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CO and NO_x emissions in porous inert media (PIM) burner system operated under elevated pressure and inlet temperature using a new flame stabilization technique

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ABSTRACT

The rapid advances in technology necessitate abundant use of fossil fuels which poses two major challenges to any nation. One is fast depletion of fossil fuel resources; the other is environmental pollution. The porous medium combustion has proved to be one of the technically feasible options to tackle the environmental pollution problem to a remarkable extent. This work presents an experimental investigation to study combustion emissions using a premixed methane–air mixture within a non-homogeneous porous inert medium (PIM) under high pressure ratio (1–9), temperature (20–400 °C) and thermal output power (5–40 kW). A new flame stabilization technique in porous inert media (PIM) combustion under high pressure and temperature has been developed and evaluated. The proposed technique avoids the draw backs of the hitherto developed techniques by properly matching the flow and flame speeds and, consequently, ensuring a stable combustion, for a wide range of operating pressure and temperature. The validity of this new technique has been assessed experimentally in details by analyzing combustion inside a prototype burner. The superiority of the new concept was confirmed by low CO and NO_x emissions, where a zero value was recorded for CO emissions throughout the whole investigation. The NO_x emissions revealed remarkable performance as compared with conventional PIM techniques. Values less than 10 ppm were obtained at relative air ratios larger than 1.65 and 1.85 with temperatures of 200 and 400 °C, respectively. This indicates the high combustion efficiency and emissions performance of the proposed technique. Observed results proved remarkable emission performance with respect to environmental pollution legislation.

1. Introduction

One of the main targets of all current combustion systems, in addition to high efficiency and robust performance, is the ability to meet current and future pollutant emission regulations. Therefore, new concepts based upon a comprehensive understanding of combustion processes have recently been developed to introduce modern combustion systems characterized by ultra-low pollutant emissions and also satisfying other traditional requirements. Porous inert media (PIM) combustion becomes increasingly important, specifically, from the viewpoints of technical interest and practical applicability [1–3]. A diverse number of outstanding industrial and residential applications have been proposed, e.g. household water heating systems [4] and radiant burners [5]. Combustion of gaseous fuel within the PIM burners distinguishes itself from other conventional techniques by several advantages such as, extended lean flammability limit, self re-lightening capability and lower pollutants emission (CO and NO_x) [6]. An extensive research has been done to improve the performance of porous medium burners with respect to radiation output, stability, lean operation and diminishing the issuing gaseous pollutants. Such elaborative experimental and numerical work employed a variation in materials and emissive properties [7]. Hsu et al. [8] proposed a novel method to enhance flame stability using two porous ceramic cylinders of equal length and diameter but different pore sizes, which were stacked together and insulated around the circumference. They were succeeded in extending the flashback limit to a low relative air ratio of 1.54. However, the influence of power density on this stabilization technique was not clear.

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Trimis [9] developed successfully a compact household PIM burner-heat exchanger system with a large turndown ratio of 1:20 in a stable range of relative air ratios between 1.3 and 1.8 using the quenching layer stability technique. This system was extensively studied at high power densities that reached a maximum value of 3000 kW/m^2, which was not achieved in previous investigations. Unfortunately, this technique becomes impractical when the operating conditions are varied from ambient conditions.

Bakry [10] proposed a modified technique based on the quenching region concept to enhance the flame stability within atmospheric porous inert media (PIM). The modified technique eliminates disadvantageous features inherent with this category of PIM combustion, such as the high-pressure drop and the continuous degradation of the quenching region. NO_x emission was less than 15 ppm at a relative air ratio of 1.4 and drops to 3 ppm at equivalence ratio of 1.8. However, these values were at atmospheric conditions.

Mathis and Ellzey [11] studied flame stabilization and emissions for a methane/air porous burner. Two different porous media materials, yttria-stabilized zirconia/alumina composite and zirconia-toughened mullite were used in the study. Results showed that unburned hydrocarbons (UHC) were elevated at low firing rates but were low at higher firing rates. CO emissions were less than 15 ppm for firing rates less than 2000 kW/m^2, while NO_x emissions were below 10 ppm for all cases studied (firing rate range 700–4000 kW/m^2). Similarly, most of the research efforts were experimentally and numerically focused toward only atmospheric pressure. Almost no application or investigation has addressed stable PIM combustion and emissions under both elevated pressures and mixture inlet temperatures (which is the case in gas turbine applications).

There is an important and well-established fact inherent with porous inert medium (PIM) combustion which is that PIM combustion is intrinsically flashback in its nature after limiting power density values of (>650 kW/m^2) [5]. Therefore, at high limiting power density value (>650 kW/m^2) a different and new flame stabilization technique should be provided to stop the flame from propagating into the mixing section.

At elevated pressure and mixture inlet temperature the quenching distance decreases to the point where the flame can continue in the quenching layer, causing classical flashback. To prevent this upstream advance of the flame, the equivalent pore diameter of the quenching region should be modified. Thus, from the above discussion, it can be conclude that the influence of pressure and initial mixture temperature on the propagation of the flame in a PIM is significant, and the design of the PIM burner under elevated pressure and mixture inlet temperature needs new and substantially different ideas from the currently applied concepts. Therefore, the aim of this work was to introduce a new flame stabilization technique, based on the understanding of both the fluid flow behavior and combustion characteristics, as a potential solution for the emissions problems (CO/NO_x) at elevated pressures and mixture inlet temperatures. In order to examine the validity of the new flame stabilization technique proposed and evaluate its performance, a special test apparatus has been designed and constructed. The test facility enables the investigation of combustion within PIM under high operating pressures (up to 10 bar) and temperatures (20–400 °C). The maximum nominal power (based on the fuel mass flow rate) is 40 kW with a variable relative air ratio up to 3.

2. Experiments

2.1. Stabilization technique

The proper selection of the relevant stabilization technique under elevated pressure and temperature is one of the main challenges that will face the designer of a PIM combustion system. The main difficulty is caused by the tendency of lean premixed combustion within PIM to be intrinsically unstable flashback at low and moderate relative air ratios. This behavior of upstream motion of the flame was not experienced in premixed free flames where the stability curves cover the entire range of relative air ratios from rich to lean limits. When the power density is increased, the rate at which the unburned mixture is supplied to the pre-heat and reaction zones exceed the rate at which the mixture can be consumed until a match between the two rates is re-established. This increase in power density also leads to an increase in the radiative and conductive heat feedback rates. This effect leads to a nonlinear augmentation in the flame speed. Under certain operating conditions, this nonlinear increase in flame speed dominates the process, and causes the flame to move upstream until a balance between the two rates is established again. If the increase in heat feedback is excessive, conditions of flashback (where the flame travels to the furthest upstream end of the ceramic matrix) can be reached. Mital et al. [5] have experimentally shown that the maximum stable power density in PIM radiant surface burner is less than approximately 650 kW/m^2. At higher power densities, PIM burners become flashback in their nature.

Therefore, in order to define a new criterion for stable combustion for high power density, the stability limits must first be defined as a guide for any further discussion. On the one hand, the flashback limit is defined in a similar way as in the free space stream, i.e. the critical minimum mass flow rate (burner power) at a predefined relative air ratio to prevent the flame from propagating in the upstream direction through the free space before PIM regardless of the location of the flame. The blow-out limit is defined as the maximum relative air ratio at each mass flow rate (burner power) at which a stable flame can be maintained within the PIM [12]. If any further increase in the relative air ratio at constant output power occur, the mixture will be diluted and the velocity will increase to push the stabilization flame position to the outside of the PIM matrix or toward the blow out limit at the downstream end, then combustion becomes unstable, i.e. it propagates into the PIM downstream end and finally leaves it. Since an increase in mass flow rate (burner power) is the main reason for flashback in a PIM, it is, in turn, the key factor for prohibiting flashback in the free stream. Thus, if the mass flow rate (burner power) in the free space before the PIM is kept higher than the critical flashback value defined by Eq. (1) for laminar [13] and Eq. (2) for turbulent [14] premixed stream, at any operating conditions, no flashback condition will exist at the upstream end and the flame will be confined to the PIM zone. Instead, the farthest location which the flame would reach is the upstream end of the PIM matrix, or, more precisely, the interface plane between the ceramic matrix and the free space zone.

$$\mathrm{Pe} = k \times \mathrm{Pe}_F^2 \quad \text{(Laminar stream)} \tag{1}$$

$$\mathrm{Re} = 2.0\,\mathrm{Pe}_F^{1.1} \quad \text{(Turbulent stream)} \tag{2}$$

Therefore, and as a design starting point, 20 mm was chosen for the premixing tube diameter resulting in a mass flow corresponding to 3 kW at a relative air ratio of 1.2 and any preheating mixture inlet temperature up to 400 °C. This estimation is based on the flashback limit (Eq. (1)) and the one-dimensional continuity equation. In Eq. (1) the flow and flashback Peclet numbers are defined as $\mathrm{Pe} = Ud/a$ and $\mathrm{Pe}_F = (S_L d/a)$, respectively. The value of k is 0.0125. The generalization of this equation was confirmed for any initial preheating temperature in the range 20–400 °C for different mixture compositions in laminar flames.

This mass flow rate (burner power) value is large enough to prevent flashback formation in the burner premixing tube, where the surroundings have no effects upon the incoming mixture. In the present case, the existence of the hot PIM ceramic at the end of

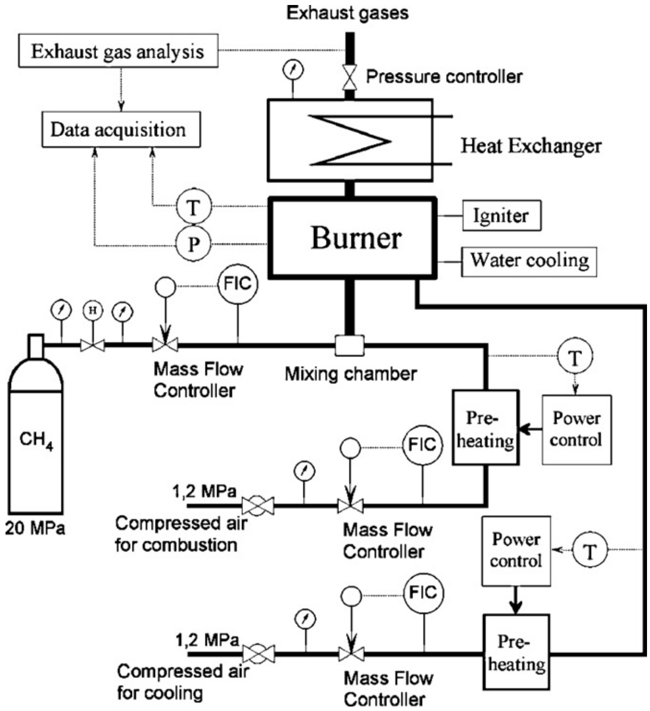

Fig. 1. Schematic diagram of experimental setup [15].

the premixing tube would influence the critical mass flow rate by increasing the radiative and conductive heat transfer from the PIM matrix into the tube wall. This decreases the quenching distance of the tube wall. In order to take these effects into consideration, and for safety purposes, the critical minimum mass flow rate was increased to a value that corresponds to 5 kW thermal output power. In fact, 3 kW was successfully tested under atmospheric conditions and was sufficient to satisfy the no flashback condition. Thus, the mixture was always pushed into the ceramic matrix and stabilized via wakes and the re-circulating zones. However, this power value (3 kW) was not suitable as a reference factor to calculate the minimum critical power which should be applied at each pressure ratio value greater than 1. Pressure ratio can be defined as the ratio between the absolute measured pressure to the atmospheric pressure (pressure ratio = 1 is the absolute value). Therefore, 5 kW was selected and successfully examined as the minimum design power at atmospheric conditions and any preheating mixture inlet temperature, and as a reference factor for the entire range of pressure ratio values. The upstream end plane of the PIM ceramic was firmly placed on the outlet rim of the premixing tube to avoid any separating or re-circulating pre-ignition regions that may develop at this position more specific and thorough details about the stabilization technique proposed and applied in this study can be found in a previous publication [15].

2.2. *Experimental setup*

Fig. 1 shows the schematic diagram of the experimental setup. Methane 2.5 (>99.5%) was regulated from high-pressure bottles using a thermal mass flow controller (Bronkhorst High-Tech B.V., The Netherlands) before flowing into the mixing chamber. The maximum mass flow rate was sufficient to provide a thermal power of 40 kW with an accuracy of ±0.05%. The air used in combustion was supplied by the laboratory main air supply (13 bar), which was limited to provide a maximum steady combustion air flow rate sufficient for 40 kW thermal output power at a pressure ratio of 9 and relative air ratio of 2.8. The air flow rate was regulated via a mass flow controller (Bronkhorst High-Tech B.V., The Netherlands) at a maximum mass flow rate of 3.5 kg/min with an accuracy of ±0.05%. Both mass flow controllers are used to control the flow of air and methane for constant thermal output powers at defined constant relative air ratio ratios. A data acquisition system was used to monitor the temperature and pressure distribution throughout the burner via thermocouples and pressure transducers. The concentrations of various species in the exhaust from the burner were measured using a gas analyzer. The test apparatus consists of the following components: combustion chamber, pressurized vessel casing, premixing tube, exhaust gas nozzle, exhaust gas heat exchanger, air preheating systems, and ignition system. A schematic diagram of the test apparatus describing the complete assembly is presented in Fig. 2.

After the premixing chamber, the feed was directed to a premixing tube (highly temperature-resistant stainless steel, DIN 1.4841) of 280 mm length and 20/32 mm inner/outer diameters, where the mixture passes through two fine screens to ensure very high mixture homogeneity. The premixing tube penetrates coaxially the combustion chamber for 100 mm. The combustion chamber contains the porous ceramic matrix. It was designed as a diffuser transitioning to a cylinder shape and is fabricated from one piece of a highly temperature-resistant grade of stainless steel. The divergence angle of the diffuser is 40°. The PIM matrix was formed in the shape of a cone with a diameter ratio of 20/180 mm and a divergence angle of 40°. An Al_2O_3-lamella (fabricated by Pritzkow for Special ceramic Co., Germany) was selected as the PIM material owing to its high working temperature, thermal-shock resistance and low pressure drop. The physical properties for this material with a sketch showing its shape and structure can be found in [16,17]. A 20 mm thickness insulating nonporous material is installed between the PIM and the inner wall of the combustion chamber. The insulating material was increased at the inlet to a length of 44 mm and then a concentric axis-symmetric passage of 20 mm diameter was formed as an inlet tube to the PIM. An additional ceramic tube of 18 mm height and 20 mm inner diameter was embedded concentric with the insulating material at the upstream end and appropriately seated on the upper edge of the premixing metal tube, which also has a 20 mm inner diameter. Eight radial holes, each 12 mm in diameter, were bored between the air gap and the inner insulation surface and positioned at a station lying next to the PIM matrix. These holes were designed to relieve any pressure differences within the combustion chamber in the very hot region. The hottest region of the combustion chamber is contained in the pressurized vessel casing, which was fabricated from one piece of highly temperature-resistant grade of stainless steel. The inner wall of the pressurized vessel casing was coated with 20 mm of insulating material.

One may note that the wall has the same angle as the combustion chamber wall, allowing a constant gap of 10 mm of air. The very low thermal conductivity of the combustion chamber and pressurized vessel insulating layers, and also the air gap, ensure almost adiabatic combustion and protect the outer surfaces from excessive thermal stresses. Combustion products continue to exhaust the heat exchanger via a nozzle, which is used to adapt the cross-sectional area of the combustion chamber to that of the inlet tube of the heat exchanger. The nozzle was fabricated from one piece of highly temperature-resistant grade of stainless steel and insulated on the inner surface with a 30 mm thick insulating material. The exhaust heat exchanger was used to cool the exhaust gas resulting from the combustion process to a reasonable temperature for laboratory conditions and for the pressure control valves (<150 °C) (AirCom Pneumatik GmbH: R240-02DV) installed at the outlet of the heat exchanger. These valves were used to investigate the influence of pressure on combustion in the PIM. Each valve can regulate the pressure in the range of 0.14–10 bar and has a

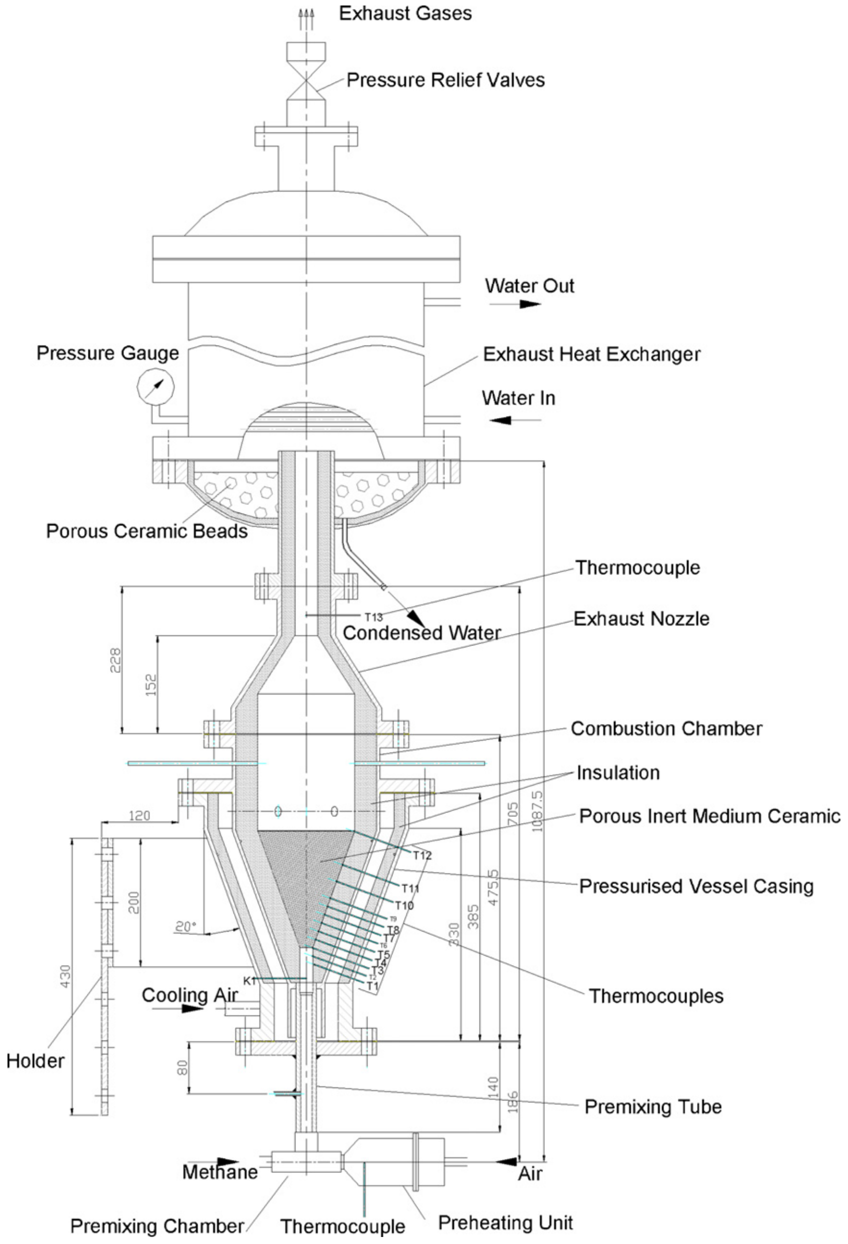

Fig. 2. Schematic diagram of the burner test apparatus (all dimensions in mm) [15].

maximum flow rate of 1.2 m^3/min at 1.4 bar outlet pressure. To prevent condensed water from reaching the combustion zone, the inlet tube was designed to penetrate the bottom base surface and then extend inside the heat exchanger to a level higher than the base. The collected condensed water on the base surface can be easily extracted from time to time during the operation through a ball valve mounted on the base.

In order to investigate the influence of mixture inlet temperature on combustion in the PIM, an air preheating system was specially designed and installed between the air mass flow controller and the premixing chamber. The system is capable of heating a mass flow rate of compressed air corresponding to 40 kW output thermal power at relative air ratio of 3.0 and a pressure of 10 bar up to 400 °C. Heat was provided by an electric heater of 3 × 5500 W. The preheating system and its connections, piping, and fittings were made of stainless steel of a grade similar to that of the combustion chamber, and carefully insulated. The temperature at the outlet of the preheating unit was adjusted to the desired value using a control unit with a K-type thermocouple. In the present investigation, the temperature distribution in the stream wise direction was measured to detect the flame and to check its stability. Therefore, thirteen thermocouples of type S (maximum operating temperature 1600 °C; SENSYCON, 1.5 mm in diameter), in addition to two thermocouples of K-type (Rössel Messtechnik, Germany), were employed more thorough details about temperature measurements procedure, thermocouples specifications, and measurement accuracy can be found in our previous publication [15].

2.3. Experimental procedure

The exhaust gas analyzer equipment is turned on and allowed to warm up for at least 2 h. The equipment is purged using zero-gas (N_2) for 20 min and then undergoes a calibration process for each of the four channels using bottled calibration gases. Then it was left on for the entire duration of the experiment. A mass flow rate of air equivalent to a total thermal output power of 5 kW with relative air ratio of 1.3 was supplied to the burner before the gaseous fuel is introduced. Once the methane has been allowed to mix with the air, the ignition system was activated and combustion takes place at the downstream end of the ceramic matrix. The burner reaches its steady state in about 30 min, during which the relative air ratio is gradually increased to 1.5. During this critical phase of operation, the thermocouple readings must be closely monitored. As the outlet temperature reaches 850 °C, exhaust analysis is performed.

The emissions levels and the relative air ratio were estimated from the measured concentrations of O_2 and CO_2, respectively. After the preheating phase, the desired experimental conditions were imposed. First, the air and the methane mass flow were adjusted for the desired power and relative air ratio. The second step was to adjust the combustion pressure to the desired value. The pre-heat mixture inlet temperature was the last parameter set in the experiment. Up to this point, no measurement was recorded for evaluation; rather, the readings taken were used only to monitor the steadiness and stability of combustion.

To judge the stability of the flame, it was necessary to monitor the variation of the temperature profiles with time. Every 5 min the temperature profiles were plotted and examined until no changes were observed. The maximum relative air ratio for a specific power output and mixture inlet temperature was estimated by increasing the air mass flow rate (g/min) incrementally (increment of 0.1) until blow-out was detected. The initial value of the relative air ratio depends on the mixture inlet temperature at which the measurements are performed. The typical values are 1.4, 1.6, and 1.8 for mixture inlet temperatures of 20, 200, and 400 °C, respectively. This procedure was applied repeatedly for each power at each set of initial conditions.

A sample of the exhaust gases was continuously extracted using a sampling tube downstream of the burner and analyzed in a gas analyzer (Rosemount Analytical Fisher-Rosemount, NGA 2000). The analyzer has four channels to measure O_2 (%), CO_2 (%), NO_x (ppm) and CO (ppm). By measuring O_2 and CO_2 concentrations simultaneously, the relative air ratio was instantaneously defined. The emissions levels for CO and NO_x were also measured. The operating ranges for the four channels were selected as 0–25%, 0–50%, 0–1000 ppm, and 0–100 ppm, respectively, with a precision of ±0.1% and ±0.1 ppm and an accuracy of $\leq$1% of full range.

Finally, the instantaneous data were transferred and recorded by the data acquisition system. The estimated uncertainty in the measurement of NO_x was calculated based on 3 replicates and found to be less than ±2% from the measured value. The accuracy with which NO_x can be measured is specified by the manufacturer of the exhaust gas analyzer equipment. The raw calibration data were curve fitted using computer software.

3. Results and discussion

3.1. CO emissions

For the entire investigation, zero CO emission value was obtained at all operating conditions applied. This may be attributed to the following reasons. Firstly, the combustion undergoes an almost adiabatic process when there is no cooling air. Thus the inner wall, at high temperature, prevents quenching effects. The second is the long residence time that the exhaust gas spends in the burner until the exit section owing to the large exit area of the PIM and the long distance separating the PIM exit and the heat exchanger. Third, there was a large efficient heat exchanger to cool down the exhaust gases from the combustion chamber. In fact, the heat exchanger also used to quench the combustion process to prevent the dissociation of CO_2 again into CO. Thus all of the CO gases oxidized into CO_2 and for this reason zero CO emissions were measured by the gas analyzer.

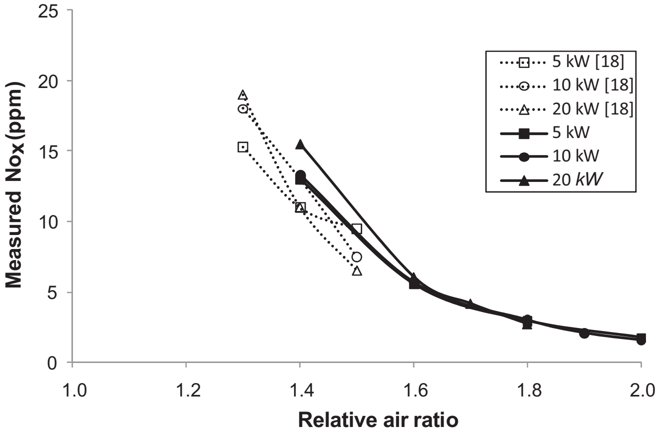

Fig. 3. NO_x emissions versus the relative air ratio at ambient temperature and atmospheric pressure at different power values.

These CO emission results confirm several important features of the new technique proposed. First, the combustion process under any conditions is highly efficient. This is one of the most important issues for any type of combustion equipment. Second, despite the operation at the blow-out conditions for a long period (~20 min), the zero-emission value is sustained. This indicates a complete combustion of the fuel in the free space following the PIM and the very slow extinction process of the PIM due to the adiabatic process. The burner is self-relighting by just reducing the value of the relative air ratio. This ensures the ultimate capability of relighting even under unexpected operating conditions. Occasionally, these results leave the NO_x emissions as the key item in evaluating the emission performance.

3.2. NO_x emissions

Currently, stationary turbines are regulated to 25 ppm or less of NO_x in many geographical regions. This limit is expressed in parts per million by volume, referred to 15% oxygen on a dry basis. This is to avoid ambiguity when comparing different sets of experimental data and to indicate the combustors burning less fuel are expected to produce less NO_x. A correction is usually made according to the following equation:

$$(NO_x),\ 15\%\ \text{oxygen} = \frac{5.9 - NO_{x\,\text{meas}}}{20.9 - O_{2\,\text{meas}}} \tag{3}$$

where NO_x concentrations are expressed in ppm (dry) and O_2 content is expressed in volume percent. Correction to constant oxygen implies correction to a standard reference state by actual or conceptual post flame addition of cooling air, in which the reported NO_x level is not affected by the degree of post-flame dilution. Thus, NO_x emissions data in this study are presented in values of both measured ppm and/or ppm corrected to 15% O_2.

3.2.1. Operation under ambient conditions

In order to compare the present burner design with already existing PIM burner designs of comparable power densities, NO_x emissions are depicted in Fig. 3 for ambient temperature and atmospheric pressure at different thermal output power rates. Fig. 3 shows the NO_x emission results of [18] who used a similar PIM material in an atmospheric PIM burner based on the quenching zone technique. Very good agreement between the two sets of results is shown. It can be seen that very low (<10 ppm) NO_x emissions can be achieved at a relative air ratio higher than 1.45. Clearly, NO_x emissions are strongly influenced by the relative air ratio, as expected. At a relative air ratio of 1.4, the NO_x level was 15 ppm,

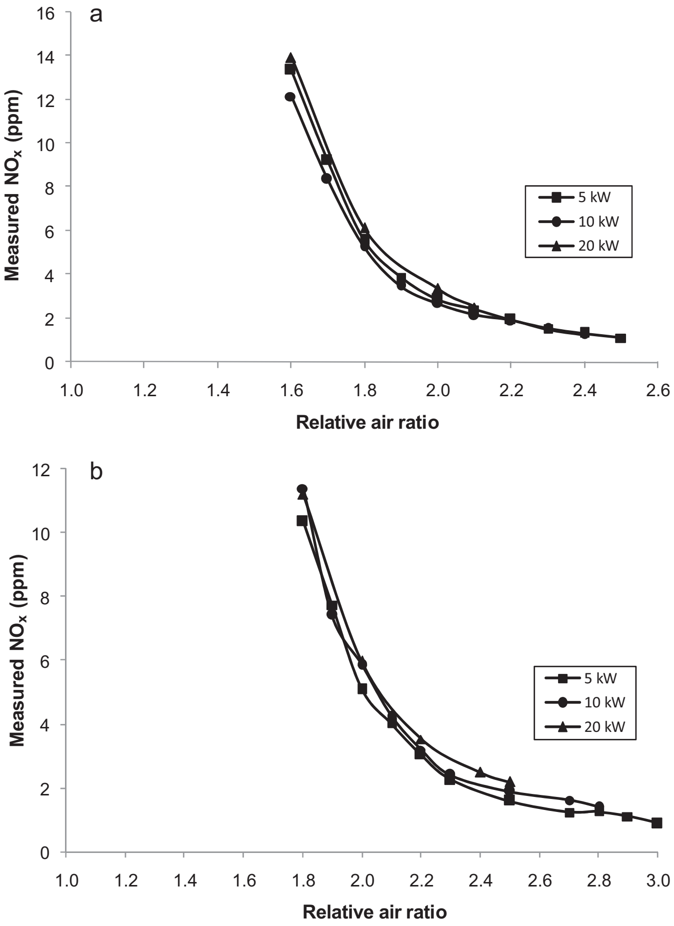

Fig. 4. NO_x emissions versus the relative air ratio at mixture inlet temperature of (a) 200 °C, (b) 400 °C and atmospheric pressure at different power values.

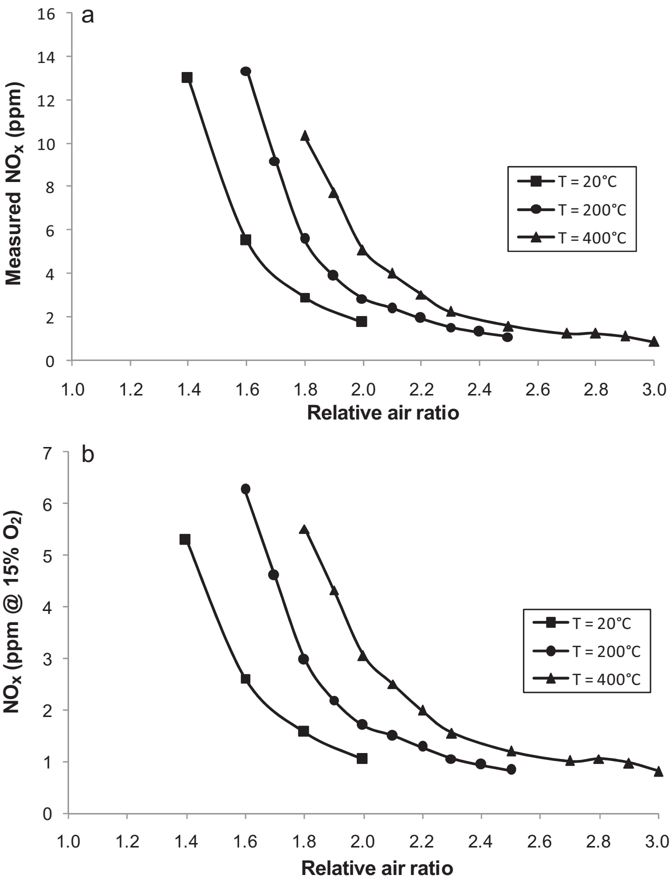

Fig. 5. NO_x emissions versus the relative air ratio at 5 kW and atmospheric pressure for different mixture inlet temperature values: (a) measured NO_x (ppm) and (b) NO_x (corrected at 15% O_2).

whereas at a relative air ratio of 1.8 it was 3 ppm. The well characterized behavior of the smooth increase in NO_x curves with relative air ratio reflects a typical effect of thermal NO_x formation as a result of increasing the flame temperature while decreasing the relative air ratio. In contrast, the obvious independence of NO_x on thermal output power implies that the residence time has a minor effect on NO_x for the moderate and higher relative air ratios studied. This trend was observed throughout the present study, regardless of the operating conditions. This is in agreement with the results reported by [19] concerning the role of the residence time.

3.2.2. *Operation at elevated initial temperature*

The effect of preheating on the formation of NO_x is shown in Fig. 4a and b, where the measured NO_x (in ppm) is plotted versus the relative air ratio for a power range of 5–20 kW and preheat initial temperatures of 200 and 400 °C, respectively. It can be seen that the thermal output power has a minor influence on NO_x formation, and becomes less important as the relative air ratio increases (as mentioned in Section 3.2.1). Again, the only considerable change is the significant decrease in NO_x formation with relative air ratio. For an increase in relative air ratio from 1.6 to 2.3 at 200 °C, for example, a decrease in NO_x emissions from 13 to 1.5 ppm can be seen. Also, remarkable emission characteristics can be obtained ($NO_x < 10$ ppm) for relative air ratios larger than 1.65 and 1.85 with temperatures of 200 and 400 °C, respectively. However, if the comparison is made for the same relative air ratio, a significant change is expected. The NO_x level results for three initial temperatures at the same thermal output power of 5 kW at atmospheric pressure are provided in Fig. 5a and b. The effect of increasing the initial temperature on NO_x formation at the same relative air ratio of 1.8 is clear: the NO_x emissions increase from ∼3 to ∼10 ppm between 20 and 400 °C. This reflects the increase in flame temperature with initial temperature at the same relative air ratio. By increasing the relative air ratio, the differences among the NO_x values decrease again due to the reduction in flame temperature with relative air ratio. Also, in Fig. 5a, NO_x increases from ∼1 ppm up to ∼13 ppm as the relative air ratio decreases. This trend is nearly unchanged by varying the initial temperature. In general, one can observe a common feature; the low-temperature characteristics of lean flames preclude significant formation of NO_x by eliminating the thermal mechanism. The prompt and nitrous oxide mechanisms, however, continue at lower temperatures and dominate the combustion process below 1400 °C. This may also demonstrate the independence of NO_x production on residence time with increasing power (Figs. 3 and 4) where the prompt and nitrous oxide mechanisms are not dependent of the residence time as is the thermal mechanism. In Fig. 5b, the measured NO_x emission data presented in Fig. 5a are reproduced and shown in corrected NO_x at 15% O_2. This is to compare the emissions values with the regulated value in gas turbine application (25 ppm at 15% O_2) where the three investigated initial temperature cases yield values of less than 6 ppm at 15% O_2 at their corresponding minimum design relative air ratio.

3.2.3. *Operation at elevated operating pressure*

Pressure effects on NO_x formation in a PIM are of special importance owing to the lack of data in the literature. The NO_x emission values are given in Fig. 6 as a function of relative air ratios for different values of operating pressure at ambient temperature.

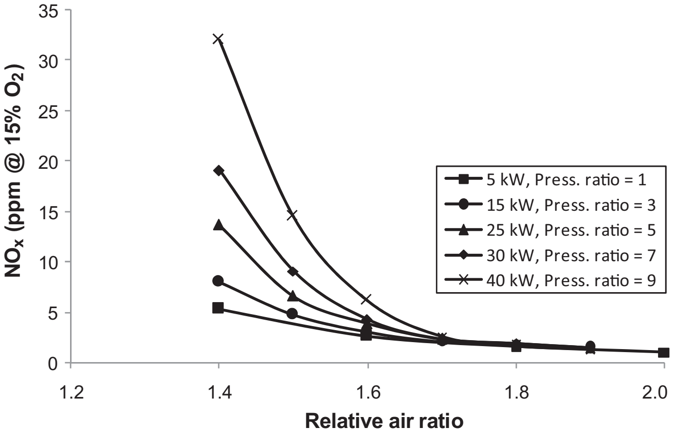

Fig. 6. NO_x emissions versus the relative air ratio at ambient temperature for different pressure ratios with the same residence time.

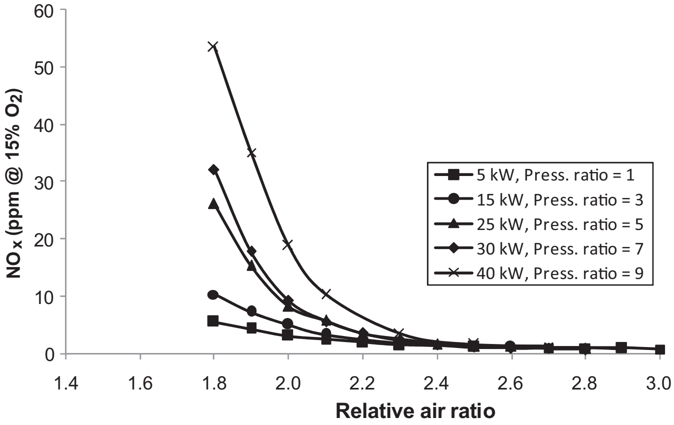

Fig. 8. NO_x emissions versus the relative air ratio at mixture inlet temperature of 400 °C for different pressure ratios with the same residence time.

These curves were plotted for the corresponding minimum design power for each pressure ratio to isolate any possible effects of the residence time by maintaining the mixture inlet velocity approximately constant. Significant pressure effects on NO_x formation are obvious for relative air ratios less than 1.6, and become negligible for relative air ratio values greater than 1.6. It is difficult to draw a conclusion based on this observation owing to the complexity and lack of proper understanding of the underlying physics. However, Maughan et al. [20] considered this trend as evidence that the nitrous oxide and prompt mechanisms, which dominate at low temperature and are independent of pressure, are the main parameters affecting NO_x formation at high relative air ratios. The higher NO_x levels at the lower relative air ratios associated with high temperatures are primarily due to thermal NO_x, which exhibits a square root dependence on pressure. These postulations and conclusions are fully consistent with those of [21]. Correa [21] studied turbulent premixed methane–air flames stabilized on the top of an un-cooled perforated plate burner between 1 and 10 bar. He showed that NO_x emissions are independent of the pressure in the leanest premixed flames. An increase in flame temperature, by decreasing the relative air ratio, caused the pressure effects on the NO_x to increase, corresponding to NO formation by a thermal mechanism. However, despite these pressure influences on NO_x formation, it is clear that the NO_x emissions level corrected to 15% O_2 at relative air ratios higher than 1.5 for any value of the pressure ratio investigated remained below 15 ppm which is less than the regulated value by 10 ppm.

3.2.4. *Operation at elevated pressure and initial temperature*

To understand the combined effects of increasing both the pressure and the initial temperature, Figs. 7 and 8 are plotted for the same conditions as Fig. 6, but for two different initial temperatures (200 °C and 400 °C). The same trends as shown in Fig. 6 are observed again, namely a significant dependence on pressure at low relative air ratio. An increase in the relative air ratio noticeably decreases this dependence. The same explanation stated in Section 3.2.3 applies also for this case. This time, however, the NO_x emission level is lower than 20 ppm (corrected to 15% O_2) at relative air ratios

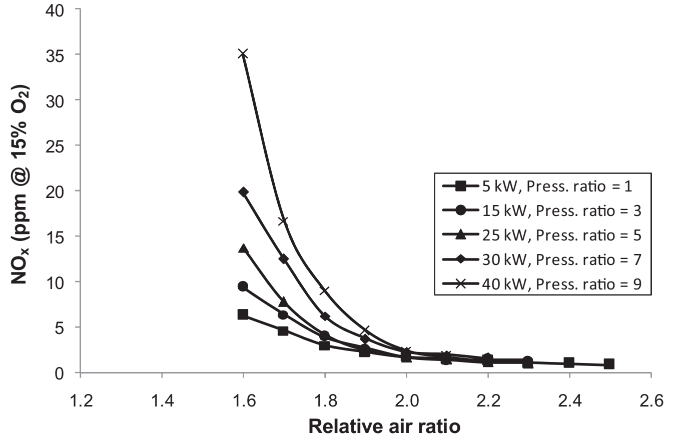

Fig. 7. NO_x emissions versus the relative air ratio at mixture inlet temperature of 200 °C for different pressure ratios with the same residence time.

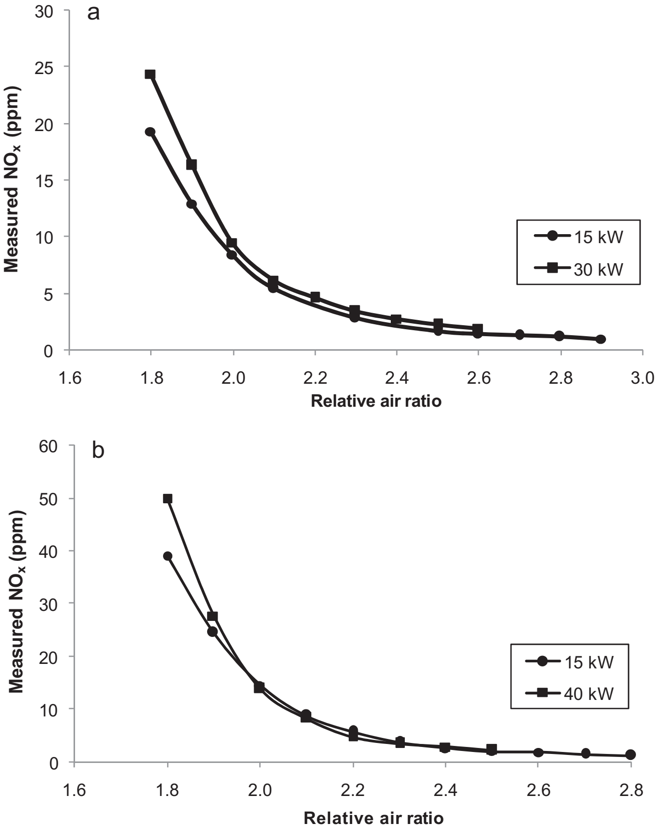

Fig. 9. NO_x emissions versus the relative air ratio at mixture inlet temperature of 400 °C for different power values: (a) pressure ratio 3 and (b) pressure ratio 5.

higher than 1.7 and 2. This corresponds to a preheating temperature of 200 and 400 °C, respectively. These NO_x emissions values, however, remain lower than the regulated value for stationary gas turbines application by 5 ppm [19].

The influence of the residence time on the NO_x formation was also examined in this study (Fig. 9). The NO_x levels for each pressure ratio at 400 °C for different powers are presented in Fig. 9a and b. The results confirm what stated in Section 3.2.2. First, the independence of NO_x formation from residence time can be clearly seen by the nearly overlaying NO_x curves, regardless of the burner power (mass flow rate). Second, the NO_x emission results measured throughout the operating relative air ratio range corresponding to each preheating temperature value showed comparable values to each other, almost independent of preheating temperature. The aforementioned observations emphasize the reliability and the wide stable dynamic modularity of this burner design, especially when increasing the preheating temperature. It would be advantageous to employ such a burner as a low emission pilot burner replacing the currently used diffusion flame burners in gas turbine applications.

4. Conclusions

In the present work, a new stability technique of combustion within a PIM based on the matching between the stream velocity and the flame speed was developed and examined experimentally. For the entire operating conditions applied in this work, zero CO emission value was obtained. The NO_x emission performance was remarkable compared with conventional PIM techniques under ambient conditions. Values less than 10 ppm were measured at a relative air ratio of 1.45. At constant initial temperature, the NO_x emissions depended significantly on pressure at low relative air ratios. This dependence decreased with increasing relative air ratio. At constant pressure and relative air ratio the NO_x emissions were significantly influenced by the initial temperature. Application of this new PIM combustion technique, with its outstanding low emissions performance, will assist in solving present and future issues of environmental pollutant emission regulations.

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