



An experimental investigation of stability and operation of a biogas fueled porous burner

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HIGHLIGHTS

- ▶ Thermal efficiency and pollutant emissions characterization of a porous burner.
- ▶ A 60% CH₄ and 40% CO₂ (molar) typical biogas composition was assumed.
- ▶ Burner stability mapping in terms of exhaust gas and temperature profiles.
- ▶ Exhaust gas measurements point towards stronger CO₂ physical over chemical impact.
- ▶ Low CO and NO_x emissions over a wide range of operating conditions.

ARTICLE INFO

Article history:

Received 2 March 2012

Received in revised form 18 September 2012

Accepted 24 September 2012

Available online 10 October 2012

Keywords:

Porous burner

Biogas

Low-NO_x emissions

Temperature and emission measurements

Biogas mixture stoichiometry

ABSTRACT

Porous media combustion constitutes a particularly attractive technology, allowing operation in ultra-lean combustion regimes with excellent fuel interchangeability and low levels of pollutant emissions. This work presents a comprehensive experimental characterization of a state-of-the-art porous burner fuelled with a simulated biogas mixture, in terms of thermal efficiency and pollutant emissions. The combustor is a rectangular two-layer porous burner with an Al₂O₃ flame trap and a 10 ppi (pores per inch) SiSiC foam. The burner was operated with a mixture of 60% methane and 40% carbon dioxide. An extensive stability mapping was performed in order to establish the range of operation in terms of thermal loads and mixture equivalence ratios. Gas and solid phase temperature profiles were measured using thermocouples and infrared thermography respectively, and gaseous emissions were quantified using an online gas analyser sampling system and a gas chromatographer. The results revealed wide stability with respect to thermal loads, low NO_x and CO levels, and negligible hydrocarbon emissions. The effects of CO₂ addition on burner operation and efficiency, the relative impact of thermal load on temperature and emission values with respect to equivalence ratio were investigated. The comparably strong physical effect of the CO₂ addition was discussed against its chemical impact on the processes.

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1. Introduction

Flameless [1] or mild [2] combustion is winning its place among cutting-edge, emission reduction and energy saving technologies. Numerous techniques have been employed in order to utilize inlet mixture preheating to reduce NO_x emissions [3]. Excess enthalpy combustion or heat recirculation from burned products to unburned mixture, has been proposed as a fuel flexible technology, with reduced emissions and enhanced efficiency [4], which also finds application in porous media combustion. In the case of super-adiabatic combustion in porous media, the flame is stabilized at the interface of the preheating section and the ceramic

foam with superior heat transfer properties and can be operated with a wide range of gaseous fuels [5]. Combustion in a porous medium is characterized by increased flame speeds, extended flammability limits and stability across a wide range of conditions [6] and it continuously improves its place in numerous combustion applications utilizing these advantages [7], which have started to be systematically examined over the last 20 years [8].

Porous matrix stabilized combustion within porous inert media along with the associated porous burner technology development and the materials used, have been thoroughly described in the past [9]. A number of detailed studies focused on describing numerically the phenomena inside the porous media [10–13], also parameterizing model uncertainties [14,15]. Most experimental studies, however, focused on gaseous fuels, such as methane or natural gas operation [16,17]. Nevertheless, there are references for

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vaporised liquid fuel operation in porous reactors, mainly for hydrogen [18] or synthesis gas production [19]. It is also worth mentioning that non-intrusive diagnostics have been utilised only recently [20–22] for examining the phenomena within the porous matrix of porous burners.

There are numerous studies employing intrusive methods to provide experimental data for porous burner operation and compare it with different types of burners [23]. Most studies focus on temperature, CO and NO_x concentration measurements at the burner exhaust, using methane as fuel [24,25] or liquefied petroleum gas (LPG) [26,27]. Moreover, there are studies examining the burner stability and behaviour over different thermal loads and equivalence ratios [28], also focusing on temperature and species concentration distribution, addressing also the issue of fuel inter-changeability, over a wide operational range [29].

In the case of low calorific fuels, the combustible domain shifts to a richer environment. The internal heat recirculation in a porous media is expected to maintain the capability of operating under fuel lean regimes, even in the case of low calorific fuels. However, there is scarce experimental experience concerning porous burner operation with low-calorific value fuels, such as coke oven gas (COG) [30] and gaseous mixtures emitted by landfills and pyrolytic processes [31]. The effect of CO₂ addition to methane mixtures is of particular importance since it is related to the increasing interest of using biogas mixtures in practical applications [32]. A two layer packed bed burner has been recently shown the ability to operate on biogas [33], with good results. Although the mean porosity of the upper layer of the packed bed burner is similar to the current porous medium structure, there are important design differences, such as the total length of the combustion matrix which is made of packed balls rather than an actual porous matrix.

In the present work, a rectangular two-layer porous burner with an Al₂O₃ flame trap and a 10 pores per inch (ppi) SiSiC foam was considered. The burner was operated without air confinement, over a wide range of operational conditions representative of regimes, from flashback to blow-off conditions. It was tested over a range of nominal thermal loads from 200 to 1000 kW/m² under varying lean combustion regimes, within its stability limits. The burner was operated with a methane and carbon dioxide mixture in a 60:40 molar ratio respectively as a typical biogas composition. An extensive stability mapping was performed in order to establish the range of operation in terms of thermal loads and mixture equivalence ratios. Gas phase temperature profiles were obtained using S-type thermocouples and burner surface using an infrared camera. Gaseous emissions were quantified using an online continuous gas analyser coupled with an in-house developed ceramic gas sampling system. Additional measurements were performed for investigating unburned hydrocarbon emissions (UHCs). Temperature and species concentrations at the burner exhaust are presented in this paper, with respect to low emission characteristics, operational range and are compared with pure methane operation.

2. Experimental apparatus

The burner main features and operational characteristics have been described in the past [29], hence only a short description is given here. The two dimensional, rectangular porous burner employed, consists of the mixing chamber connected to the flame trap made of alumina (Al₂O₃) and the porous matrix with a pore size of 10 ppi, which serves as the combustion zone, made of silicon infiltrated silicon carbide foam (SiSiC). The inert porous matrix and the flame trap have a height of 15 mm and 20 mm respectively, as illustrated in Fig. 1.

Species sampling was realized directly at the burner exhaust, through a non-cooled, in-house Al₂O₃ probe with an inner

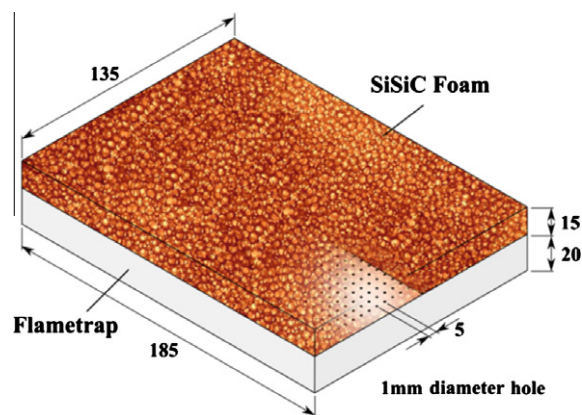


Fig. 1. The burner configuration.

diameter of 2 mm, which led the exhaust gas samples to the gas analysis system. A humidity trap was connected between the sampling system and the gas analyser. Along with the probe, a ceramic insulated S-type thermocouple was located at the same measuring position, to allow real time monitoring of the temperature. Additional solid phase temperature measurements were performed using an infrared camera (FLIR PM 595) for monitoring solid phase temperature, in order to correct the S-type thermocouple values for radiation losses. The simplified equation for correcting the thermocouple temperature values based on the semi-empirical Nusselt functions was implemented as proposed by Baehr et al. [34], as in similar studies [35]. The temperature dependence of the thermocouple emissivity coefficient was also taken into account [36]. Fuel and air flows were monitored through mass flow controllers (Bronkhorst MFCs) with total capacity of 1600 slpm for air (two separate MFCs connected in parallel) and 120 slpm for the fuel stream. For CO₂ supply a methane-calibrated MFC was used with a correction factor (approx. 1.04 according to the manufacturer). The CO₂ stream was mixed with methane at a distant position (more than 40 diameters upstream) and then introduced as the fuel stream at the burner inlet.

The utilised gas analysis system incorporated a UV spectrometer (ABB Limas11) calibrated for detecting NO and NO₂ at a range of 0–1000 ppm with 2% accuracy per volume, an IR spectrometer (ABB Uras26) calibrated for detecting CO at a range of 0–10,000 ppm and CO₂ at a range of 0–25% (vol.) with 2% accuracy per volume and, finally, an electrochemical cell detector to measure the O₂ concentration. Finally, additional measurements for detecting hydrocarbon emissions were performed for selected cases with an Agilent 7890A gas chromatographic (GC) system. The sampling was realized by two-way sampling valves which introduced the sample into the GC system. The sample was sucked through the GC system by a peristaltic pump connected at its exit. The GC system was equipped with an FID detector, analyzing C₁–C₄ alkanes and alkenes, calibrated close to the expected range to ensure a linear response. Calibration uncertainty was less than 1% for all hydrocarbons analyzed. The overall accuracy of the gas sampling measurements is estimated to be ±5%.

3. Burner stability mapping with biogas operation

The formulation of stoichiometry in a biogas mixture is not unambiguous and poses several difficulties since carbon dioxide, although contained in the fuel stream, does not contribute to the nominal thermal load. Moreover, the methane/air ratio remains the same (namely 1:2) in both, biogas and pure methane, air combustion. According to the strict definition of the equivalence ratio,

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