the compressibility factor (Z) of CO_2 near its critical point, which is the space between the blue curves, with the black line representing the approximate critical temperature of 32.5°C. The critical pressure at this temperature is between 7.3 and 7.5 MPa. Eq. (1) shows how Z is calculated (Ahn *et al.* 2015).

$$Z = \frac{PM}{\rho RT} \tag{1}$$

In Eq. (1), P is the pressure of the fluid, M is the mass of the fluid, ρ is the density of the fluid, R is the gas constant, and T is the temperature of the fluid. Z can range between 0, which is an incompressible fluid, and 1, which is almost an ideal gas. Near its critical point, Z ranges between 0.2 and 0.5 for Supercritical CO_2 (Ahn *et al.* 2015).

One practical benefit of supercritical CO_2 cycles is that the turbo machinery used in SCO_2 is one-fourth the size of the turbo machinery used in a steam Rankine cycle. Also, printed circuit heat exchangers (PCHE), which are used in SCO_2 cycles, are one-tenth the size of traditional shell and tube heat exchangers (STHE) (Ahn *et al.* 2015).

6 CONCLUSION

The worldwide development of molten salt energy storage systems has increased significantly due to the success of Solar Two, although it has yet to significantly catch on in the United States. Technological advancements in molten salt technology include the testing and development of chloride salts that can be used at 700°C, allowing for the use of a more efficient Brayton cycle to produce power. In addition, research into molten salt solar and nuclear hybrid systems show that these could be viable for energy production.

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