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# Analytical assessment of a novel hybrid solar tubular receiver and combustor

Jin Han Lim *, Graham J. Nathan, Eric Hu, Bassam B. Dally

*Centre for Energy Technology, School of Mechanical Engineering, The University of Adelaide, SA 5005, Australia*

## HIGHLIGHTS

- We present a novel hybrid between a solar cavity receiver and a combustor.
- The economic benefit of this integration is confirmed.
- The combustor can achieve the same efficiency as a conventional boiler.

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## ABSTRACT

This paper presents a novel hybrid between a tubular solar receiver and a combustor, called the Hybrid Solar Receiver Combustor (HSRC), and reports on the development and application of an analytical model to describe its performance. The analytical model accounts for the variability of the solar resource with a pseudo steady state balance of the mass and energy flow, which calculates the heat transfer throughout the device. A systematic investigation of the influence of variation in all controlling parameters on performance and weight is undertaken. The results provide new understanding of the performance of the device relative to the solar-only and combustion-only counterparts, and further justification for its ongoing development.



## 1. Introduction

The growth of the renewable energy sector has continued world-wide, driven by policies that seek to mitigate climate change, reduce air pollution, and access the growing market in this field, together with recognition of the finite reserves of fossil fuels. Among all renewable energy sources, solar energy is receiving particular attention because it is both clean and abundant [1]. Concentrating solar thermal, CSP, energy, currently has a lower penetration than solar photovoltaic, PV, but is undergoing rapid recent growth in the number and size of power plants being built worldwide [2]. However, in common with wind and solar PV, a key barrier to the ongoing growth in the penetration of CSP is the challenge associated with managing the intermittent and variable nature of the resource, which adds to the cost. One opportunity to mitigate this challenge is through the use of hybrid systems that combine fossil and renewable energy sources into one plant. The ready availability and stored chemical energy in fossil fuels especially, and biomass to a lesser extent, means that hybrid systems are expected to make an important contribution to the ongoing penetration of renewable energy [3]. In this regard, CSP is particularly well suited to hybridisation with combustion plants because the thermal nature of both types of technology makes them synergistic. However, nearly all previous reports of hybrid concepts between CSP and combustion employ standalone solar receivers and combustors, which are designed to run in a series or parallel, rather than to be directly integrated. To the best knowledge of the authors, while a few concepts of integrated systems have been proposed [4], none of these directly integrate a tubular solar receiver and a combustor. Furthermore none of them report any analysis of the effect of such integration on performance. Hence the overall aim of this assessment is to present and analyse the performance of a novel concept of hybrid between a solar receiver and a combustor that seeks to harness the energy from both sources in a single device.

The device used to harness the concentrated solar radiation is called a solar receiver. Of the wide range of solar receivers that have been developed, the vast majority heat the medium indirectly through tubes. These tubular receivers can be used to heat either the working fluid (e.g. steam), or a heat transfer fluid, HTF, which can also provide thermal storage, such as a molten salt. Tubular

* Corresponding author. Tel.: +61 425748780.
*E-mail address:* jin.lim@adelaide.edu.au (J.H. Lim).

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**Nomenclature**

| | |
|---|---|
| $(GS_1)_R$ | total exchange area between combustion gases and receiver tubes ($m^2$) |
| $\dot{V}$ | volumetric flow rate ($m^3/s$) |
| $A$ | area ($m^2$) |
| $C$ | heat capacity rate (W/K) |
| $c_p$ | specific heat capacity (J/kg K) |
| $C_s$ | cold surface fraction |
| $D_c$ | diameter of cavity (m) |
| $f$ | friction factor |
| $h$ | heat transfer coefficient ($W/m^2$ K) |
| $L_c$ | length of cavity (m) |
| $\dot{m}$ | mass flow rate (kg/s) |
| $OD$ | outer diameter (m) |
| $P$ | pressure (Pa) |
| $Pr$ | Prandtl number |
| $\dot{Q}$ | heat transfer rate (W) |
| $Re$ | Reynolds number |
| $T$ | temperature (°C) |
| $U$ | overall heat transfer coefficient ($W/m^2$ K) |
| $u$ | specific internal energy (kJ/kg) |
| $u_m$ | mean velocity (m/s) |
| $\dot{W}$ | electric power (W) |

*Greek symbols*

| | |
|---|---|
| $\varepsilon$ | emissivity |
| $\eta$ | efficiency |
| $\rho$ | density |
| $\sigma$ | Stefan–Boltzmann constant |

*Abbreviations*

| | |
|---|---|
| CPC | compound parabolic concentrator |
| CSR | concentrated solar radiation |
| CSP | concentrating solar power |
| EPGS | electricity power generating system |
| HSRC | Hybrid Solar Receiver Combustor |
| HTF | heat transfer fluid |
| HX | heat exchanger |
| HXT | heat exchanger tube |
| LCE | levelized cost of electricity |
| LHV | lower heating value |
| MSEE | molten salt electric experiment |
| PV | photovoltaic |
| RT | receiver tube |

*Subscripts*

| | |
|---|---|
| *ap* | aperture |
| *c* | cold |
| *comb* | combustion |
| *conv* | convection |
| *elec* | electric |
| *h* | hot |
| *int* | internal |
| *noz* | nozzle opening |
| *rad* | radiation |
| *s* | surface |
| *sec* | secondary |
| *th* | thermal |

receivers offer both advantages and disadvantages over direct heat-transfer receivers, such as the particle vortex reactor of Z'Graggen et al. [5]. Other devices include volumetric receivers, typically used to heat air for a Brayton cycle, although these suffer the disadvantage of requiring a window if the air is to be pressurised before heating [5]. The advantages of mechanical robustness and relative ease of sealing typically outweigh the disadvantage of a lower exergetic efficiency and a lower maximum operating temperature, which is limited by the temperature of the tubes [6,7], under current conditions. In addition, while tubular receivers are most commonly employed for Rankine cycles at present, they are also applicable to other power cycles, such as supercritical $CO_2$ and to high temperature reactors [6,8]. Hence, there is an ongoing need to continue to develop tubular receivers.

There are many drivers to hybridise solar energy with combustion technologies. The current cost of implementing a solar-only system would require an unreasonably large amount of storage to meet 100% of electricity demand at any site [9]. This is, in part, because although thermal storage is currently among the lowest cost of energy storage technology, it nevertheless remains expensive with a current price of US\$90/kW $h_{th}$, although this price is expected to decrease to US\$22/kW $h_{th}$ by 2020 [10]. In contrast, the current price of fossil fuelled electricity is presently significantly lower than that of grid-connected solar only power plants (presently ~US\$0.06/kW h in USA from natural gas compared with a projected cost of ~US\$0.14/kW h for solar power towers [11]). To address this issue, Kolb identified certain configurations of CSP hybrids, with Rankine cycle boilers that are economically beneficial [12]. Ying and Hu proved that a highly thermodynamically efficient way to utilise low-grade solar thermal heat is to pre-heat feedwater in a regenerative Rankine cycle boiler [13]. Yang et al. [14] also demonstrated that medium to low temperatures from solar energy could be used in regular coal-fired plants to generate electricity efficiently. Similarly, Zoschak and Wu found that an instantaneous fraction defined as the ratio of the solar energy input to the total input energy, of 0.27 could be achieved in a fossil fuelled steam powered plant through feedwater heating, steam superheating, air preheating and/or water evaporation [15]. However, the intermittent nature of the resource means that the average solar fraction is typically around 0.05. A range of investigations have found that the use of CSP to heat the feedwater of a Rankine cycle with a combined cycle can lower costs of $CO_2$ mitigation relative to stand-alone CSP [16,17]. However, of all these processes that employ solar tubular receivers and combustion boilers, none of them report any assessment of the potential benefits of directly integrating the solar receiver with a combustor.

CSP is particularly well suited to hybridisation with combustion technology, since both employ thermal power systems. CSP is receiving growing interest due to its potential to achieve energy storage at a relatively low cost and high efficiency [18]. Solar Power Towers are particularly well suited because their high concentration ratio allows them to achieve higher temperatures than parabolic troughs [9], while their larger scale compared to dishes leads to lower surface-area to volume ratio, and hence lower heat losses. Towers are also considered to have greater long-term potential owing to their higher efficiency than troughs [9] and greater potential to achieve economy of scale [18]. Hence, it is highly desirable to develop hybrids with the tower system.

Nathan et al. [19] first proposed the concept of directly integrating the functions of both a solar-receiver and a combustor into a Solar Power Tower system, or on the ground surrounded by a heliostat field with a beam-down configuration. The integration of a solar cavity receiver and a combustor is known to yield the following benefits [19]: