Experimental study of the flame structure inside a porous inert medium burner using planar LASER induced fluorescence

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Abstract It is well established that combustion in porous inert media holds important advantages like low pollutant emissions, high power density and the potential of operating in lean and ultra lean combustion regimes. Although burners of this type have started to be examined and characterized over the past years, non intrusive experimental methods are needed to describe the actual processes taking place inside the porous structure. In the present work, the technique of laser induced fluorescence - LIF is employed to visualize the flame zone, utilizing the excitation of the Hydroxyl radical - OH. A pumped Nd:YAG, frequency doubled dye laser was utilized for this purpose. Hydroxyl radical is the most widely examined species with the LIF technique on the combustion field, because it gives a good understanding of the flame zone and hence it was used in the present study. In order to perform LIF measurements inside the porous combustion zone, optical access along the porous structure for the laser beam to reach the probe volume and furthermore, to allow a sufficient amount of fluorescence to reach the detector was realized by a thin gap of a similar size as the porous cavity size. A parametric study for the optical gap size and positioning was made, yielding the most suitable configuration for a sufficient signal to noise ratio without significant disturbance of the combustion process in the porous reaction zone. The experiments were conducted over an area of various thermal loads and excess air ratios for methane/air combustion. The main scope of this work is to demonstrate how an appropriate optical access in a porous combustion zone can be achieved for combustion diagnostics, hence demonstrating the capabilities of the methodology. Besides this, an experimental characterization of the wide, stable operating conditions of the porous burner is given, along with the description of the flame zone inside the porous matrix.

1. Introduction

The increasing need for more efficient, less emissive and less energy consuming technologies has shifted the focus of combustion research towards technologies involving flameless applications. The porous burner technology is a state of the art solution that fulfills these requirements. Combustion in inert porous media has many important advantages including low pollutant emissions, high power density, high turn-down ratio, high combustion stability and the potential to operate even in ultra lean combustion regimes [1]. As a result, it continuously improves its place in numerous combustion applications utilizing these advantages. Porous matrix stabilized combustion within porous inert media, the associated porous burner technology development and the materials used, have been described by Trimis and Durst [2]. Although the advantages of porous burners have started to be systematically examined over the last 15 years, the actual processes taking place within the porous inert structure could not be investigated experimentally by means of non-intrusive optical methods, due to the difficulties in achieving optical access inside of the porous matrix. There are numerous studies using intrusive methods that provide experimental data for the porous burner operation such as [3-5], but most of them concern concentration measurements at the exhaust of the burner, or intrusive temperature measurements by utilizing thermocouples in the porous matrix. In the case of slow partial oxidation reforming processes in inert porous media also concentration measurements by gas sampling through probes placed inside the porous matrix were
performed [6]. However for the case of lean combustion the reaction zone is not thick enough to allow resolving it by gas sampling. Thus, the most detailed studies focused on describing numerically the phenomena inside the porous medium such as [6-9]. Zhou and Pereira [10] investigated the influence of the combustion model on temperature, species distribution and exhaust gas emissions. Only recently, non intrusive gas-phase temperature measurements inside the porous burner were carried out by Kiefer et al [11] using the CARS technique for temperature and hydrogen concentration measurements along the burner axis. In these measurements the optical access was provided axially along the burner axis by guiding the laser beam through a hole in the flame trap structure and by creating an empty cylindrical path in the porous reaction zone downstream. Thus, the measuring volume was always lying within a single jet exiting the flame trap structure and was not representative for a random position in the porous structure.

The present work examines methane/air combustion inside a porous burner in the lean combustion regime by means of Planar Laser Induced Fluorescence (PLIF). The depiction of the combustion process within the porous structure supports the understanding of the complex local physico-chemical phenomena. The planar LIF technique is used in the combustion field for qualitative and quantitative measurements of species concentrations as well as for determining mixing efficiency and temperature in reacting flows [12-14]. Among its various advantages, the LIF technique provides a more intense signal compared to other non intrusive techniques, such as RAMAN spectroscopy, and thus, can be also used as a planar technique [15]. The signal intensity is essential for the current study, because the fluorescence signals are received at a small solid angle from within the glowing radiating porous structure of the porous burner.

Experimental determination of the flame front location is based on measurement of quantities, which show a large spatial gradient at the flame front boundary. The hydroxyl radical, OH, is an important intermediate species and, since it is formed in the high-temperature regions, it is commonly employed as a flame front indicator [16]. Besides acting as a flame front indicator, OH holds important advantages for the LIF technique, that makes it the most widely examined species in the combustion field, such as well established structure and distribution of the energy levels, along with the possible transitions and transition probabilities. Due to these reasons the hydroxyl radical was selected as species to be determined for the present study. Its distribution was visualized for various thermal loads and excess air ratios in order to support the understanding of the flame zone structure and behavior over the operational range in the porous reaction zone.

Optical access through the porous structure cannot be achieved in a fully non-intrusive way, due to the opacity of the employed ceramic porous material and the relatively low optical thickness, which does only allow a direct optical access up to a few porous cavity sizes distance inside of the inner part of the foam with a lot of shadowed regions. In the present work, appropriate optical access has been created for the sending optics (planar laser light sheet) and for the receiving optics by cutting two slices in the foam. The slice gap for the sending optics had to ensure sufficient space for the parallel light sheet thickness, whereas the detector opening had to provide a solid angle allowing a sufficient amount of fluorescence to reach the detector. Since the experiments focused on describing the actual phenomena in a random place inside the porous structure, the gap width for the optical paths had to be less than the characteristic length of the porous structure, which is considered to be the porous cavity size/diameter. Possible disturbances of the combustion process in the porous matrix due to the gap size and position were investigated in the current work by parametrically varying the size and position of the gap. Moreover, the structure of the reaction zone over the burner operating condition was examined.
2. Experimental Setup

In the present study a flat rectangular (135x185 mm) porous burner geometry was utilized. The burner consisted of a mixing tube with two supplies for air and fuel connected to a distribution chamber, the flame trap made of alumina (Al₂O₃) and a porous matrix as combustion zone made of silicon infiltrated silicon carbide foam (SiSiC) with a pore size of 10 ppi (pores per inch). The inert porous combustion zone and the flame trap had a height of 15 mm and 20 mm, respectively. The geometry of the flame trap consists of a hole pattern with 1 mm holes in a non-staggered arrangement with 5 mm spacing. Thermal quenching of the flame is accomplished within the flame trap at low thermal loads, while at high thermal loads the flow velocity within the holes is significantly higher than the burning velocity additionally to thermal quenching. The low heat conductivity of the flame trap material (< 0.2 W/mK at ambient conditions) prevented the upstream propagation of a thermal wave, which could lead to a black flash in the flow distributor. This type of burner is very similar to the one described in [5,9,17] and has approximately the same dimensions, as illustrated in Figure 1, especially in axial direction. The characteristic length scale of the porous cavity equivalent diameter for the 10 ppi SiSiC foam structure is slightly less than 5 mm as elaborated by Pan et al [18]. Since achieving optical access in the porous structure is a compromise between the disturbance of the actual phenomena taking place and obtaining the required optical characteristics, all parametric studies conducted concerned gap sizes smaller than 5 mm. The laser beam was passed through a cylindrical lens to obtain a planar laser sheet. For obtaining the fluorescence of the excited OH radical an intensified CCD camera with receiving optics was placed perpendicular to the laser light sheet in front of another slice gap created in the foam for this purpose (Figure 2). The paths were made in a way that allowed the width of the cut in the foam to be adjustable, so that their effect upon the actual process could be evaluated. As a reference test case, the burner was tested without the porous matrix, resulting to a free flame carpet structure consisting from connected individual small flames. The comparison between the flame structure with or without the porous matrix delivers valuable information about the effect of the heat and mass transfer of the porous structure on the flame structure.

![Figure 1. Experimental setup for achieving optical access inside the burner](image)

The burner was assembled over a traversing system for the fine tuning of the beam path alignment, as well as for the detector side. The arrangement of the foam gap sizes was achieved using length prototype specimens in order to satisfy the minimum tolerance demand.
The LIF system

The fundamentals of Laser Induced Fluorescence have been described in detail by Eckbreth [19] and Mayinger and Feldmann [20]. Additionally, important review papers are provided by Kohse-Höinghaus [21-22] and Daily [23]. The OH radical was one of the first and most commonly used in combustion diagnostics from the beginning of the application of LIF in this field due to the strong signal and the advanced possibilities for a thorough physicochemical interpretation of the results. For the excitation of the OH radical, the transition between the ground and the first energy state, which is described as $A^2Σ \rightarrow X^2Π_i$, is chosen for the high probability of transition, the relatively same nuclear distance and the relatively low energy needed for excitation. The influence of collisions is the most troublesome aspect of making accurate profile measurements of minor species with LIF. As it is also followed by most of the studies in this area, the rotational levels of the OH radical (1-0) band that are chosen from the excitation spectrum are the Q₁(1) near 282 nm and the Q₁(6) near 283 nm. Using the LASKIN software [24] it can be clearly seen that the Q₁(6) holds important advantages and it is the one chosen for OH imaging. The Q₁(6) appears to be more temperature independent, providing a good depiction of the population. For the present study, in order to facilitate the measurements, a frequency doubled Nd:YAG laser was used pumping the frequency doubled dye laser (Quantel Brilliant B/TDL90), with a Rhodamine 6G dye solved in ethanol which provided a wavelength in the UV region near 283 nm to excite the Q₁(6) line of the OH (1-0) band. The mean energy of the OH LIF beam was approximately 8mJ/pulse. The signal of the OH (0-0) transition has been selectively filtered to observe the two dimensional LIF images.

![Figure 2. Schematic illustration of the Planar Laser Induced Fluorescence system](image)

The current LIF setup is similar to the one used in previous studies [25] and it is shown in Figure 2. The results presented here concern average mean pictures made from hundred single shots. The fluctuation of the beam energy was recorded for each shot and equalized. The background noise from the radiating foam and from the detector (ICCD-camera) was subtracted. The thermal radiation of the foam was lower than expected according to Planck’s law in the receiving band of the OH fluorescence signal (FWHM~300-330nm). In a different case, conflict between foam radiation and fluorescence would arise, compromising the experiment, since the effective emission coefficient for SiSiC foams, could reach that of a black body [26-27].
3. Results and Discussion

Since it could influence the process taking place inside the porous matrix, the gap width for achieving optical access is a crucial factor. The probe volume was set near the centre of the burner where the influence of heat losses is minimal. In order to attain optical access near the probe volume, the foam was precisely cut in three pieces (Figure 1). The first cut, parallel to the laser beam, served as a path for the planar laser sheet. This path was made along the main burner axis to insure that the beam would pass through the probe volume in order to avoid reflections from the random porous structure. The second cut was created with the purpose of letting, as much fluorescence amount as possible, to reach the detector. The modifications needed for the optical access might influence the combustion process taking place inside the porous media. In order to minimize this effect, the influence of the foam structure disturbance on combustion process was investigated through a parametric study with a varying gap width. The gap size for the laser beam cannot be smaller as the largest beam width in the foam region, while the beam waste is located in the central foam region. As a result, a gap size of 1mm was chosen. Fluorescence signal power is proportional to the detection solid angle, hence a parametric study for the gap size from the detector side was also conducted, in order to clarify, which is the minimal width for achieving sufficient amount of fluorescence signal. The gap width for the detector side was gradually reduced down from 5mm, which as mentioned above, is considered to be the characteristic length of a 10 ppi foam. In the results presented here, a gap size of 2 mm from the detector side allowed a sufficient amount of fluorescence to reach the CCD camera. The 2 mm gap yielded a sufficient signal to noise ratio, and did not disturb significantly the actual phenomena inside of the porous reaction zone.

Besides the gap sizing, the optically accessible position in relation to the hole pattern of the flame trap is of great importance, since the flame structures resulting form the interaction between the exiting jets and the SiSiC foam are going to be different in the axial direction pending on the relative position of the optically accessed area to the holes pattern. Since an optical access just above the holes could lead to a channeling of the flow, a position between four flame trap holes was selected. Alternatively, one can visualize the jets formed by the flame trap. During the parametric experiments, it was observed that, if the optical access opening was made above a flame trap hole, the formed jet -depending on the gap size- could even maintain the familiar Bunsen-like structure, which was disappearing for gap widths < 3 mm. In order to get a better picture of the porous foam influence upon the flame zone, without the interaction with jets possibly directly exiting the combustion zone due to the channel formed by the gap, the optical access was finally adjusted in a way so that no jet exiting a flame trap hole was monitored.

![Figure 3. OH LIF for same excess air ratio and thermal load (a) above the flame trap jet and (b) above two neighbour flame trap jets (CCD gap width of 5 mm) and (c) between the jets (CCD gap width of 2 mm)](image)

Figure 3 depicts the difference in the OH concentrations above discussed scenarios under the same thermal load (600 kW/m²) and excess air ratio $\lambda = 1.2 (\Phi = 0.83)$ condition, for gap widths of 2 and 5 mm. The visualized area included (a) the area of a single jet exiting a flame trap hole, (b)
the interaction area between two jets exiting two neighboring flame trap holes and (c) the area around the middle distance among four neighboring jets and at a gap width of 2 mm, thus without axial free paths (due to the gap) to the combustion zone exit for any jet. The flame jet is clearly seen in the first picture, whereas in the second one, the nearby jets seem to start interacting towards creating a unified zone. It can be also seen that the 5 mm gap width significantly disturbs the phenomena taking place. In conclusion, the parametric studies established the optimum configuration to describe the homogeneous interaction between nearby flame trap jets, in the random porous matrix. This configuration was set and kept for all further experiments in this work, namely 2 mm gap width for detector side and 1 mm for laser sheet, focusing the probe volume in the middle distance among four flame trap holes.

**Influence of the thermal load on the flame front inside inert porous media**

The influence of the thermal load on the flame structure was parametrically investigated by varying it from 200 to 800 kW/m², in steps of 100 kW/m². The excess air ratio was kept constant at \( \lambda = 1.4 \) \( (\Phi = 0.71) \), corresponding to industrial application conditions operating in the lean combustion regime. The aim was to visualize the combustion inside the porous media and show the way the flame stabilizes over a wide range of mass flows. Normalized OH concentration profiles are presented at Figure 4. The normalization was made with the maximum fluorescence value for each case in order to obtain a comparable picture for the flame front position inside the porous matrix between the different test cases. The depicted bars correspond to 55-65% of the maximum fluorescence value, serving as an indicator for the flame zone. It can be observed that the position of the maximum OH concentration does not significantly move over a wide range of thermal loads. For the lower thermal loads studied (200 to 300 kW/m²), combustion takes place directly downstream the flame trap. For the thermal loads of 400 to 700 kW/m², the flame stabilizes approximately in the middle of the porous media, whereas, for higher loads, the flame moves slightly further downstream.

![Figure 4. Position of maximum OH concentration for various thermal loads at an excess air ratio of \( \lambda = 1.4 \) \( (\Phi = 0.71) \)](image)

This behavior seems to be in agreement with Kiefer et al. [10]. The later results show the wide range of stable operating conditions of a porous burner and prove the advantages of internal heat recirculation. The results also show that the starting position of the flame zone is almost independent of the thermal load for thermal loads > 400 kW/m². Besides the obvious trend for the
maximum OH concentration position, also the flame zone length remains almost constant for 200 to 700 kW/m².

The flame stabilization can be divided into three regimes. In the first regime (200 to 300 kW/m²), the flame front starts directly above the flame trap. The flame speed is much higher than the flow speed and the flame trap acts to stop the flashback by thermal quenching. The second regime can be found for thermal loads from 400 to 600 kW/m². In this range the flame maintains an almost constant height and a similar structure. Hanamura comments in [28] that the flame is stabilized by internal heat recirculation. In the third regime (700 to 800 kW/m²), the reaction zone moves further downstream and the flame is at the point of crossing over to blow off conditions, since the combustion zone has a depth of only 15 mm. This process is noticeable by reactions showing OH radicals at the exit of the porous structure. These findings are in good agreement with the numerical studies by Mendes et al [29].

**Influence of the excess air ratio on the flame front inside inert porous media**

In order to determine the influence of the excess air ratio on the flame structure, a parametric study was conducted for three different thermal loads: 200, 400 and 600 kW/m². The excess air ratio was varied in a range of $1.2 \leq \lambda \leq 1.8$ ($0.83 \leq \Phi \leq 0.56$). Here, as in the previous paragraph, normalized OH concentration profiles are presented normalized for each case to the respective maximum fluorescence value, in order to obtain a clear picture of the flame zone location inside the porous matrix. The bars following the graphs correspond, again, to 55-65% of the maximum fluorescence value, serving as an indicator for the flame zone height.

Figure 5 presents the flame front measurement as a function of the excess air ratio ($\lambda = 1/\Phi$). It is evident, that the flame front does not significantly move downstream by varying the excess air ratio up to values of 1.6, while afterwards a clear movement downstream can be observed. In the case of a thermal load of 200 kW/m² the maximum OH concentration can be found at a height of approximately 4.5 mm within the porous structure for all investigated excess air ratios. Similar measurements for the cases of higher loads (400 and 600 kW/m²; Figure 6 and Figure 7 respectively), indicated that the maximum OH concentration remains at the same position for varying excess air ratios at approximately 7 mm.

![Figure 5. OH distribution for various excess air ratios at a thermal load of 200 kW/m²](image-url)
In Figure 5, the flame stabilizes just downstream the flame trap, for most excess air ratios. It can be clearly seen from the figure that for lower excess air ratios, the flame peak has a horizontal flat shape at approximately 1 mm height above the flame trap, creating a homogeneous flat flame. This distance is relatively low compared with the optical path width (2 mm) and the distance between two neighboring jets (5 mm). It can be anticipated that the incoming gas is preheated and ignites immediately expanding in the horizontal axis due to the temperature rise and the higher pressure loss in the foam structure. This argument is supported by numerical predictions [30]. Increasing the excess air ratio causes the flame to start to lift up and to stabilize in the porous inert combustion zone while the flame peak zone starts to compress. It can be seen from the figure, that OH radicals do not reach the exit of the foam.

Figure 6 and Figure 7 (400 kW/m² and 600 kW/m² respectively) show a stabilized flame which is fully developed inside the porous inert media, over the total excess air ratio range. In both cases the normalized OH concentration peak can be found in almost the same position for all excess air ratios (6.5 mm to 7 mm).

![Figure 6. OH distribution for various excess air ratios at a thermal load of 400 kW/m²](image)

![Figure 7. OH distribution for various excess air ratio at a thermal load of 600 kW/m²](image)
The starting point of the lifted flame moves slightly downstream in the porous media while increasing the total mass flow, whereas this change is more significant with the increase of the excess air ratio. The comparison shows that the flame zone shrinking follows the same trend on the lower and upper part of the flame peak zone. When the total mass flow increased by changing the thermal load or excess air ratio, the starting point of the lifted flame moves slightly downstream in the porous media.

![Figure 8. Flame zone length for stable thermal loads (400 and 600 kW/m²) and various excess air ratios](image)

Figure 8 presents the flame zone length indicated as in previous figures, independent of the actual flame position inside the porous matrix for two thermal loads, 400 and 600 kW/m², where the flame zone is located completely inside the foam. The total length of peak OH concentration increases marginally with the thermal load in these operation conditions. In total however, the flame zone length remain almost constant for each excess air ratio.

4. Summary, conclusions and outlook

In the present work, measurements of the hydroxyl radical in a combustion environment inside porous inert media were performed for the first time, and a methodology for visualizing the flame front inside a porous inert media by planar laser induced fluorescence was proposed. By monitoring the maximum OH concentration, the position of the stabilized flame front could be determined for various excess air ratios at different thermal loads, which allowed conclusions for the investigated ranges to be made.

It was proven that the thermal radiation could be separated from the fluorescence signal of detected hydroxyl radicals for the operating temperature range of a porous burner’s glowing foam. Additionally, a study about the flame disturbance, induced by creating the optical access, was carried out. The configuration used in order to overcome technical difficulties was presented and useful parametric studies were conducted in such a way as to facilitate future theoretical and numerical studies.

In the context of burner operation, it was observed that the position of the maximum OH concentration is almost independent of the excess air ratio for the same thermal loads in the stable operation regime. However, the flame zone length decreases with higher excess air ratios. Flame
stabilization directly downstream the flame trap was noticed at a thermal load of 200 kW/m² for lower excess air ratios. At thermal loads in the range of 600 to 800 kW/m², the flame moved further downstream at high excess air ratios until.

For the present work, the hydroxyl radical was chosen as a marker for the flame zone. OH LIF combined with formaldehyde - CH₂O LIF can also produce interesting results concerning besides the flame zone, the heat release rate [31-32]. Quantitative OH LIF experiments could also improve the understanding of the complex phenomena inside the porous matrix. Finally, the search for less intrusive and more efficient methodologies is of great interest for such studies, in order to minimize the effect of the measuring method upon the actual physicochemical phenomena to be studied.

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