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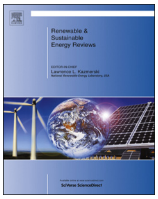

High-efficiency thermodynamic power cycles for concentrated solar power systems

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ABSTRACT

This paper provides a review of high-efficiency thermodynamic cycles and their applicability to concentrating solar power systems, primarily focusing on high-efficiency single and combined cycles. Novel approaches to power generation proposed in the literature are also highlighted. The review is followed by analyses of promising candidates, including regenerated He-Brayton, regenerated CO_2-Brayton, CO_2 recompression Brayton, steam Rankine, and CO_2–ORC combined cycle. Steam Rankine is shown to offer higher thermal efficiencies at temperatures up to about 600 °C but requires a change in materials for components above this temperature. Above this temperature, CO_2 recompression Brayton cycles are shown to have very high thermal efficiency, potentially even exceeding 60% at 30 MPa maximum pressure and above 1000 °C maximum temperature with wet cooling. An estimate of a combined receiver and power cycle operating temperature is provided for the cycles considered and compared to the traditional approach of optimization based on the Carnot efficiency. It is shown that the traditional approach to optimizing the receiver and turbine inlet temperatures based on Carnot is generally not sufficient, leading to an optimum temperature shift of more than 100 °C from the Carnot case under various conditions.

Contents

1. Introduction

Among renewable energy approaches, concentrating solar power (CSP) holds significant promise for adoption as a utility-scale

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Nomenclature

C	solar concentration ratio
h	enthalpy, kJ/kg
$h_{\mathrm{convection}}$	convection heat transfer coefficient, $\mathrm{W/m^2\,K}$
HEX	heat exchanger
I_{DNI}	nominal direct solar flux, $\mathrm{W/m^2}$
$\dot{m}$	mass flow rate, kg/s
p	pressure, MPa
$\dot{Q}$	heat rate, W
T	temperature, °C
$\dot{W}$	power, W

Greek

$\alpha_{\mathrm{receiver}}$	radiative absorptivity
ΔT_{rel}	temperature shift in peak system efficiency relative to Carnot, °C
$\varepsilon_{\mathrm{receiver}}$	radiative emissivity
$\varepsilon_{\mathrm{regen}}$	regenerator effectiveness
η	efficiency
σ	Stefan–Boltzmann constant, $5.670 \times 10^{-8}\ \mathrm{W/m^2K^4}$

Subscripts

(T, p)	at temperature T and pressure p
ambient	at ambient conditions
bottom	related to the bottoming cycle of a combined configuration
Carnot	predicted by Carnot
combined	related to the entire combined cycle
compressor	related to the gas compressor
field	related to the heliostat field
HP	high-pressure
HT	high-temperature
in	inlet quantity
loss	drop
LP	low-pressure
LT	low-temperature
max	maximum
min	minimum
net	out minus in
opt	optimum
pump	related to the liquid pump
R	ratio
receiver	related to the solar receiver
shaft	related to the turbine-compressor shaft
stage	related to one stage, e.g. for intercooled compression
system	related to the heat engine and solar receiver
th	thermal
top	related to the topping cycle of a combined configuration
turbine	related to the heat engine turbine.

solution in an environment of increasing energy demand, limited fossil fuel resources, national incentives for renewable energy deployment, and growing concerns over the environmental implications of the continued use of traditional fuel sources like coal, gas, and nuclear fission material. CSP technology shares the clean energy portfolio primarily with wind turbines, hydroelectric generators, and solar photovoltaics. Each technology has specific advantages and may be particularly well-suited to one climate or application over another, such as using photovoltaics in dry sunny areas or hydro power near a natural moving water source. However, it is common for renewable energy sources to be intermittent, which limits their penetration into utility markets as well as their reliability for on-demand operation. CSP distinguishes itself by being dispatchable through the use of cost-effective thermal energy storage, exhibits versatility in its output capability (heat, mechanical work, or electric power), and enables integration with existing turbomachinery hardware.

While the benefit of an abundant renewable energy source through a solar-driven power cycle is clear, there exists the unavoidable complication that direct solar radiation is only available during the day, and even then is often interrupted by weather transients. Electric power loads are not confined to daylight hours; thus, the instantaneous supply from an intermittent source may not always meet the electricity demand. Thermal storage facilitates a power production shift from available daytime hours to accommodate diurnal cycling and weather transients. CSP with thermal energy storage is viewed as an enabling technology allowing greater market penetration for all renewable energy technologies [1–3]. Thermal storage technologies have been developed to allow for a range of storage times, from short transient buffers to longer-term nighttime storage [4], with well-designed CSP plants demonstrating full 24-hour operation [5]. Historically, the development of CSP technology has required a balance between capital cost, performance, and suitability for a particular application. While parabolic trough technologies are the most mature, the relative capital cost of thermal storage in power tower construction has been estimated to be about half that for parabolic trough construction (6% vs. 12%) [6]. Additionally, power tower systems are capable of achieving higher temperatures and efficiencies due to increased concentration ratios. As thermal storage is being identified as a significant differentiator between CSP and other renewable technologies, high-efficiency tower systems are gaining favor over the more mature trough technology, which is limited to lower solar fluxes and temperatures. Use of molten salts as a sensible storage medium is the standard against which current storage options are compared. However, many molten salts solidify at temperatures above ambient, causing blockage and potential damage to the piping and heat exchangers. An active area of CSP research involves fluid materials that can accommodate a broad range of temperatures necessary for CSP plant receivers [7].

Despite the unique benefits of thermal storage, CSP has been viewed to be a relatively costly renewable energy option. Techno-economic analyses have shown a significant potential for cost reduction through efficiency improvement of the power block [8–10]. Due to the widespread use of turbomachinery and heat engine technology, CSP is somewhat unique in the renewable energy portfolio in that it stands to benefit from economies of scale and technological advances in the larger coal, natural gas, and nuclear industries. While modern subcritical steam cycles (the most common thermodynamic power cycle to date for CSP) may be limited to thermal efficiencies up to approximately 42% [9], supercritical steam cycles have been developed with thermal efficiencies exceeding 47% [11]. Combined cycles, which use the rejected heat from a high-temperature cycle to drive a lower-temperature cycle to supplement the power output, typically offer higher thermal efficiencies (potentially exceeding 60%) and have been used in traditional power cycles for decades [12]. Such high-performance cycles have been shown or considered to be adaptable to CSP systems [13–15], and represent an important step in reducing the levelized cost of electricity and promoting CSP technology as a true competitor to traditional methods for