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Porous burners for low emission combustion: An experimental investigation

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ABSTRACT

Porous media combustion offers significant advantages against free flame burners, concerning pollutant emissions, power density, turn down ratio, combustion stability and the potential to operate in ultra-lean combustion regimes. The objective of the present work was to perform a comprehensive experimental characterization of a state-of-the-art porous burner in terms of thermal efficiency and pollutant emissions and assess its operating limits. The combustor was a rectangular two-layer porous burner with an Al_2O_3 flame trap and a 10 ppi (pores per inch) SiSiC foam. The burner was operated with methane and LPG. An extensive stability mapping was performed in order to establish its range of operation in terms of thermal loads and mixture equivalence ratios. Gas phase temperature profiles were measured using thermocouples and the solid phase temperature distribution was obtained using an IR camera. Gaseous emissions were quantified using an online gas analyser sampling system. The results revealed a homogeneous temperature distribution, low NO_x and CO emissions and wide flexibility with respect to fuels and thermal loads. The effects of fuel interchange on efficiency and emissions were also analysed. Finally, the relative impact of thermal load on temperature and emission values, with respect to equivalence ratio or fuel type, is discussed.

1. Introduction

The increasing need for more efficient, less polluting and less energy consuming combustion technologies has sparked an interest towards low-temperature, flameless combustion modes [1]. Porous burner combustion fulfils these requirements being characterized by low pollutant emissions, high power density, high turn down ratio, enhanced combustion stability and the potential to operate in ultra-lean combustion regimes [2]. Such burners are suited for numerous applications including heat exchanger systems, off gas burners, reformers and household heating appliances and can be operated with a wide range of gaseous fuels. The porous inert medium burners operate on the principle that the premixed fuel/air mixture burns within the cavities of a solid porous matrix with superior heat transfer properties, serving as a means of internal heat recirculation [3]. The incoming mixture is thus preheated leading to excess enthalpy burning, also commonly referred as super-adiabatic combustion. Combustion in a porous medium is characterized by increased flame speeds, extended flammability limits and stability across a wide range of conditions and it continuously improves its place in numerous combustion applications utilizing these advantages [4,5], such as combined burner and heat exchanger systems, off gas burners, partial oxidation reformers and household heating. These advantages have started to be systematically examined over the last 20 years [6]. 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 [7].

In particular, for the case of lean combustion, the reaction zone is not thick enough to allow resolving it by gas sampling. Thus, a number of detailed studies focused on describing numerically the phenomena inside the porous medium e.g. [8–11]. Zhou and Pereira [12] investigated the influence of different combustion models on temperature, species distribution and exhaust gas emissions. The actual processes taking place within the porous inert structure could not be investigated experimentally by means of non-intrusive optical methods, due to difficulties in achieving optical access inside the porous matrix. Only recently, non-intrusive laser diagnostic techniques where employed, using the CARS (Coherent Anti-stokes Raman Scattering) technique, for temperature and hydrogen concentration measurements along the burner axis [13,14], and the OH-pLIF (Hydroxyl-radical planar Laser Induced Fluorescence) technique for visualization of the flame structure [15].

There are numerous studies employing intrusive methods to provide experimental data for porous burner operation and

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compare it with different types of burners [16]. Most studies focus on maximum temperature and maximum CO and NO_x concentration measurements at the exhaust of the burner e.g. [17–20]. Concentration measurements have been performed by gas sampling through probes placed inside the porous matrix, for the case of slow partial oxidation reforming processes [21]. However, there are only few studies examining the burner behaviour over different thermal loads and equivalence ratios e.g. [22], but without focussing on the temperature and species concentration distribution. A parametric experimental assessment of the temperature and species distribution along the burner, addressing also the issue of fuel interchangeability, over a wide operational range has not been performed, to the authors' knowledge.

In the present work, a rectangular two-layer porous burner with an Al_2O_3 flame trap and a 10 pores per inch (ppi) SiSiC foam was considered. The burner was operated without any air confinement, over a wide range of operational conditions representative of all combustion regimes (from backflash to blow off conditions). It was tested over a range of nominal thermal loads from 200 to 1000 kW/m^2 under varying lean combustion regimes, namely of $1.2 \leq \lambda \leq 1.6$ ($0.83 \leq \varphi \leq 0.625$), within its stability limits. The burner was operated with methane and propane based typical low-calorific value fuels. 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 the solid phase temperature distribution was obtained using an IR camera. Gaseous emissions were quantified using an online gas analyser (UV and IR sensor, Paramagnetic) coupled with an in-house developed ceramic gas sampling system. Temperature and species distribution above the burner are presented in the paper, serving as a means of experimental evaluation of the porous burner homogeneous distribution with respect to low emission characteristics, operational range and fuel interchangeability.

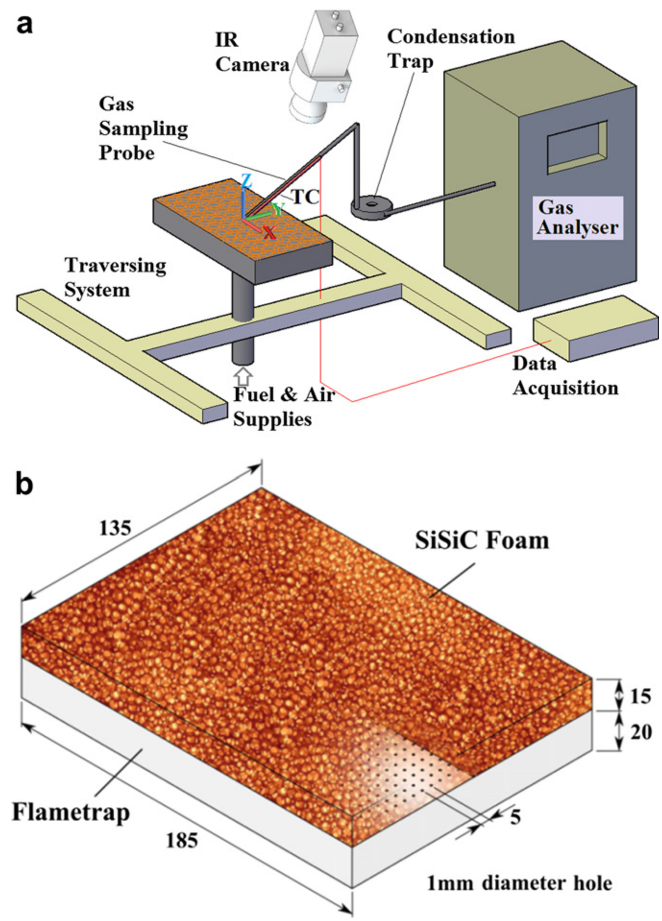

Fig. 1. a The experimental setup. b The burner configuration.

2. Experimental apparatus

The burner assembly (Fig. 1a) was placed on a traversing system that allowed measurements in the two horizontal directions above the burner. The sampling was realized at 1 mm height above the burner, through a non-cooled, in-house Al_2O_3 probe with an inner diameter of 2 mm, which led the exhaust gas samples to the gas analysis system. 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. A humidity trap was connected between the sampling system and the gas analyser. Fuel and mass flows were monitored through mass flow controllers with total capacity of 800 slpm for air and 120 slpm for the fuel stream.

The gas analyser consisted of three channels capable of detecting different species. The first channel incorporated a UV spectrometer (ABB Limas11) calibrated for detecting NO and NO_2 at a range of 0–100 ppm with 2% accuracy per volume. The second channel utilised an IR spectrometer (ABB Uras26) calibrated for detecting CO at a range of 0–100 ppm and CO_2 at a range of 0–25% (vol.) with 2% accuracy per volume. Finally, a paramagnetic detector (ABB Magnos206) was installed in the third channel to measure the O_2 concentration for re-evaluating the equivalence ratio and low air entrainment. The detectors were calibrated close to the expected operational range to ensure a linear response. The presented gas measurements are absolute and have not been corrected to reference oxygen concentration.

An IR thermo-camera (InfraTec-VarioCAM hr) was used for solid phase surface temperature measurements, with a maximum range near 2000 °C (nominal accuracy ± 10% of local temperature). The IR-data were used to correct the radiation losses from the thermocouple measurements and to depict clearly the homogeneous temperature distribution of the burner. During the IR thermographic measurements, both the burner and the camera were rotated by a slight angle less than 10° to prevent the exhaust gas stream damaging the sensor, but still maintaining that the sensor and the burner surface were perpendicular to each other.

Gaseous phase temperature measurements were obtained along the main burner axes, using S-type thermocouples, attached on a 2D traversing system. The simplified equation for correcting the thermocouple temperature values based on the semi-empirical Nusselt functions was implemented as proposed by Baehr et al. [23]. The temperature dependences of the thermocouple emissivity coefficient was taken into account, as described by Deemyad et al. [24].

2.1. The burner

The burner main features and operational characteristics have been described in the past (e.g. Ref. [3]) and hence only a short description is given here. In the present work, a two dimensional, rectangular (130 × 185 mm) porous burner is considered. Here, the long axis is referred as *x*-axis. The burner consists of the mixing chamber connected to the flame trap made of Alumina (Al_2O_3) 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. 1b. The flame trap material has lower heat conductivity than the porous matrix.