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Experimental investigation of a radiant porous burner performance with simulated natural gas, biogas and synthesis gas fuel blends

Ch. Keramiotis [a,*], M. Katoufa [a], G. Vourliotakis [a], A. Hatziapostolou [b], M.A. Founti [a]

[a] *Laboratory of Heterogeneous Mixtures & Combustion Systems, School of Mechanical Engineering, National Technical University of Athens, Zografou Campus, Greece*
[b] *Department of Energy Technology Engineering, Technological Educational Institute of Athens, Egaleo Campus, Greece*

HIGHLIGHTS

- Fuel blends resembling compositions of typical biogas, natural gas and syngas mixtures.
- Characterization of a porous burner performance for wide range of operating conditions.
- Radiation efficiency was parameterized as a function of fuel, thermal load and stoichiometry.
- CO_2 impact on CO and NO_x emissions and radiation efficiency.

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ABSTRACT

The general performance of a porous inert media burner system in terms of radiative efficiency, fuel flexibility, pollutant formation and reliability was determined experimentally. The porous burner of choice has been previously proven of being capable to operate on conventional and alternative gaseous fuels. The present study examines its operation with virtual blends of model fuels in order to assign and evaluate synergistic effects. In this regard, the present work examines mixtures of CH_4, CO, H_2 and CO_2 on a two-layer burner with a 10 ppi (pores per inch) SiSiC foam flame zone. The study focused on gaseous and solid phase temperature levels and pollutant formation trends over various nominal thermal loads in the lean combustion regime. The burner optimum operating range was identified and results revealed low NO_x levels. For a given stoichiometry, the burner is characterized by a NO_x level threshold systematically below 20 ppm, independently of the fuel, with however, distinct behaviour especially with respect to CO_2 content. The opposing effects of CO and H_2 addition on CH_4/air combustion, aside the influence of CO_2 dilution, were assessed on burner operation and radiation efficiency. The CO_2 addition increased measured CO emission levels and decreased the radiation efficiency of the burner. This may also be attributed to the lower adiabatic flame temperature and burning velocity of CO_2 enriched blends, as also acknowledged by supportive numerical calculations. The relative impact of thermal load on temperature, emissions and burner radiation efficiency with respect to equivalence ratio was also studied. It was identified that the specific burner design, delivers wide power flexibility at lean combustion regimes, providing, at the same time, low total pollutant emissions, *i.e.* less than 50 ppm and high radiation efficiency, *i.e.* up to 70% for low thermal loads and depending on the stoichiometry.

1. Introduction

Notwithstanding the increased penetration of renewable energy sources, fossil fuel availability and costs dictate the optimization of existing combustion technologies. Consequently, efficiency and reliability of modern combustors must be further improved in order to ensure the sustainable use of fossil and alternative (or even bio-) fuels with reduced environmental footprint, so as to increase diversity and security of the energy supply [1]. In this regard, new concepts which utilize excess renewable electricity for synthetic fuels development are winning their place among traditional techniques. For instance, power-to-gas conversion chains allow daily or seasonally adjusted power storage and provide CO_2 neutral fuels through existing infrastructure [2]. Such processes may involve methane, hydrogen, carbon monoxide and carbon dioxide streams. The latter fuels are also major constituents in conventional coal or biomass gasification processes.

* Corresponding author.
E-mail address: xkeram@central.ntua.gr (Ch. Keramiotis).

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In addition, waste-heat recovery is essential in terms of efficiency in industrial thermal processing, and cutting edge solutions include recuperative and regenerative burners [3,4]. Being characterized by increased operating flexibility, porous burners have been used in the past for the utilization of main process byproducts [5], among its other applications [6]. Nevertheless, air-quality regulations increasingly demand the reduction of combustion-generated pollutant emissions to lower levels, utilizing highly efficient combustors capable of a wide range of applications and conditions. In principle, pollutant reducing procedures need to satisfy competing trends and achieve a fine trade-off between reducing nitric oxides and carbonaceous species formation. While low flame temperature favors NO_x reduction, it rapidly prevents the complete fuel oxidation, hence increasing CO and unburned hydrocarbon exhaust levels. Practically, the objective is to cope with emission limits imposed by the legislation, by choosing the appropriate burner type and controlling its operating point. Porous media combustion offers comparably low pollutant levels, high turn down ratios, increased flame speeds and extended flammability limits over a wide stability range providing the capability to burn CO on the spot [7].

The premixed flame in a porous burner propagates in either randomly or structured arranged cavities formed by an inert super-conductive porous medium. The excess enthalpy combustion in a porous burner exhibits important design assets, such as high radiant efficiency and the potential to operate even in ultra-lean combustion regimes, offering significant prospects for the mitigation of anthropogenic methane emissions [8]. These advantages, the associated materials, geometries and burner developments have been overviewed in detail in the past [9–11], and along with thorough analytical investigations [12,13] improve nowadays the understanding of the combustion inside porous media. In this direction, nonintrusive laser diagnostics have been recently employed in order to visualize the flame structure [14] and obtain realistic temperature and species measurements inside the combustion zone [15,16], although measurements with intrusive techniques have been reported as well [17]. Nevertheless, the opacity of the porous matrix constitutes the application of optical diagnostics rather complicated hence the majority of the experimental effort has been focused in characterizing porous burners with respect to operating features. In this context, there are studies examining burner stability and behaviour, temperature distribution and pollutant formation using conventional fuels, over a wide operating range [18–22].

The internal heat recirculation from the porous matrix hosting the flame zone enhances burner stability and offers outstanding fuel interchangeability capabilities. This is of major importance especially for the case of low calorific value fuels, where there are studies examining the performance of porous media combustors under such operation conditions [23,24]. Moreover, the porous burner technology provides a particularly attractive combustor for fuels presenting large variation in their constituent composition. Such fuels, as for instance synthesis gases from gasification plants, exhibit as a result diverge combustion characteristics such as burning velocities, ignition time delays and flammability limits [25]. Porous inert medium and packed bed burners have been also proven to operate satisfactory, as far as pollutant levels and combustion efficiency are concerned, for CO_2-rich fuels, such as biogas mixtures, which are increasingly penetrating modern applications [26,27]. In addition, there is a fostered request on burning hydrogen-enriched fuels. The last years there is an increasingly shifting interest from applying porous media technology for hydrogen and synthesis gas mixtures reforming [28,29] to burning such blends as well [30–32]. In this regard, the present study focuses on characterizing a porous media burner while operating in typical mixtures which involve the latter streams and resemble natural gas, biogas and synthesis gas blends in near equimolar ratios.

In the present work, a rectangular two-layer porous burner was operated without air confinement, over a wide range of operating conditions representative of different combustion regimes, namely, from flashback to blow-off conditions. The combustion section was comprised of a 10 pores per inch (ppi) SiSiC foam. The burner was tested over a range of nominal thermal loads from 200 to 800 kW/m^2 under lean combustion regimes between $1.1 \leqslant \lambda (=1/\phi) \leqslant 1.8$. The prime case studied concerned a mixture of methane, hydrogen and carbon monoxide at molar ratios of 50:20:30 respectively. This study concerned a virtual blend of natural gas, where methane is the major constituent, and synthesis gas, where H_2/CO ratios typically range at approximately 2:3. Afterwards, the work focused on CO_2 addition in the latter mixture; the initial CO_2 addition was realised so as to maintain the CH_4/CO_2 fraction at molar ratios respectively resembling typical biogas compositions. Gas phase temperature profiles were obtained using S-type thermocouples and burner surface temperatures using infrared thermography. The work systematically examined major pollutant formation levels at the burner exhaust with respect to fuel, firing rate and stoichiometry variation. Furthermore, the effect of CO_2 addition was further investigated with a parametric experimental study and supportive numerical calculations. Finally, the effect of the chosen fuels on the burner radiation efficiency with respect to pure methane and biogas combustion was presented.

2. Experimental apparatus

Geometry, material properties and main features of the burner under study have been described in detail in previous studies [14,27]. It is here briefly stated that the flame trap consists of 1 mm arrayed holes along its alumina (Al_2O_3) solid structure and the porous matrix serving as the combustion zone, is made of silicon infiltrated silicon carbide foam (SiSiC) with a pore size of 10 ppi. Dimension-wise the flame trap and foam structure exhibit a total length of 15 mm and 20 mm respectively downstream the flame direction. A detailed account of the material thermal properties may be found in [33]. Fuel and air flows were monitored and controlled through mass flow controllers (Bronkhorst MFCs) with a total capacity of 1600 slpm for the air and 120 slpm for the fuel stream. The detailed composition of the fuel streams used is described in Table 1. The separated streams were mixed at a distant position (more than 40 diameters upstream) and then introduced to the burner inlet. Sampling was realized directly at the burner exhaust at a point just above the top layer of the porous burner. An Al_2O_3 probe led the gaseous samples to a condenser and subsequently to the gas analysis system. A ceramic insulated S-type thermocouple was positioned at the tip of the sampling probe so as to obtain gaseous phase temperature measurements. In this way, the thermocouple junction sat at a height approximately 1 mm above the porous structure. An infrared thermography camera (FLIR PM 595), with spectral range 7.5–13 μm, positioned at an angle, so as to avoid hot exhaust gases harming the detector, and at a 1 m distance from the burner surface, was

Table 1
Detailed compositions of the cases under study.

Fuel	CH_4	H_2	CO	CO_2
Case A	47.3	19.8	32.9	–
Case B	38	16	26	20
Case C	28	12	20	40