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Performance improvement of dry cooled advanced concentrating solar power plants using daytime radiative cooling

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ABSTRACT

In this study, utilization of daytime radiative cooling to enhance the performance of air-cooled concentrating solar thermal power plants is investigated. Water scarcity and environmental concerns are the driving forces for solar thermal power plants to use dry cooling systems. In order to overcome the energy conversion efficiency penalties associated with using air cooled technologies various supplemental cooling techniques have been proposed. Recent advancements in manufacturing structures with selective radiative properties have made the daytime radiative cooling to the cold outer space practical. In this work, the efficiency improvement of the air-cooled advanced supercritical carbon dioxide power cycles coupled with a radiative cooler is explored.

It is shown that for the simple supercritical carbon dioxide cycle operating at hot source temperature equal 550 °C by employing 14.02 m^2/kW_e radiative cooler, it is possible to overcome the efficiency losses due to air cooling and the net output of the cycle improves by 5.0%. At hot source temperature equal 800 °C, the required radiative cooler area is 4.38 m^2/kW_e and respective performance improvement is equal 3.1%. For the recompression supercritical carbon dioxide cycle operating at hot source temperature equal 550 °C by employing 18.26 m^2/kW_e radiative cooler, it is possible to overcome the efficiency losses due to air cooling and the net output of the cycle improves by 7.5%. At hot source temperature equal 800 °C, the required radiative cooler area is 10.46 m^2/kW_e and respective performance improvement is equal 4.9%.

1. Introduction

Of all renewable power generation technologies available today, Concentrating Solar Power (CSP) stations are moving to the forefront and might become the technology of choice to supply the future electricity demands of the world. It has been estimated that CSP could satisfy 11% of global electricity demand by the year 2050 [1]. CSP plants equipped with thermal energy storage can produce dispatchable power with high capacity factors even with a cloudy sky or after sunset, which makes them suitable candidates for base load power supply [2]. Research and development programs to improve the performance of CSP plants are undergoing by numerous research entities around the world. As an example, in 2011, 'SunShot Concentrating Solar Power R&D' initiated by US Department of Energy [3] to develop more efficient and reliable technologies with lower cost than existing CSP plants.

Central Receiver Systems (CRS) are currently attracting a lot of attention amongst researchers. The high achievable operating temperature (up to 800 °C) in a CRS would result in higher thermal efficiency and makes more efficient thermal storage possible [4]. Dostal et al. [5] showed that the super-critical carbon dioxide (S-CO_2) cycle can reach higher thermal efficiency than super-heated steam cycle at temperatures above 470 °C, making it suitable for high-temperature heat sources available by CRS plants. In order to meet the targets proposed by 'SunShot', several configurations of S-CO_2 power cycle have been investigated as candidates for power cycle in advanced CRS plants by several researchers. Turchi et al. [6] showed, thermal efficiencies higher than 50% for recompression and partial cooling S-CO_2 cycle configurations under dry cooled conditions. Temperature of the heat sink is an important factor for high efficiency thermal power cycles. Lower the heat rejection temperature, higher the energy conversion efficiency. Besarati and Goswami [7] investigated the performance improvement of the S-CO_2 cycles by adding an organic Rankine cycle as a bottoming cycle to the system. Neises and Turchi [8] performed a detailed study on the integration of S-SO_2 cycles with direct solar receiver and sensible heat storage into CSP plants. Furthermore, Sarkar [9] conducted the second law analysis of recompression S-CO_2 cycle for heat sources up to 750 °C. He showed the effect

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Nomenclature

$\bar{h}$	heat transfer coefficient (W/m^2 C)
$\hat{h}$	Plank's constant = $6.62606957 \times 10^{-34}$ (m^2 kg/s)
$\dot{P}$	heat flux (W/m^2)
$\dot{m}$	mass flowrate (kg/s)
c	speed of light = 3×10^8 (m/s)
DBT	Dry Bulb Temperature (°C)
E	effectiveness
k	Boltzmann's constant = $1.3806488 \times 10^{-23}$ (m^2 kg/s^2 K)
h	enthalpy (kJ/kg)
HTR	High Temperature Recuperator
I	intensity (W/m^2 μm)
LTR	Low Temperature Recuperator
P	pressure (kPa)
SR	split ratio
T	temperature (K)
WBT	Wet Bulb Temperature (°C)

Greek symbols

α	absorptivity
ε	emissivity
λ	wavelength (μm)
θ	azimuth angle (°)

Subscripts

1–8	power cycle states
amb	ambient
atm	atmosphere
bb	blackbody
b	beam solar radiation
c	convective–conductive
d	diffuse solar radiation
h	cycle maximum temperature
l	cycle minimum temperature
MC	main compressor
V	normal solar radiation
net	net
rad	radiative
RC	re-compressor
s	surface
solar	solar
T	turbine

of minimum cycle temperature on the cycle performance was more significant than the maximum cycle temperature. Hence, any improvement to the cooling system can result in substantial energy saving and performance enhancement.

Current thermal power generation stations are mostly relied on water cooling technologies due to efficiency and economic advantages. According to the studies by U.S. Department of Energy [10], more than 99% of base-load thermoelectric power plants in the U.S. are using wet cooling systems. However, environmental concerns, climate change, and higher water demand as a result of population growth have made the water consumption for power plant cooling to go under increasing scrutiny. In addition, CSP systems require abundant direct solar radiation to work efficiently. Therefore, the best locations for the CSP plants are hot and dry regions where available water for cooling is even more scarce and expensive. Finding an effective way to dissipate the low-grade heat from the power block with minimum or no water usage is an essential design challenge for advanced CSP plants.

The inherent limitation on water consumption for CSP plants is the driving force behind new plants to use dry cooling rather than wet cooling. There are three main disadvantages to the dry cooling system. First, cooling temperature for the dry cooling processes is limited by the ambient Dry Bulb Temperature (DBT) as opposed to the Wet Bulb Temperature (WBT) of evaporative wet cooling processes. DBT is typically higher than WBT depending on humidity [11]. The average yearly difference between DBT and WBT in arid regions is often as high as 10 °C. Secondly, the low thermal capacity of air and the low heat transfer rates, necessitate that a large temperature difference between the air and working fluid is maintained. For counter flow heat exchangers, approach is defined as the difference between the temperatures of inlet cooling medium and outlet cooled fluid. According to Bloemkolk and Van der Schaaf [12] a typical approach for an air cooler is 15 °C, which is about double the evaporative wet cooling approach. Third, dry cooled heat exchangers are much larger with more parasitic load requirements. Collectively, Resulting dry–cooled power stations perform at lower thermal efficiencies.

The performance analysis of dry cooled thermal power cycles has been reported in the literature for a wide range of operation conditions. Moser et al. [13] analyzed the performance of dry cooling on the CSP plants under various condenser layouts and different operation strategies. Liqreina and Qoaider [14] showed that using dry cooling reduces the water consumption of a parabolic trough CSP plant by 92% at the expense of 3.1% thermal efficiency penalty. Furthermore, in order to compensate the performance penalties associated with dry cooling, different approaches have been proposed. Hybrid dry–wet cooling, supplemental cooling systems (radiative cooling and sorption/desorption cooling) and cool storage are the most common ones. Several researchers have investigated the performance of thermal power stations using hybrid wet–dry cooling systems. Wagner and Kutscher [15] performed a dynamic simulation on a parabolic trough CSP plant using a hybrid wet–dry cooling system. They concluded that equal cooling load divided between wet and dry systems would reduce the annual water usage of the system by 52%, although net cycle efficiency will drop by 1.67%. Moreover, several design improvements on dry cooling towers are proposed to enhance the overall performance of the power cycle. Barigozzi et al. [16] simulated a CHP steam cycle with a combined wet and dry cooling system, and concluded that in order to find the optimum cooler load distribution a comprehensive analysis of the plant and ambient conditions should be performed. Rezaei et al. [17] studied the parallel and series arrangements for hybrid cooling systems. Sadafi et al. [18] investigated the water spray assisted dry cooling towers as an option to reduce the inlet air temperature, resulting more compact tower size, as well as improved cooling performance. Goodarzi and Keimanesh [19] developed radiator type windbreakers for natural draft cooling towers to improve the performance under crosswind condition. Detailed analysis and modeling of hybrid cooling tower solar chimney systems as another potential enhancement method are presented by Zou et al. [20,21]. Ghorbani et al. [22] performed a numerical design improvement analysis on a 250 MW thermal power plant using a hybrid cooling tower solar chimney system, and claimed approximately 0.5% increase in thermal efficiency of the plant. Despite the vast amount of research going on dry cooling technology improvement, none of the proposed approaches is entirely successful making up the efficiency losses due to the elimination of wet cooling.

Recently tailored thermal radiative structures have found many applications in energy systems such as local heating [23],