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Comparison of sodium and KCl-$MgCl_2$ as heat transfer fluids in CSP solar tower with sCO_2 power cycles

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ABSTRACT

This work assesses the performance of a solar tower power plant based on liquid sodium as heat transfer fluid and supercritical CO_2 cycles. The adoption of liquid sodium as heat transfer fluid allows maximum temperatures up to 750 °C and higher heat fluxes on the receiver with respect to molten salts (both Solar Salts and KCl-$MgCl_2$) also considered as reference. The assessment is carried out through detailed modeling of the solar to electricity conversion processes accounting for detail optical, thermal and power block models. Results at design conditions show that plants using sodium as HTF in the receiver can achieve overall efficiency above 25%, whereas the use of Solar Salts at 565 °C and KCl-$MgCl_2$ at 750 °C reach 21.5% and 24% respectively. The higher efficiency is consequence of the higher thermal efficiency of sodium which is achieved increasing the concentration ratio. Considering a yearly analysis, the overall efficiency of sodium reduces to 20.5% and 19.3% in Seville and Las Vegas respectively which is 7–9% higher than using KCl-$MgCl_2$ and 11% with respect to Solar Salts. Outcomes of this work are the importance of (i) coupling higher temperatures with higher allowable fluxes on the receiver and (ii) defining the system operating conditions on overall yearly efficiency rather than design point.

1. Introduction

Concentrating Solar Power (CSP) can play a strategic role in the future energy scenario for its capability of providing dispatchable carbon-free and renewable electric energy. Dispatchability, a peculiarity of CSP among other renewable energy sources, is possible as the solar radiation is harnessed in the solar field in the form of heat, which can in turn be cost-effectively stored in Thermal Energy Storage (TES) systems, thus decoupling the primary solar energy harvesting from the actual electric power production (IRENA, 2012). Currently though, the Levelized Cost of Electricity (LCOE) of CSP, ranging from 150 to 200 €/kWh_{el} (IRENA, 2012), is higher than competitive renewable technologies (i.e. PV, wind). Therefore, several research programs are trying to achieve further developments in this technology, in order to increase performances and lower costs (Energy USD of SunShot Vision Study, 2012; ASTRI, 2016). Until a few years ago, parabolic trough collectors (PT) were the state of the art technology for CSP plants, due to the experience gained at the SEGS plants (Cohen et al., 1999), and in more recent installations in the United States (ACCIONA, 2017) and in Spain (AGSM, 2008; Fernández-García et al., 2010; Relloso and Delgado, 2009). In the last years, the interest in Solar Tower (ST) returned, resulting in several CSP installations based on this technology (NREL, 2017; Gemasolar, 2014). With respect to PT, ST have a higher concentration ratio (500–1000 vs. 80), and can employ molten salts as Heat Transfer Fluid (HTF) more easily than linear systems: having a much smaller receiver, which can be emptied by gravity, it is much easier to deal with an HTF that solidifies at temperatures much higher than ambient temperature. Salt mixtures currently employed in operating plants allow reaching maximum temperatures of 565 °C, with respect to about 400 °C employed in conventional PT plants using diathermic oil as HTF. The consequent advantage in thermodynamic performance that follows higher maximum temperatures, and the fact that ST are better suited for advanced high-temperature HTFs, makes this CSP technology the most promising option in order to attain LCOE reduction (Energy USD of SunShot Vision Study, 2012). As of 2017, about 600 MW_{el} of commercial ST plants are in operation (mainly in Spain and in the US), 715 MW_{el} are under construction in China, Chile, Marocco and Israel, and an additional 1800 MW_{el} are in the planning phase (NREL, 2017). The commercially available ST plants are based on two main alternative configurations: Direct Steam Generation (DSG) plants, where water serves both as Heat Transfer Fluid (HTF) in the receiver and working fluid in the steam power section (Ivanpah, NREL, 2017); Indirect Cycle configuration, where an intermediate HTF is heated up by solar radiation in the receiver and then transfers the thermal energy to the power block. In particular, molten salts (typically *Solar Salts*, a mixture of 60 wt% $NaNO_3$ and 40 wt% KNO_3) are a common

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Nomenclature

A_h	heliostats area [m^2]
D	diameter [m]
E	energy [Wh]
h	enthalpy [kJ/kg]
H	height [m]
L_{path}	overall HTF path length in the receiver
N_h	number of heliostats
N_p	number of panels in the receiver
N_{tp}	number of tubes per panel
p	pressure [bar]
P	electric power [W]
Q	thermal power [W]
T	temperature [°C]
t	thickness [m]
v	velocity [m/s]
w	specific work [kJ/kg]

Greek letters

α	absorptance
ε	emissivity
η	efficiency
γ	Solar azimuth angle [°]
θ_Z	Solar Zenith angle [°]
Δ	variation

Subscripts

a	axial
aux	auxiliaries
diff	diffuser
el	electric
gen	generator
int	intermediate
max	maximum
min	minimum
opt	optical
rec	receiver
sol-el	solar-to-electric
th	thermal
TS	Total to Static
y	yearly

Acronyms

CF	Capacity Factor
CSP	Concentrated Solar Power
DNI	Direct Normal Irradiance
DSG	Direct Steam Generation
EOS	Equation of State
HTF	Heat Transfer Fluid
HTR	High Tmperature Regenerator
LBE	Lead Bismuth Eutectic
LCOE	Levelized cost of Electricity
LTR	Low Temperature Regenerator
PB	Power Block
PC	Partial Cooling cycle
PCHE	Printed Circuit Heat Exchangers
PERS	Potential Energy Recovery System
PHX	Primary Heat Exchanger
PT	Parabolic Trough
RMCI	Recompression Main Compressor Intecooling cycle
RR	Recompression Cycle
SC	Simple Cycle
sCO_2	supercritical CO_2
SF	Solar Field
ST	Solar Tower
SR	Split Ratio
TES	Thermal Energy Storage
TIT	Turbine Inlet Temperature

choice as HTF (Gemasolar and Crescent Dunes plants (Gemasolar, 2014; Crescent Dunes, 2014). DSG has the advantage of heating the power cycle working fluid up to the maximum temperature attainable by the receiver, avoiding exergy losses and additional costs due to the intermediate heat exchanger between the ST and the power cycle; on the other hand, this technology is penalized by the lack of commercially available compatible TES, and by the low allowable heat fluxes on the collectors (< 0.4 MW/m^2) Schiel and Geyer, 1988. On the contrary, the adoption of molten salts as HTF takes advantage of the possibility to store thermal energy at low prices (IRENA, 2013), which is a fundamental feature that can drastically reduce the generation cost. Still, currently employed salt mixtures are limited by the maximum allowable heat fluxes (0.8–1 MW$_{th}$/m^2) Kolb, 2011; Benoit et al., 2016 and operating temperatures (below 565 °C) Pacio et al., 2013.

Independently from the adopted configuration, all ST power plants currently in operation perform thermal to electric energy conversion by means of traditional Rankine steam cycles. This fact by itself introduces an implicit limitation in the maximum cycle temperature, since the thermodynamic efficiency advantages that can follow a further increase in maximum steam temperature above 550 °C hardly justify (in the context of CSP power plants) the additional cost coming from the need to adopt more expensive materials. This is particularly true for small-scale power plants that do not benefit of economy of scale.

Therefore, significant technology developments can still be attained, both in the receiver and in the power conversion system, to enhance the ST performance and reduce costs, as discussed in Behar et al. (2013). Focusing on the power block configuration, several research programs and key international energy stakeholders (Energy USD of SunShot Vision Study, 2012; aCo2-hero, n.d.; Mecheri and Le Moullec, 2016; Rochau, 2011; Willian Penn, 2014; Musgrove et al., 2016) have indicated the supercritical CO_2 Brayton cycle as the future of the thermal to electric conversion technology. Supercritical CO_2 cycles were first proposed in the late 1960s (Angelino, 1969) to overcome the performance improvement limitations for steam cycles. They have been traditionally considered for application in nuclear power plants (Dostal et al., 2004), but recently they have become increasingly popular also in relation to their potential application in CSP plants, due to the high performance that can be achieved at moderate maximum temperatures, and their contextual power block compactness and simplicity: two features that have the potential to substantially drive down CSP LCOE.

The sCO_2 cycles superiority in CSP applications over steam cycles with maximum temperature above 600 °C is widely discussed in literature (Turchi et al., 2013; Neises and Turchi, 2013; Dunham and Iverson, 2014). In general, steam cycle maximum temperature is limited to 550 °C for solar plant scale: 600–620 °C is the maximum temperature for large scale power plants, i.e. > 500 MW (Sanchez Fernandez et al., 2014), which is not compatible with ST plants featuring thermal storage.

The advantages can be summarized as follow:

- higher marginal improvements in thermal to power conversion efficiency can be achieved in the temperature range of 550–750 °C