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A pressurized air receiver for solar-driven gas turbines

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Abstract

A pressurized air-based solar receiver is considered for power generation via gas turbines using concentrated solar energy. The modular solar receiver is designed for heating compressed air to the entrance conditions of a gas turbine in the pressure range 4 – 30 bar and temperature range 800 – 1200 °C. The development work involved the design, fabrication, testing, and modelling of a 3 $\mathrm{kW_{th}}$ and a 35 $\mathrm{kW_{th}}$ solar receiver prototypes. System integration of an array of modular solar receivers with fossil-fuel hybridization was analysed.

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Keywords: Solar air receiver; cavity; silicon carbide; RPC; windowless

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1. Introduction

Concentrated solar power (CSP) plants can be integrated into conventional fossil-fuel-based power plants for hybrid operation to secure round-the-clock (24/7) dispatchability [1]. For example, in integrated combined cycles using parabolic trough technology, solar thermal energy is introduced to the bottom steam-based Rankine cycle at below 600 °C [2]. Solar tower technology can achieve solar concentration ratios exceeding 1000 suns, and therefore, supply solar process heat at higher temperatures. This offers significant improvement in terms of solar-to-electricity efficiency by supplying concentrated solar thermal energy directly to the topping air-based Brayton cycle at above 800 °C, while the hot gases exiting the gas turbine supply the heat to the bottoming steam-based Rankine cycle [3,

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4]. The key component of such a solar-driven combined cycle (SCC) is the solar receiver, where concentrated solar radiation is absorbed and transferred to the pressurized working fluid, usually air. The solar receiver requirements are defined by the inlet conditions of the gas turbine, i.e. temperatures in the range 800 – 1200 °C and pressures in the range 4 – 30 bar.

Some previous designs of solar receivers for SCC were based on windowed concepts, which use directly-irradiated volumetric absorbers made of ceramic fins or foams [5-9]. Prototypes have reached outlet temperatures up to 1200 °C at operating pressures up to 20 bar, with peak thermal efficiencies of 70%. The direct irradiation provided an efficient means of heat transfer. However, windows are critical and troublesome components since they must be relatively thin for minimum radiation attenuation, yet strong and durable at high temperatures and pressures. As quartz windows have an upper limiting operational temperature of about 800 °C, they require active cooling, which further complicates the design while increasing fabrication costs [10, 11]. Furthermore, windows exposed to high-flux irradiation should be kept clean and clear from contamination by condensables or dust deposits at all times. These complications are further augmented in scaled-up designs.

Simpler solar receivers use opaque heat exchangers [12, 13]. Such indirectly-irradiated concepts eliminate the need of a window at the expense of having a less efficient heat transfer by conduction through the absorber walls and limited outlet air temperatures. Thus, the disadvantages are linked to the limitations imposed by the materials of construction of the metallic/ceramic absorber such as the maximum operating temperature, thermal conductivity, resistance to thermal shock, and inertness to oxidation. In previous publications [14-16] we reported on the development and experimental testing of an air-based pressurized solar receiver for power generation via solar-driven gas turbines. In this paper, we briefly review the engineering development and present a conceptual design of a large-scale hybrid system.

Nomenclature

$h_{f,in}$	fluid enthalpy at receiver inlet conditions	(kJ/kg)
$h_{f,out}$	fluid enthalpy at receiver outlet conditions	(kJ/kg)
$\dot{m}_f$	fluid mass flow	(kg/s)
Q_{inc}	concentrated solar flux incident on receiver aperture	(kW)
$T_{f,out}$	fluid temperature at receiver outlet	(°C)
$\eta_{th,rec}$	thermal receiver efficiency	(-)

Acronyms

CPC	compound parabolic concentrator
CSP	concentrated solar power
RPC	reticulated porous ceramic
SCC	solar-driven combined cycle

2. The solar receiver design

The proposed design is depicted in Fig. 1. It consists of an annular reticulated porous ceramic (RPC) foam, made of silicon carbide (SiC), bounded by two domed concentric cylinders. The inner cylinder is also made of SiC and has an aperture for the access of concentrated solar radiation. A 3D compound parabolic concentrator (CPC) is incorporated at the aperture to boost the solar concentration ratio and reduce the aperture size and consequently the re-radiation losses. Absorbed radiant heat is efficiently transferred by conduction, radiation, and convection to the pressurized air flowing across the RPC. The outer cylinder is made of non-porous insulating material and is surrounded by a sealed metallic shell to contain the inner pressure. To characterize the receiver performance, its thermal efficiency is defined as follows:

$$\eta_{th,rec} = \frac{\dot{m}_f (h_{f,out} - h_{f,in})}{Q_{inc}}$$

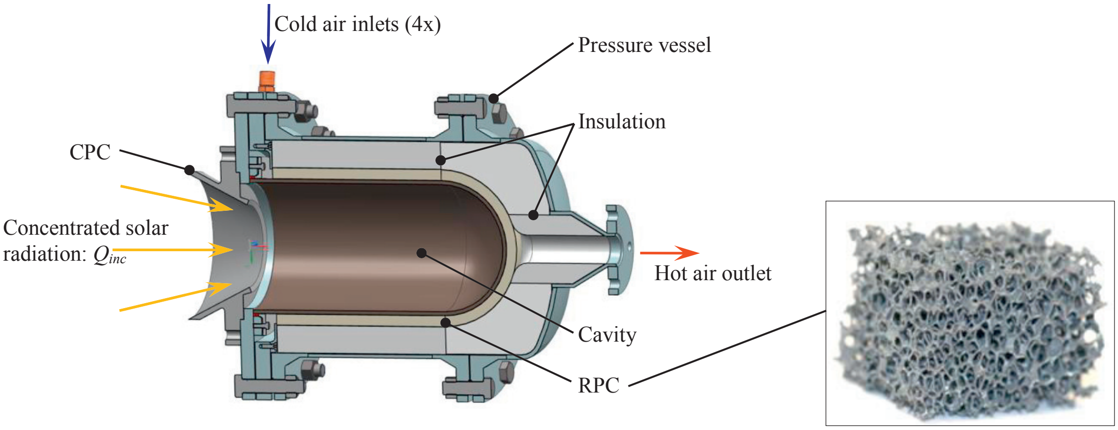

Fig. 1. Section of the solar receiver configuration consisting of an inner cylindrical cavity and a concentric annular RPC foam, both made of silicon carbide, surrounded by insulation in a sealed pressurized vessel. *Inset*: the SiC RPC foam; size: 30 x 35 x 43 mm.

Heat transfer and fluid flow analysis — The 2D steady-state mass-, momentum- and energy-conservation equations coupling radiation-conduction-convection heat transfer were formulated and solved by the finite volume technique and by applying the Rosseland diffusion, P1, and Monte Carlo radiation methods [14]. Key results include the temperature distribution and the thermal efficiency as a function of the geometrical and operational parameters. For a solar concentration ratio of 3000 suns, the outlet air temperature reaches 1000 °C at 10 bar, yielding a thermal efficiency of 78%. In general, the dominating loss mechanism is re-radiation through the cavity's aperture, which to some extent can be reduced by incorporating a CPC. With increasing air mass flow rates across the RPC, a beneficial cooling effect at the cavity entrance is obtained, further minimizing re-radiation losses. For solar concentration ratios above 3800 suns, conduction through the SiC cavity becomes the limiting heat transfer mode. Minimization of the cavity wall thickness will have to be performed in accordance with its mechanical stability to withstand the operating pressures.

3. Experimental

A solar receiver prototype for an input solar radiative power of 3 kW_{th} was fabricated and experimentally tested at the Paul Scherrer Institute's High-Flux Solar Simulator with average solar radiative fluxes in the range 1870 – 4360 kW/m^2 [15]. Experimentation was carried out with air and helium as working fluids, heated from ambient temperature up to 1062 °C at an absolute operating pressure of 5 bar. Peak thermal efficiencies obtained were 77% for air at $T_{f,out}$ = 553 °C and 78% for helium at $T_{f,out}$ = 619 °C. For an optimized design, thermal efficiencies of 90% at air outlet temperatures of 1000 °C are predicted. Fluid outlet temperatures exceeding 1327 °C are possible, but maximum temperatures are limited by conduction heat transfer rates through the cavity walls and by limitations imposed by the materials of construction. Cavity and RPC thickness have been identified to be important geometrical dimensions influencing the efficiency.

A set of SiC cavity-receivers attached to a CPC were tested at the solar tower of the Weizmann Institute of Science at stagnation conditions for 35 kW_{th} solar radiative power input under mean solar concentration ratios of 2112 kW/m^2 and nominal temperatures up to 1322 °C [16]. In the scope of these on-sun tests, no air-circuit was incorporated and no RPC was installed. The temperature measurement of the outer cavity surface was performed by means of infrared thermography at ambient pressure. 85 – 89% of the incident solar radiation was conducted across the cavity walls and available as useful power, while re-radiation was the dominant source of heat loss. Table 1 summarizes the key values obtained.

Table 1. Summary of results [14-16]

Project stage	Peak efficiency $\eta_{th,rec}$	Corresponding $T_{f,out}$ (°C)	Peak cavity temperature (°C)
3 kW prototype (air)	0.77	553	-
3 kW prototype (helium)	0.78	619	-
35 kW small cavity (Ø188mm)	$0.85^{\dagger}$	-	1322
35 kW large cavity (Ø234mm)	$0.89^{\dagger}$	-	1154

† modeled values

4. Power cycle integration

A preliminary conceptual design for a 50 MW$_{el}$ hybrid solar power plant was analyzed using a cluster of modular solar receivers with hexagonal CPCs mounted in a downward-facing spherical cone configuration on top of a 200 m solar tower. The multiple-receiver scheme, also known as fly-eye configuration, is shown in Fig. 2 (a). The layout of the solar combined-cycle power plant system, with hybridization and thermal storage, is shown schematically in Fig. 2 (b) [17].

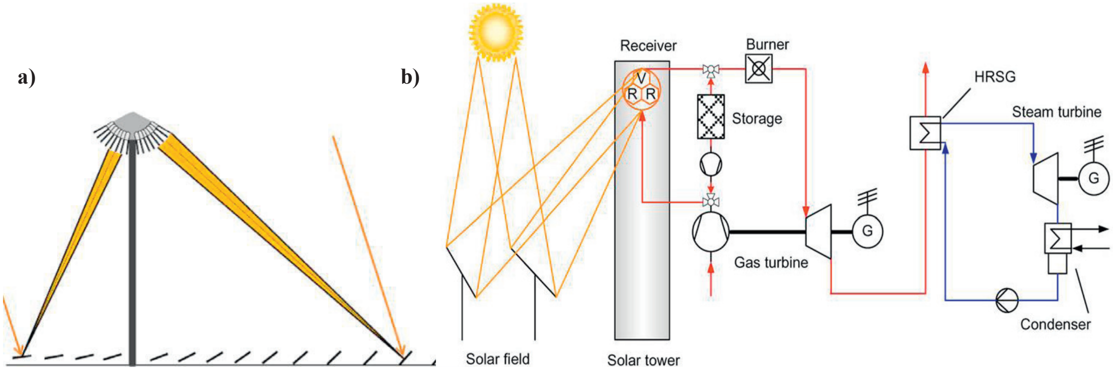

Fig. 2. (a) Illustration of a 50 MW$_{el}$ commercial solar power tower plant, using an array of multiple modular solar receivers with CPC secondary optics of hexagonal entry, aligned in a downward-facing spherical cone configuration and exposed to concentrated solar radiation from the heliostat field. (b) Schematic of a conceptual solar combined cycle power plant system, with hybridization and thermal storage. Figure extracted from [17].

The integration of an air receiver into a gas turbine cycle requires a trade-off analysis. The power cycle efficiency increases with higher turbine inlet temperature, however the efficiency of a solar receiver decreases at a higher average operating temperature due to re-radiation losses. The issues associated with operational temperature ranges are shown in Fig. 3. Up until a solar receiver temperature of 700°C, the receiver based cycle would not always be competitive against a direct steam central receiver, even if it were to operate at a somewhat higher temperature due to the higher radiative efficiency of steam receivers for a given mass flow rate. The main advantage of the air receiver is at temperatures above 700°C where the higher achievable efficiency provides a competitive advantage. The downside is that the solar heat is produced on a tower receiver and this high-temperature air needs to be contained and transported to the power generation unit on the ground. Above 700°C, the piping cannot be made of standard steel; nickel-based alloys need to be used. This significantly increases the cost of construction thereby driving up cost of electricity. Some other integration methods are being investigated due to which this cost increase would be prevented, e.g. by extracting energy near the receiver or using advanced cooling options.

We consider a hybridized gas turbine where the solar heat is being directly integrated into a combustion chamber for firing to $T > 1600$°C, which are normally in use with cooled gas turbines. A transient high-temperature injection into the combustion chamber would pose many problems associated with pulsations and NO_x emissions. Another important aspect of cycle integration is the pressure level. A high compressor pressure ratio is typically desired for high efficiency cycles; however, the associated pressure losses due to passage through the RPC and the higher inlet temperature due to the pressurization (which increases radiative losses) could negate this efficiency rise.

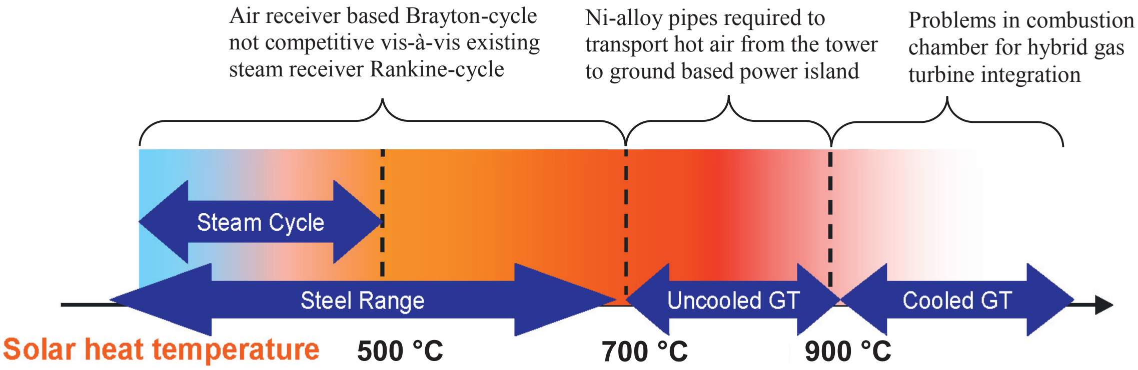

Fig. 3. Possible temperature ranges and issues associated for receiver integration into a solar-based Brayton cycle. The receiver exit temperature should provide high solar-to-electricity efficiency for the integrated cycle but not increase the cost to ensure a low levelized cost of electricity.

5. Outlook

A 35 kW_{th} full receiver system as depicted in Fig. 1 is currently subject to on-sun testing. RPC containing 10 and 20 pores per inch will be investigated at absolute pressures of 4 – 6 bar. Effects on efficiency, pressure drop and exit temperature will be experimentally investigated. The set goal is to reach thermal efficiencies above 80% in the range of $T_{f,out} = 700 – 900$ °C.

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