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Performance characteristics of a Hybrid Solar Receiver Combustor fed with Hydrogen and operating in the MILD combustion regime

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Abstract

This study describes the performance characteristics of a Hybrid Solar Receiver Combustor operated in the Moderate or Intense Low oxygen Dilution (MILD) combustion regime, in which the functions of a solar receiver and a combustor are integrated into a single device. The device was tested at a nominal capacity of 12-kWth for both the combustion-only (MILD) and mixed-mode (a combination of both solar and combustion simultaneously), using hydrogen (H_2) as fuel. A 5-kWel xenon-arc lamp was used to simulate solar radiation into the device. The influence of the mode of operation on the thermal efficiency, heat losses, heat flux distribution within the cavity and pollutant emissions are reported for a range of values of the heat extraction. It was found that MILD combustion can be successfully stabilised within the HSRC over a wide range of operating conditions, and in the mixed-mode of operation, providing ultra-low NOx and uniform temperature/heat flux. The thermal performance was found to be similar for both the combustion-only (MILD) and mixed modes of operation, despite the different nature of the two energy sources, confirming that an overall benefit can be derived from the device. Overall, this study highlights that, if renewable H_2 (which can be produced by different renewable energy sources, including solar, wind or biomass) is used as fuel, the device can efficiently operate in all the modes of operation employing 100% renewable energy.

Introduction

"Direct hybrid" systems, which harness the solar and combustion processes within a single device, are receiving growing attention due to their potential to overcome the challenges associated with the intermittent nature of concentrated solar radiation [1]. Such hybrid systems offer the potential to lower the costs of renewable energy while providing a firm and dispatchable source of heat/power by reducing total infrastructure and by thermodynamic synergies [2], and by reducing the need for, or cost of thermal energy storage [3].

Of all "direct hybrids" proposed to date, the HSRC [4-6] has received the most attention. Its design allows the system to operate in three modes: solar-only (when solar radiation is abundant), combustion-only (in the absence of 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). In one particular arrangement, the HSRC has also been designed to operate the combustion mode in the Moderate or Intense Low oxygen Dilution (MILD) regime [8], to potentially achieve enhanced heat transfer rates and lower NO_x emissions than conventional combustion processes MILD.

Despite its many potential benefits [1,5-7], the HSRC has the disadvantage of a compromised receiver-combustor design to extract the heat efficiently from both a radiation source (solar) and a combined radiation/convection source (combustion). Also, this integration introduces other combustion-related challenges, namely the need to assess the influences of CSR and direct exchange of heat/mass between the combustion process and the ambient through the aperture on the performance of the combustion process. However, while the potential benefits have been demonstrated by techno-economics analyses and recently by experimental evidence [5-9], only limited measurements of the performance of direct hybrids are presently available, with no data for systems fed with alternative, renewable fuels (e.g. hydrogen), so that a systematic investigation is needed to fully confirm these potential benefits and assess the influence of fuel type on performance. This is critical, as the use of "direct hybrids" with renewable fuels offers the additional potential for carbon-negative energy with relatively low cost (while also increasing the total amount of renewable in the system).

Therefore, the present paper aims to meet the aforementioned needs by providing direct measurement of the performance of a Hybrid Solar Receiver Combustor (HSRC) fed with hydrogen (which can be produced renewably) and operated in the MILD regime.

Methodology

In this study, a lab-scale HSRC is used, as presented in Figure 1. All the details of the device have been described in a previous work [8], so that only its key features are presented here. The experimental rig features an insulated cavity with an aperture (d_{ap} = 60 mm) to let the CSR into it. The internal length (L_i) and diameter (D_i) are 700-mm and 300-mm, respectively. The inner surface is a coiled heat exchanger, HX, carrying the heat transfer fluid, HTF (air), and consisting of four contiguous sections. A layer of alumina (50-mm thick), which surrounds the HX, and a layer of ceramic material (100-mm thick) are used to mitigate losses. The outer shell (3-mm thick) is made from 316L stainless steel.

N-type thermocouples were used to monitor the inlet and outlet HTF temperatures, and the surface temperature of the inner (alumina) layer. The annular burner configuration consists of six jets with an inclination angle, supplying air (d_{air} = 4 mm) and fuel (d_{fuel} = 2 mm) for MILD and mixed operations. The cavity also features a conical outlet (made in stoneware clay) with an outlet diameter (d_{out}) of 40 mm, and a swirl burner to close the aperture and preheat the cavity during combustion operations.

The flow rates of HTF, combustion air and fuel were electronically controlled (accuracy of ALICAT controller = ±0.2%). Hydrogen (LHV = 120 MJ/Kg), was used as energy source. The equivalence ratio, ϕ, and the thermal capacity, P_{in}, were fixed at 0.9 and 12 kW, respectively. For MILD operations, the cavity was preheated above 800 ºC (employing the swirl burner), prior to switch to the MILD regime by supplying air and fuel through the annular jets. A TESTO 350XL (portable) gas analyser and a R-type thermocouple were used to monitor continuously the composition and temperature of the exhaust stream.

For the mixed mode, a 5-kWel short-arc xenon lamp [7, 9] was used as the energy source while the device was operated in MILD with the aperture open (i.e. no swirl burner). The measured total simulated solar energy introduced into the receiver, $\dot{Q}_s$, was ≈0.8 kW, while the solar-to-fuel energy input ratio (*S/F*) was fixed at 6.7%. For both modes of operation, the the total HTF flow rate was varied in the range 150-1000 standard litres per minute (*slpm*).

Heat Transfer Analysis

The heat transfer analysis carried out here follows our previous studies [8,9], so that only its key details are reported here. For each mode of operation, the ratio of the heat absorbed by the coil ($\dot{Q}_{abs}$) to the total thermal input is termed 'absorption efficiency', η_{abs}, and was calculated as follows:

$$\eta_{abs} = \dot{Q}_{abs}/(\dot{Q}_f + \dot{Q}_a + \dot{Q}_s)\ , \qquad (1)$$

where $\dot{Q}_a$ and $\dot{Q}_f$ represent the thermal input of the combustion air and fuel streams, respectively. To account for the influence of the heat recovery from the exhaust on the overall performance, a 'potential thermal efficiency', η_{th}, was also defined as follows:

$$\eta_{th} = (\dot{Q}_{abs} + \dot{Q}_{HR,ex})/(\dot{Q}_f + \dot{Q}_s)\ . \qquad (2)$$

Here, $\dot{Q}_{HR,ex}$ represents the sensible heat from the exhaust, calculated by assuming 80% of heat recovery [8].

Results and Discussion

Thermal characteristics and pollutant emissions

Figure 2 presents the measured distribution of surface temperature of the alumina lining, T_c, along the length of the receiver, the heat flux distribution on the HTF coils, *Q*, and the NO_x emissions, for both the combustion-only and mixed modes of operation. It can be seen that a uniform temperature and heat flux distribution, typical of the MILD regime [7,9], features all the cases investigated. This indicates that the MILD regime can be successfully established in the cavity without air preheating, owing to an intense (internal) recirculation of hot products into the cavity. Furthermore, it can be seen that under MILD conditions, ultra-low NO_x emissions (20 ppmv) were measured for all cases.

The trends reported in Figure 2 also highlight that the key characteristics of the MILD process, i.e. low-NOx and uniform temperature and heat flux distribution, are preserved in the mixed-mode of operation. This despite the introduction of concentrated solar radiation into the cavity and the transfer of heat and mass between the ambient and the cavity through the aperture.

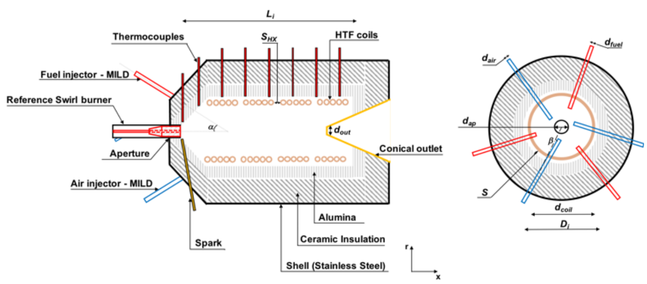

Figure 1. Schematic diagram of the HSRC unit employed in this work, showing a side-view (left) and an end-view (right).

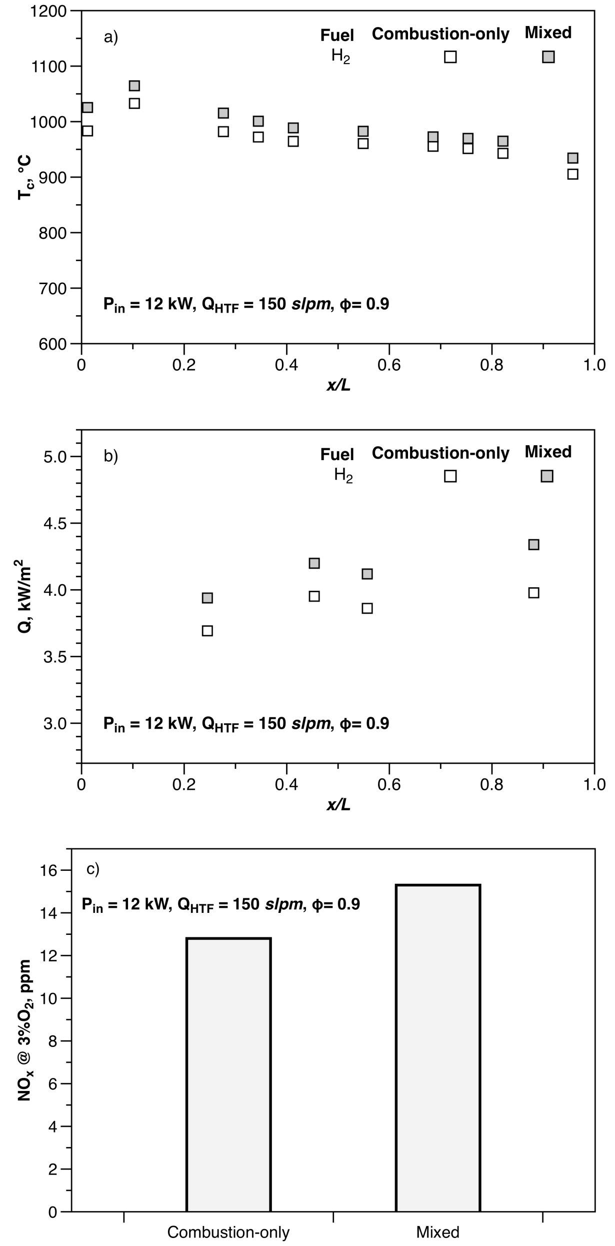

Figure 2. (a) Axial distribution of the surface temperature of the alumina lining, T_c, (b) heat flux through the HTF coils, *Q*, and (c) the NO_x emissions for the combustion-only and mixed modes of operation, and a fixed HTF flow rate.

Thermal performance analysis

Figure 3 presents the values of the absorption (η_{abs}) and potential thermal (η_{th}) efficiencies, for the combustion-only and mixed modes of operation, and by varying the HTF flow rate. A comparison of η_{th} between combustion-only and mixed operations highlights that the device can achieve similar performance (of up to ≈90%, assuming 80% of heat recovery from the exhaust) in both modes, with an outlet HTF temperature of up to 800 ºC. A similar trend was found for a NG-fuelled MILD HSRC in previous works [8, 9]. Also, it can be seen that for all the range of Q_{HTF}, the measured values of η_{abs} for the mixed mode are higher than those for combustion-only operations (of up to ≈ 15%, for a fixed value of Q_{HTF}). This indicates that, for the operating conditions and geometry considered here, a positive thermal gain (net) can be obtained in the mixed mode, notwithstanding the additional convective and re-radiation heat losses (< 10% of total losses, not shown). In particular, despite a slight decrease in η_{th} (by ≈ 2.5% in comparison with combustion-only operations) when operating the device in the mixed mode, the specific fuel consumption, *sfc* (i.e. the fuel consumption per unit of useful thermal output to the HTF), is significantly reduced (of up to ≈20%, not shown) for mixed operations relative to the combustion-only case.

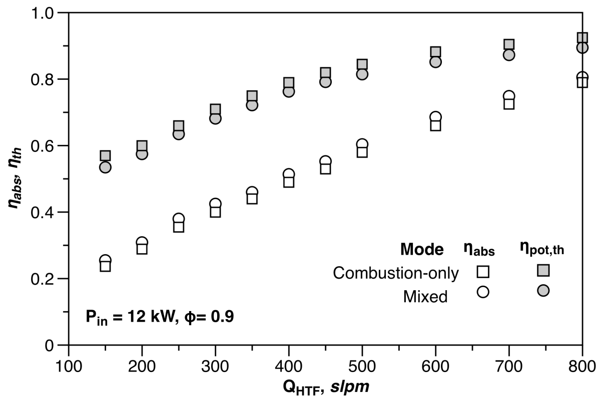

Figure 3. Values of absorption (η_{abs}) and potential thermal (η_{th}) efficiencies, for combustion-only and mixed operations, and by varying the total HTF flow rate (P_{in} = 12 kW, ϕ = 0.9).

Conclusions

The key outcomes from the experimental analysis of the performance characteristics of a laboratory-scale HSRC operated in the MILD regime and fed with hydrogen are as follows:

- Successful, stable MILD operations have been reported for both the combustion-only and mixed modes of operation. Similar thermal efficiency, heat flux and emissions can be achieved in both modes, despite the different nature of the energy sources;
- The key characteristics of MILD combustion, namely uniform temperature distribution and ultra-low NO_x emissions, were also preserved in the mixed mode of operation;
- The device can efficiently operate employing 100% renewable energy if renewable hydrogen is used as fuel, offering potential for carbon-neutral or carbon negative energy, depending on the routes and/or feedstock used to generate hydrogen.

Acknowledgments

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