Applied Thermal Engineering 109 (2016) 1023–1030

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Development of a syngas-fired catalytic combustion system for hybrid solar-thermal applications

Mayank Gupta, Santanu Pramanik, R.V. Ravikrishna *

Department of Mechanical Engineering, Indian Institute of Science, Bangalore, India

HIGHLIGHTS

- Syngas-fired combustor concept as hybrid heat source for solar thermal application.
- Experimental characterization of catalytic combustor under fuel-rich conditions.
- Stable operation, quick startup, and high turn-down ratio demonstrated.
- Reacting flow CFD simulations of single channel of catalytic monolith.

ARTICLE INFO

Article history:
Received 10 March 2016
Revised 29 April 2016
Accepted 29 April 2016
Available online 3 May 2016

Keywords:
Solar-thermal
Biomass
Hybrid
Catalytic combustion
Syngas

ABSTRACT

This paper describes the development and operation of a catalytic combustion system for use with syngas as an important component of a hybrid heating source for solar-thermal power generation. The reactor consists of a cylindrical ceramic monolith with porous alumina washcoat in which platinum is distributed as the catalyst. Two fuel-rich equivalence ratios were studied over a range of flow rates. The fuel-rich conditions permit low temperature combustion without the problem of hotspots likely to occur under fuel-lean conditions with hydrogen-containing fuels. Experimental data of temperature and species concentration at the exit of the reactor have been reported for a maximum fuel thermal input of 34 kW. The system exhibited quick start-up with a light-off time of around 60 s and a steady-state time of around 200 s as determined from the transient temperature profiles. The experimental results have also been complemented with detailed two-dimensional numerical simulations for improved understanding of the combustion characteristics in the reactor. The simulations suggest that the combustion system can be operated at a turn-down ratios far in excess of 1.67, which is the maximum value that has been investigated in the present setup. Stable operation, quick startup, and high turn-down ratio are some of the key features that enable the proposed combustion system to accommodate the transients in solar-thermal applications.

1. Introduction

Hybridization of energy sources such as solar, wind and biomass are an effective strategy to accommodate the transients in renewable power generation [1]. Such systems are commonly referred to as Hybrid Renewable Energy Systems (HRES). The idea is to leverage the output from multiple sources against the intermittency of weather conditions. This reduces the cost of energy production and increases the reliability of the power generation system. Several hybridization schemes such as photovoltaics and wind [2,3], wind and solar-thermal [4], solar-thermal and biomass [7–9], and a combination of these [5,6] have been proposed in the literature. In spite of hybridization, systems such as wind and solar usually require a fossil fuel backup for continuous operation. A promising renewable strategy for the elimination of fossil-fuel backup is hybridization with biomass. The focus of the present work is to develop a combustion system based on biomass-derived syngas for the continuous operation of solar-thermal power generation units.

Biomass is a versatile fuel due to its availability from multiple sources and several methods of utilization. One such established method for the generation of power is gasification. Gasification is a process in which the chemical energy of the solid biomass is converted into that of a gaseous fuel known as syngas or product gas. For air-blown gasification of biomass, the typical composition of syngas can be represented as 20% CO, 20% H_2, 2% CH_4, 12% CO_2 and 46% N_2 with a calorific value of around 5 MJ/m^3 [7]. When

---

* Corresponding author.
E-mail address: ravikris@mecheng.iisc.ernet.in (R.V. Ravikrishna).

http://dx.doi.org/10.1016/j.applthermaleng.2016.04.150
1359-4311/

compared to direct combustion of biomass, gasification offers the additional advantage of syngas storage and easy transportation from the point of production to the point of utilization. The capacity of a gasification unit is different for different types of gasifier and can vary from 1 MW to about 300 MW [10–12]. The efficiency of biomass to electricity conversion reported in the literature varies between 15% and 43%, with a mean value of 27% [13]. In comparison to fossil fuels such as coal, the cost of electricity from biomass is cheaper when environmental externalities such as human health and soil erosion are taken into account [14]. The highest reported CO_2 emission by a biomass electricity plant [15] is less than the lowest emitting natural gas plant by a factor of 3 and the lowest emitting coal power plant by a factor of 5 [10].

The primary considerations in the development and operation of a syngas combustion system for a solar-biomass hybrid system are the relatively lower temperature requirement, ultra-low pollutant emissions and startup time. Among these requirements, the achievement of low temperature relevant to solar-thermal technologies is particularly challenging. The maximum solar cycle temperature can be as low as 700 K for parabolic troughs to 1300 K for solar towers with central receivers [16,17]. This temperature range is below the flammability limit of syngas and can only be achieved in conventional gas-phase combustion systems by the staging of air. Another technology that is particularly suitable for such low-temperature applications is catalytic combustion. In catalytic combustion, the fuel is oxidized in the presence of catalysts that help to extend the flammability limit by lowering the activation energy [18]. Catalytic combustion systems have the potential for near-zero NO_x emission levels and can facilitate quick startup when the inlet temperature is greater than the catalyst light-off temperature.

Catalytic combustion systems can be operated both under fuel-rich and fuel-lean conditions. For syngas and other hydrogen containing fuels, fuel-rich combustion is preferred as fuel-lean combustion can give rise to hot spots that are detrimental to the structural integrity of the catalyst substrate [19,20]. The excess fuel in the exhaust of a fuel-rich combustion system can be subsequently oxidized in a second-stage combustor possibly to feed other power cycles [21–23]. Thus, the motivation for the present work is to develop a catalytic combustion system for utilizing biomass-derived syngas typically associated with very low calorific value ($\sim$5 MJ/m^3). Fuel-rich catalytic combustion of methane and coal-derived syngas for gas turbine applications has been studied by Etemad et al. [22,23]. Experimental and numerical studies on rich catalytic combustion of hydrogen over catalysts such as platinum and rhodium have been reported by various authors [24–26]. Rich catalytic combustion of methane (also known as catalytic partial oxidation) is of special interest in the production of syngas from hydrocarbons [27–29]. Catalytic combustion of H_2/CO mixtures has been studied under fuel lean [30,31] and fuel-rich conditions [32] to understand the intrinsic chemical kinetics in such systems. However, fuel-rich catalytic combustion of biomass-derived syngas, with its particularly low calorific value, has not been reported in the literature. The present study also fills this gap in the literature.

The present study reports experimental results for the development and operation of a 34-kW syngas combustion system operating under conditions relevant to solar-thermal plants. This power level has been chosen to provide a hybrid heating source for a supercritical CO_2 Brayton cycle loop currently being setup as part of the SERIIUS initiative [33]. The novelty in the current work concerns the application of catalytic combustion of biomass-derived syngas for the continuous generation of renewable power. Platinum has been chosen as the catalyst due to its superior activity with H_2 and CO. The experimental results have been complemented with detailed numerical simulations for gaining insight into the combustion process. The next few sections describe the details of the catalytic combustor, experimental setup, results from the experimental studies, numerical model, comparison of model predictions with data, followed by a summary of the findings from the present study.

2. Experimental work

2.1. Catalytic combustor

The catalytic combustion system comprising of the reactor and the flow lines is shown in Fig. 1. The diffuser is fitted with a perforated chamber containing stainless steel spheres of 3-mm diameter. This ensured a uniform velocity profile at the entrance of the monolith that varied within ±5% of the mean value. This was verified by measuring the exit velocity using a hot-wire anemometer. The perforated chamber also avoided possibility of any flashback of the flame in the premixed charge. The diffuser was followed by a flow-straightening section that consisted of a 20-mm thick cylindrical honeycomb made of Hastelloy. This was followed by the catalytic monolith, a converging section and the exhaust nozzle. The monolith was 150-mm long and 150-mm in diameter and consisted of square channels with a density of 400 cells per square inch. The substrate of the monolith was made of the ceramic material cordierite, while the inner walls of the channels were lined with a porous washcoat of alumina (Al_2O_3). Platinum was distributed in this porous washcoat. Table 1 gives the detailed specifications of the catalytic monolith.

2.2. Flow system

The air and fuel flow into the system were controlled by mass flow controllers (make: Alicat) with a range of 0–1000 SLPM with an accuracy of ±1% at the maximum flow rate. At startup, for the purpose of achieving catalyst light-off, the fuel was preheated in a 15-kW furnace-type heater with PID temperature control. The fuel was supplied from pressurized cylinders and had a volumetric composition of 20% CO, 12% CO_2, 20% H_2, 2% CH_4 and 46% N_2. A bypass line was incorporated to preheat the catalytic combustion system using air rather than fuel prior to starting the experiments in order to avoid wastage of fuel. After reaching a steady temperature, the bypass valve was closed and fuel and air were separately introduced into the mixing chamber. The preheated fuel was mixed with the air in the mixing chamber at a particular

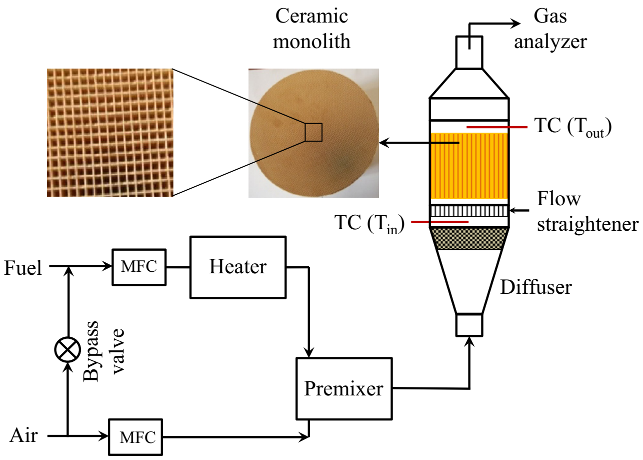

Fig. 1. Schematic diagram of the experimental setup. Thermocouples were also placed at various radial locations (at 10-mm intervals) at the outlet of the monolith. Abbreviations: MFC – mass flow controller; TC – thermocouple; T – temperature.