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Experimental demonstration of the hybrid solar receiver combustor

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HIGHLIGHTS

- First-of-a-kind demonstration of a direct hybrid between a solar cavity receiver and a combustor.
- Effects of concentrated solar radiation on MILD combustion regime assessed.
- Similar thermal performance in the three different modes of operation.
- Net thermal benefit derived in the mixed-mode of operation.

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ABSTRACT

We report the first-of-a-kind experimental demonstration of a direct hybrid between a solar cavity receiver and combustor, in which the functions of a solar receiver and a combustor are integrated into a single device. The device was built and tested at a nominal capacity of 20-kW_{th} for all the three modes of operation, namely solar-only, combustion-only and mixed-mode (a combination of both solar and combustion). Here, a 5-kW_{el} xenon-arc solar simulator and natural gas were used as the energy sources, while the combustion mode was operated in the Moderate or Intense Low oxygen Dilution (MILD) combustion regime to offer low NO_x emissions and good heat transfer. The thermal efficiency, heat losses, heat flux distribution within the cavity and pollutant emissions are reported for the solar-only, combustion-only and mixed-modes of operation. The thermal performance was found to be similar in all modes of operation, assuming reasonable heat recovery from the exhaust gas. Since system losses are reduced by integration (e.g. by avoiding start-up and shut-down losses), this confirms that an overall benefit can be derived from the device. Nevertheless, there is a need to manage the significantly different heat flux distribution for the three modes of operation.

1. Introduction

Hybrid energy technologies, which combine alternative energy sources at the generator, are among the emerging technology options being developed to lower the cost of increasing the penetration of intermittent renewable energy generation into energy systems [1–4]. Hybrids offer firm supply, which is an important component of a secure energy network, and can also offer a high solar share when combined with energy storage [5–8]. Hybrids between concentrating solar thermal and combustion technologies offer potential to capitalise on the low cost of thermal energy storage, which is driving the development of Concentrating Solar Thermal energy, CST [9], and the benefits of integration with combustion that arise because of the complementary nature of these two sources of high-temperature thermal energy [3]. Furthermore, while the fuels that drive present combustion technologies are mostly fossil in origin, there are growing developments to transform fuel supply chains through the use of alternative fuels such as hydrogen and ammonia [10,11]. These hybrid systems offer the potential to lower the costs of renewable energy by reducing total infrastructure and by thermodynamic synergies [12,13], and by reducing the need for, or cost of thermal energy storage [14]. However, all of the hybrid energy thermal energy systems employed commercially to date utilise a solar receiver designed solely to harvest the solar energy and a combustor designed solely to harvest the energy from the fuel. This leads to inefficiency because the two heat exchangers are operated intermittently, which requires the combustor to be started before it is needed to overcome the heat losses from intermittent operation. These losses can potentially be avoided by "direct hybrids", which harness the solar and combustion processes within a single device [3]. However, while the potential benefits of these direct hybrids have now been demonstrated by analysis [3], they are yet to be confirmed by a demonstration. Hence the aim of the present investigation is to confirm the benefit of integration by direct measurement of the performance of a Hybrid Solar Receiver-Combustor (HSRC).

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Nomenclature

c_p	specific heat capacity, (kJ/kg K)
d	diameter, (m)
D	receiver-combustor diameter, (m)
L	receiver-combustor length, (m)
P	power (kW)
$\dot{Q}$	heat transfer rate, (kW)
Q	heat flux, (kW/m^2)
r	radius, (m)
S	distance between outer surface coil and wall cavity, (m)
S_{HX}	distance between each section of HX, (m)
T_c	nominal cavity temperature, (°C)
T_{HTF}	heat transfer fluid outlet temperature, (°C)
T_{shell}	outer shell temperature, (°C)

Greek symbols

α	jet inclination angle, (°)
β	jet azimuthal angle, (°)
ϵ_{eff}	effective emittance of the cavity
ε_{HX}	effectiveness of the heat exchanger
η	efficiency
ϕ	equivalence ratio
σ	Stefan-Boltzmann constant

Subscripts

abs	absorption
air	combustion air stream
ap	aperture
c	cavity
coil	HTF coil
cond	conduction
conv	convection
eff	effective
ex	exhaust
fuel	fuel air stream
i	internal
in	inlet
loss	heat losses
out	outlet port
rad	radiation
th	thermal

Abbreviations

CSR	concentrated solar radiation
CSP	concentrated solar power
CST	concentrated solar thermal
HSRC	heat solar receiver combustor
HTF	heat transfer fluid
HX	heat exchanger
MILD	Moderate or Intense Low oxygen Dilution

Interest in solar cavity receivers is driven by their lower radiation heat losses relative to other receivers [15], which become increasingly important with the drive to develop solar thermal systems to operate at higher temperatures [16,17]. Solar cavity receivers are also well suited to be adapted to accommodate combustion, resulting in the development of several proposed configurations [18–20]. Of these, the Hybrid Solar Receiver-Combustor, HSRC [21,22], has received the most attention. This device is configured to allow operation in three modes: solar-only (when the intensity of concentrated solar radiation is above a useful threshold), combustion-only (in the absence of sufficient direct or stored solar energy) and the mixed-mode (a combination of both solar and combustion, to manage short and/or long-term variability of the solar source). A schematic diagram of one potential arrangement of the device [22] for real applications is presented in Fig. 1. It features an annular burner configuration to allow solar radiation into the cavity. Tubes are employed here to transfer the heat from the concentrated solar radiation (CSR) and/or the combustion to the heat transfer fluid. A shutter mounted at the aperture plane can be closed during the combustion-only mode of operation to mitigate heat losses [22]. Compared with commercially available hybrid solar-combustion systems [18,22–24], which harvest the thermal energy from combustion and solar sources in different devices and then combine them subsequently, the HSRC offers advantages of reduced start-up/shut-down losses (avoid the need to start-up the combustor), and surface area for heat losses [7,8,21], shared infrastructure (one system instead of two, hence reducing capital costs), and lower pollutant emissions (associated with the need to start the back-up combustor before its heat is required). Other potential advantages include increased harvesting of low solar energy flux [22] and flexibility to different applications, including combined heat and power generation and fuels production. Recent

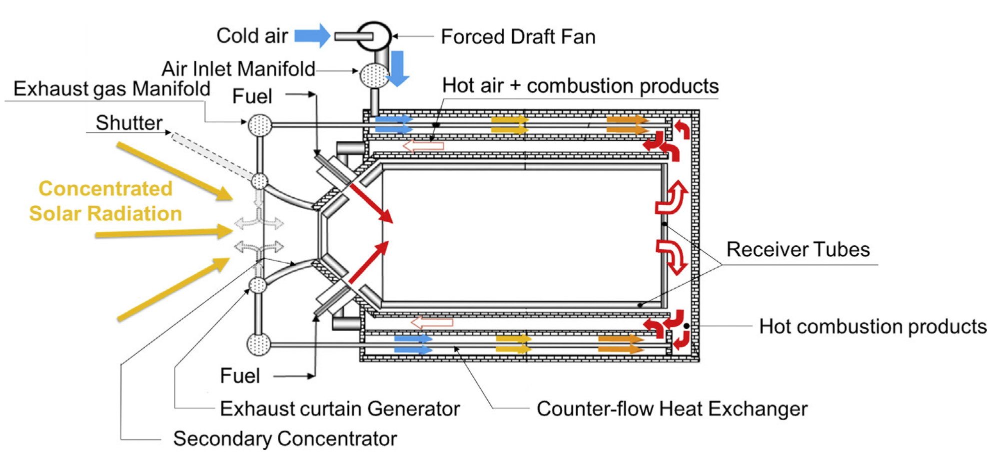

Fig. 1. Schematic diagram of a HSRC configured to operate with the MILD combustion regime. The co-annular heat exchanger enables both the preheating of the combustion air and the recirculation of flue gases. The shutter allows heat losses to be mitigated during the combustion-only mode of operation.