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NOVEL BURNER CONCEPT FOR PREMIXED SURFACE-STABILIZED COMBUSTION

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ABSTRACT

Surface-stabilized combustion is credited with high burning rates, extended lean flammability limits, wide modulation range and other advantages. This makes it an attractive technology for compact low-emission combustors.

The experimental gas turbine surface burners reported to this date are produced from compressed and sintered Fe-Cr-Al fiber mats. The authors have developed a new concept of surface burner fabricated by braiding ceramic cords around a ceramic frame. This simple method produces a basket-type surface suitable for stabilizing lean premixed flames over a broad range of operating conditions. The use of ceramics extends possibilities for operation at very high inlet temperatures with reduced risks of material sintering and oxidation.

This paper presents test results with an experimental burner on a pressurized combustion rig with optical access. The experiments were performed under the following conditions: inlet temperatures of 22-740 C, pressures of 1-3 bar, thermal power between 4 kWTh and 32 kWTh and equivalence ratios of 0.28-0.95. Measurements of flue gas composition and pressure drop are also reported in the paper. The operating window for low-NOx and low-CO combustion is analyzed.

With the demonstrated performance, the burner could cover the operating envelope of a 3 kWe recuperated micro turbine [1]-[2] with no pilot and no staging. This would also limit NOx to <40 ppm @ 0% O_2 within the micro turbine load range of 100% to 50%.

NOMENCLATURE

K	Ratio of mixture surface speed to laminar burning velocity, -
p	Pressure (absolute), bar
S_L	Premixed laminar burning velocity, m/s
T	Temperature, C
T_{ad}	Adiabatic flame temperature, C
V_{surf}	Combustible mixture speed through burner surface, m/s
ϕ	Fuel-to-air equivalence ratio, -
ω	Mass flow rate, g/s

Subscripts

comb	Combustion
in	Inlet

INTRODUCTION

Premixing (typically, fuel-lean) is a widely accepted approach for clean and low-NOx gas-phase combustion. Premixed flames can be stabilized: 1) aerodynamically in either reverse, stagnant or divergent flows; 2) within porous media; and 3) on surface patterns. Gas turbine combustors traditionally feature aerodynamically stabilized flames. Submerged combustion in both inert and catalytic porous media is used for infrared heating and gas cleaning. It has been also considered for gas turbines [3], yet so far remained primarily restricted to catalytic combustion: both in R&D [4] and very limited commercial application [5].

Surface-stabilized burners are widely used today for domestic boilers, radiating heaters, dryers, etc. One can distinguish burners with surface combustion realized over: 1) rigid porous plates (ceramic monoliths, perforated metal plates, etc.); and 2) fiber decks composed of compressed and sintered fibers, as well as prefabricated knitted and woven mats or cloths. Another distinction can be made for burners that combine surface combustion with Bunsen-type flames anchored by the adjacent surface combustion.

Surface fiber burners have been considered for gas turbine combustion since, at least, 1990s. Yet, the authors are aware of only very limited practical development in this respect: e.g., ALZETA Corp. has been reporting on prototype burners for gas turbine combustors based on perforated fiber mats [6]-[7]. Ramadan, et al. presented the development of Fe-Cr-Al wire-mesh burners at the Carlton University for supplementary firing in the exhaust of micro-turbine based CHP systems [8].

The surface fiber burners known to this date, including those proposed for gas turbines [6]-[8], are typically made from Fe-Cr-Al based alloys**.**

This paper presents a novel concept of a braided ceramic-cord burner developed under the specific criteria of:

- Design simplicity;
- Ease of fabrication; and
- Suitability for complete and low NOx combustion at very high inlet temperatures.

The primary application of this concept is foreseen for low-cost recuperated micro gas turbines. The experimental burner presented in the following sections of this paper is scaled for a 3 kWe micro turbine that is being developed by MTT [1]-[2]. Measurements and visual observations of the burner are reported under the conditions within the micro turbine's operating envelope.

The authors also envisage other applications – in gas turbines in general and beyond.

CONCEPT OF A BRAIDED BURNER FOR PREMIXED SURFACE-STABILIZED COMBUSTION

Today's aerodynamically stabilized low-NOx gas turbine burners incorporate achievements of decades-long dedicated developments in various disciplines with the investment of large resources. Commonly, very sophisticated flow systems with complex swirl generation, fuel injection, mixing and cooling devices are featured. These also require intensive aerodynamic tuning (numerical and experimental), advanced materials and fabrication methods. This is justified to ensure meeting the design and operating requirements. One of the particular challenges is to ensure complete, low-NOx and stable combustion with fuel-air premixing.

The transfer of low-NOx combustion technologies from the "mainstream" large-scale gas turbines into micro turbines would typically translate into prohibiting costs – related to both development costs and combustor cost-price. This particularly holds for the emerging very small gas turbines rated below 10 kWe. Herein, the challenges increase, at least, due to:

- A range of factors that may promote flashback and burner overheating:
    - o High temperature of the air inlet and, consequently, cooling flows in recuperated cycles;
    - o Higher surface-to-volume ratios;
    - o Operation without a qualified operator and under a high probability of blunder in the very attractive consumer applications (e.g. micro CHP, automotive, etc.); and
    - o Requirement for prompt modulation of the operating point;
- Low allowable pressure loss;
- The small scale that limits design choices by the applicability of conventional fabrication methods; and
- Low cost-price requirements.

Premixed surface burners present an interesting alternative to aerodynamic flame stabilization that can effectively address the challenges listed above. Both the popularity of this burner type in various appliances and the reported gas turbine experience [6]-[7] confirms: relative simplicity of manufacturing; low cost price potential; potential for complete and very low NOx combustion; durability; wide stability limits and resistance to flashback; wide range of modulation; low pressure drop; high burning rates; and straightforward scaling.

The authors have developed a new concept of surface burner fabricated by braiding a high-temperature ceramic fiber cord across a ceramic frame (see Figure 1).

The commonly accepted Fe-Cr-Al based fibers were not selected on the grounds of thermal resistance in small micro turbines, wherein the combination of a low compressor pressure ratio and exhaust-heat recuperation can translate into very high combustor inlet temperatures – e.g. above 700 C [1]-[2]. This leaves the margin of ~300 deg. with respect to the typical Fe-Cr-Al material limits of 1050-1100 C. With the expected flame temperatures of 1450-1650 C for both low NOx and CO, this margin will be very difficult to maintain, especially during modulation and transients. Besides, the authors are not aware of Fe-Cr-Al applications in premixed combustion above inlet temperatures of 455 C [7].

The method of braiding was selected as an alternative to knitted and woven fiber cloths. Braiding shapes the surface without tailoring any prefabricated material. Thereby, there are no material edges that require framing, fixing and other types of handling. This is particularly advantageous in the case of ceramics.

Furthermore, braided surfaces are very advantages for flame stabilization at high burning rates: The flow of combustible mixture naturally divides very uniformly over the surface. The cord readily sustains surface burning. The voids between the cord braids issue flow jets that produce Bunsen-type flames. Their stabilization is greatly enhanced by the adjacent surface combustion. In order to establish such a burning mode on sintered fiber burners, a surface perforation is required.

Besides, the voids can be seen through braided surfaces as curved flow channels of a variable cross section. The narrow sections help resist flashback. A braided burner also does not require a substrate surface.

EXPERIMENTAL BURNER

Several burner configurations were hand-fabricated for the experimental proof of concept. These included flat and undulating surfaces, as well as burners with frames made of either crossing and non-crossing arches. The latter burners featured the best surface pattern for flame stabilization. Therefore, only a burner of this configuration is described below.

The experimental burner is shown in operation in Figure 1. The burner frame is ceramic. It consists of an even number of U-arches and one half-U arch. The surface cord is the "Nextel^{TM} 440" fibers (70% of Al_2O_3, 28% of SiO_2, 2% of Ba_2O_3) interwoven together into as a "sleeve". The cord is of ~2 mm in diameter in a non-stretched state, while the fiber diameter is ~10-12µm. The recommended material application temperature is up to ~1400C, while the melting temperature is ~1800C.

The diameter of the burner is 30 mm at the frame base. The flame stabilization surface area is ~35 cm^2.

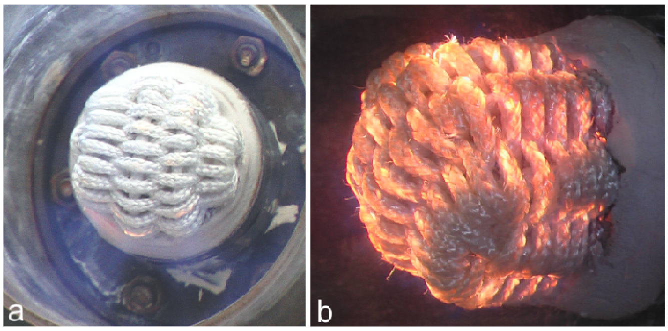

Figure 1: An experimental braided burner in operation: a) at fuel-lean condition; b) at nearly stoichiometric condition.

This burner was scaled for the operating conditions of the MTT 3 kWe recuperated micro gas turbine [1]-[2]. The thermal input in the micro turbine is up to 30 kWTh during thermal ramp-up, 18-20 kWTh at base load and 10-12 kWTh at 50% load. The inlet air temperature ranges between 720 C at the base load and 20 C at cold-recuperator start-up. The pressure range is between 3 bar at base load and ~1.15 bar at start-up.

EXPERIMENTAL SETUP

MTT and TU Eindhoven have jointly developed a micro turbine combustion test rig, which has been used in the MTT development program since 2009. The braided burner in Figure 1 was tested on this test rig (see Figure 2).

The burner was installed inside a quartz tube of 90 mm in diameter, which is representative of a can-type liner (Figure 2). This assembly was placed inside an oversized pressurized cell. The cell has two quartz-glass windows: for a side view and a front view of the burner.

The air supply was divided between the burner (combustion) and dilution air. Pure methane was supplied as the fuel through a custom-designed injector. The injector was succeeded by a mixing volume of ~50cm^3.

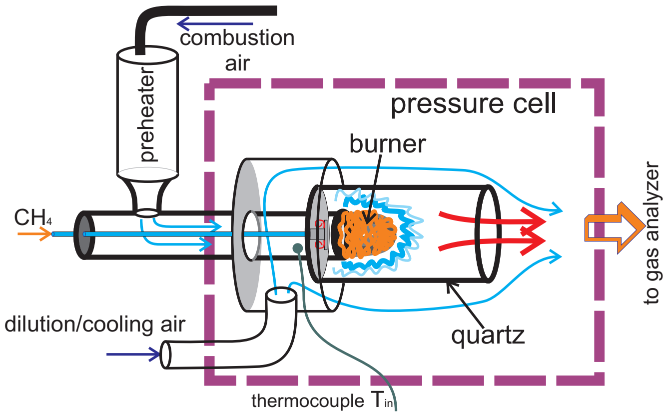

Figure 2: Experimental setup.

All flows on the test rig are controlled by Bronkhorst mass flow controllers with an accuracy of 1-2 %. The combustion air is preheated by a SUREHEAT® MAX HT unit with a maximum temperature capability up to 900 C. The air temperature is measured within ±10K by a thermocouple closely upstream the fuel injector.

The system pressure is measured in the pressurized cell by a transducer. The measurement signal is used to manually control pressure via a throttling valve in the exhaust duct. The exhaust flow composition is measured with an automotive "AREX" analyzer. The mole fractions of CO, UHC, O_2, CO_2 and NOx, are measured. In testing at the lowest NOx and CO, the measurement limits of the AREX analyzer (~±1-2 ppm @ actual O_2) were approached. Due to this, the measurement accuracy of CO, UHC and NOx in these regimes is not higher than 20-30%.

The following operating conditions were established in the measurements: 1) combustion air temperatures between 22 C and 740 C; 2) pressures between 1.01 and 3 bar (absolute); 3) combustion air flows and equivalence ratios of 3-20 g/s and 0.28-0.95 respectively. The latter corresponds to thermal inputs between ~4 kWTh and ~32 kWTh.

A snapshot of the experimental points and conditions is given in Figure 3: Each point is marked by a red circle. It corresponds to the inlet temperature and pressure on the T-p plane, as well as ranges of mass flow and equivalence ratio indicated below and to the right of the T-p plane respectively.

Figure 3 also relates the experimental points to the operating envelope of the MTT micro turbine. The five and four-pointed stars correspond to the base load and 50% load respectively. The dashed line shows the ramp-up of the micro turbine.

One may see that the experimental points were selected as to fully cover the operating envelope of the micro gas turbine.

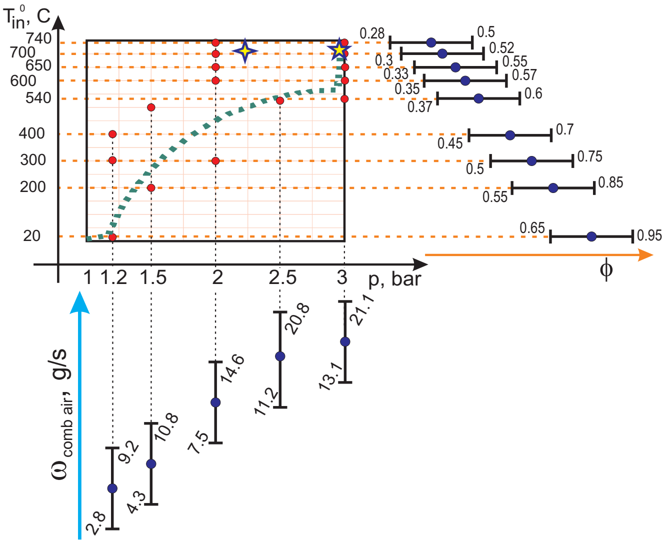

Figure 3: Experimental points (red circles) and conditions: inlet temperature, pressure, mass flow and equivalence ratio. Relation to micro turbine operating points: ★ - base load; ✦ - 50% load; - - - ramp-up.

EXPERIMENTAL RESULTS

Pressure drop over the burner surface

The burner pressure drop is a key design parameter and an important performance characteristic. At this stage, there are no methods to predict the pressure drop of the braided burner. Many factors – surface area, material and thickness of the frame and cord, braiding density pattern and patter, etc. etc. – affect the resulting pressure drop.

Pressure drop measurements were carried out on a separate setup at the inlet temperature of 20 C only, both with and without combustion. The effect of combustion was negligible. Results are shown in Figure 4 versus the dynamic head evaluated on the basis of cold flow at the burner inner surface.

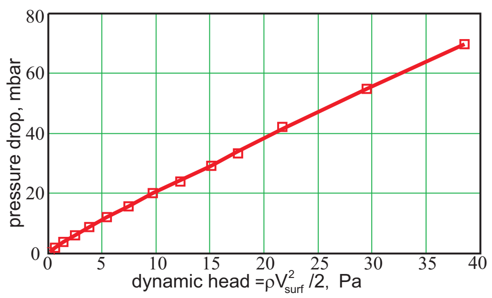

Figure 4: Non-reacting flow pressure drop over the burner surface versus dynamic head at T_{in}=20 C.

A virtually linear relation was measured between the surface pressure drop and dynamic head. The relation corresponds to a hydraulic resistance coefficient of ~200 [mbar/mbar].

Thermal input

Figure 5 provides another snapshot of experimental points (differences in marker type and color should be neglected – related to the authors' post-processing decision). Each point is characterized by the burner thermal input versus air flow rate, pressure and inlet temperature.

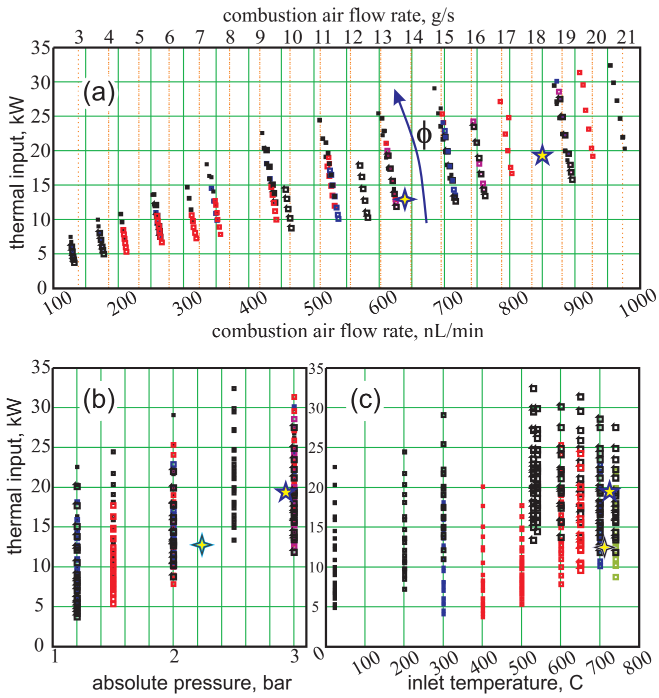

Figure 5: Burner thermal input versus: a) combustion air flow rate (ω); b) pressure (p); and c) inlet temperature (T_{in}). Relation between ω, p, T_{in} and ϕ is given in Figure 3. Relation to micro turbine operating points: ★ - base load; ✦ - 50% load.

Flame stabilization

At low mixture speeds through the burner surface, the heat transfer from the flame to the burner is significant and leads to the heating of the surface. This combustion mode is sometimes referred to as "radiant". At high mixture speeds, the flame detaches from the surface which can lead to a blow-off. The optimal operating mode lies between these two extremities. Therein, the braided burner operation is characterized by Bunsen-type flames stabilized on the cord braids. The stabilization is additionally facilitated by burning on the cord surface.

It can be shown that the modes of burner operation and flame stabilization can be best parameterized by the ratio of the mixture surface speed to the laminar burning velocity ($K=V_{surf}/S_L$). The K ratio derived for the experimental points shown in Figure 5 is plotted versus inlet temperature in Figure 6. Herein, S_L is evaluated by the well known correlations in [9].

The exact K values corresponding to various burning modes will always depend on the particular surface (braiding) pattern, surface configuration, cord type, etc. For the experimental burner considered in this paper (Figure 1) the K ratio could be varied between 2 and 20.

Visual observations showed that the radiant mode was established at K ~ 2-3. The flames start to detach from the surface at K>10-12. The optimal range of K was found between ~3 and ~10.

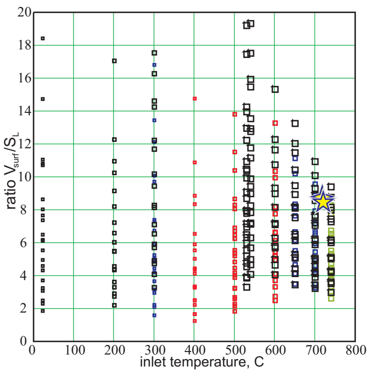

Figure 6: Ratio of mixture surface speed to laminar burning velocity versus inlet temperature. Experimental conditions are given in Figure 3. Relation to micro turbine operating points: ★ - base load; ✦ - 50% load.

Emissions

Figure 7 presents measured NOx and combined (CO+UHC) mole fractions versus adiabatic flame temperature. The measurements are scaled to 0% O_2 (as common for domestic boilers and can be used for micro turbines for domestic CHP).

The emission measurements show a very strong flame temperature dependence. The rates of CO and UHC oxidation are generally strongly temperature-dependent. As per NOx: within the range of experimental conditions, the likely dominant NOx formation pathway is the thermal (Zel'dovich) mechanism. Variations in the measurement results at each given flame temperature can be related to variations in the residence time (via varying pressure and flow rates), as the next significant governing factor. Other factors are O_2 and OH availability at varying equivalent ratio and other secondary effects.

If one would adopt emission limits depending on the application of the burner, Figure 7 will help selecting the flame temperature range for both low NOx and products of incomplete combustion (CO+UHC). For example, the T_{ad} range between 1425 C and 1625 C corresponds to NOx between ~ 0 ppm and 40 ppm and (CO+UHC) between 100 ppm and ~0 ppm respectively.

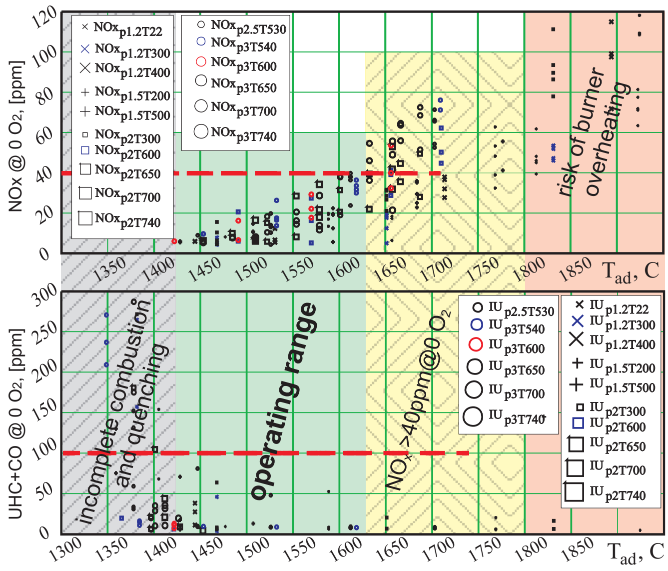

Figure 7: NO_x and combined (CO+UHC) mole fractions versus adiabatic flame temperature. T_{in} and p are given in the legends: p1-p3 – 1-3 bar; and T22-T740 – 22-740 C. Relation between ω, p, T_{in} and ϕ is given in Figure 3.

At lower flame temperatures, combustion completeness starts to reduce rapidly. Higher flame temperatures can still be accepted, should the NOx limit be relaxed. Yet, the risk of burner overheating increases with an increase in T_{ad}, particularly when accompanied by an increase in T_{in}. In the experiments, T_{ad} > 1900 C were also allowed at low inlet temperatures, as shown in Figure 8.

Figure 8 also explicitly shows that NOx < 40 ppm and (CO+UHC) > 100 ppm could be maintained within a very broad range of inlet temperatures: from 22 C up to 740 C. The corresponding equivalence ratios are shown in Figure 9.

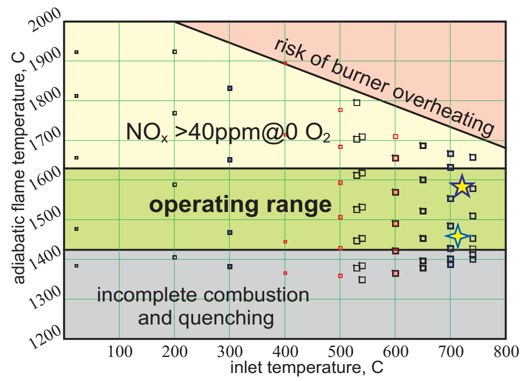

Figure 8: Experimental points on the plane of adiabatic flame temperature – inlet temperature. Relation between ω, p, T_{in} and ϕ is given in Figure 3. Relation to micro turbine operating points: ★ - base load; ✦ - 50% load.

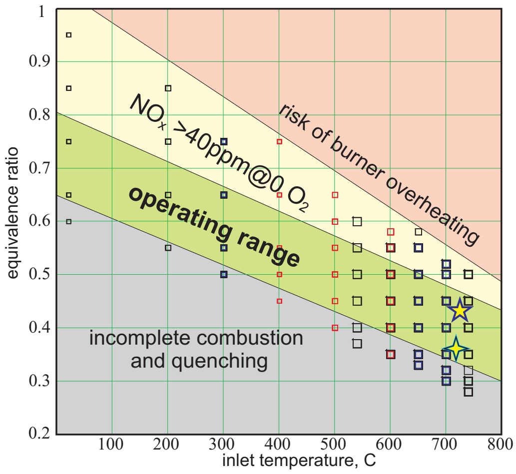

Figure 9: Experimental points on the plane of equivalence ratio – inlet temperature. Relation between ω, p, T_{in} and ϕ is given in Figure 3. Relation to micro turbine operating points: ★ - base load; ✦ - 50% load.

MICRO TURBINE APPLICATION POTENTIAL

The experimental burner has permitted a very broad modulation of operating parameters. Complete and stable combustion without hardware overheating was maintained within (Figure 5-Figure 9):

- The pressure range of 1 bar to 3 bar;
- Inlet temperature range of 22 C to 740 C;
- Adiabatic flame temperatures between 1425 C and 1800 C; and
- Thermal power range between 4 kWTh and 32 kWTh.

Apart from the proof of concept, this demonstrates a high application potential for recuperated micro turbines. With the demonstrated performance, the burner could cover the operating envelope of the MTT 3 kWe micro turbine [1]-[2] with no pilot and no staging, including (Figure 3, Figure 5):

- Cold light-off at nearly atmospheric pressures and inlet temperatures;
- Ramp-up with:
    - A reduction in the equivalence ratio and increase in the inlet temperature corresponding to the recuperator heat-up; and
    - Increase in the air flow rate and pressure corresponding to the turbomachinery characteristics;
- Base-load at T_{in} ~ 725 C, p ~ 3 bar; and
- 50% load at T_{in} > 700 C, p > 2 bar, which corresponds to modulation at constant recuperator gas-side inlet temperature.

In addition to this, such a single burner would limit NOx to <40 ppm @ 0% O_2 within the micro turbine load range of 100% to 50% (Figure 7-Figure 9). This is a common limit for domestic boilers, which is relevant for micro CHP applications. At 15% O_2, as commonly expressed in the gas turbine community, this corresponds to ~ 11 ppm.

No specific pressure loss requirement was taken into account in the fabrication of the experimental burner. Extrapolation of the cold-inlet pressure loss measurements (Figure 4) onto the MTT base load operating point, translates into a burner pressure loss of ~60 mbar or ~ 2%. For such a low pressure-ratio micro turbine, this is high. Therefore, the burner – particularly the surface and braiding pattern – requires further optimization.

Such issues as structural mechanics and life of the braided burner have not yet been investigated. In general, the use of a flexible cord is advantages for managing thermal stresses. By now, several braided burners were tested without failures. The burner presented in the paper has clocked few tens of hours, including operation in the radiant mode and frequent starts-stops. The burner surface did not show any visible indications of deterioration. Yet, this time is surely very short to draw any conclusions on life.

Besides, the authors acknowledge that the novel concept proposes new structural solutions and materials for gas turbine combustors. The authors are also aware that the use of ceramics in gas turbines has been long associated with uncertainties, lack of experience and a requirement for more R&D [10].

CONCLUSIONS

- A new concept was developed for a surface burner fabricated by braiding ceramic cords around a ceramic frame.
- An experimental burner has clocked few tens of hours on a combustion test rig. It has demonstrated complete and stable combustion without hardware overheating within a broad range of operating conditions: a) 1-3 bar; b) T_{in} = 22-740 C; c) ϕ = 0.28-0.95; d) T_{ad} = 1425-1800 C; and e) 4-32 kWTh.
- Combustion was stabilized within the range of mixture surface speed to laminar burning velocity ratio (K) of 2-20. A combination of attached Bunsen-type flames and surface burning was established at K = 3-10.
- When corrected to 0% O_2, NOx of 0-40 ppm and (CO+UHC) of 100-0 ppm were produced in the range of T_{ad} = 1425-1625 C at 1-3 bar.
- The braided concept is an interesting technology candidate for low-emission, low-cost gas turbine combustors.
- The experimental burner has been tested at points covering the operating envelope of a 3 kWe recuperated micro turbine [1]-[2].
- The single burner without a pilot and staging could cover the points corresponding to cold light-off, ramp-up, base load and 50% load. Complete and stable combustion was maintained.
- The same single burner would also limit NOx production to <40 ppm @ 0% O_2 at conditions similar to the micro turbine base load and 50% load.

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