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CFD Based Improvement of the DLN Hydrogen Micromix Combustion Technology at Increased Energy Densities

Anis Haj Ayed[a]*, Karsten Kusterer[b], Harald H-W. Funke[c], Jan Keinz[d]

[a,b]*B&B-AGEMA GmbH, Juelicher Strasse 338, 52070 Aachen, Germany*
[c,d]*FH Aachen University of Applied Sciences, Hohenstaufenallee 6, Aachen, 52064, Germany*

Abstract

Combined with the use of renewable energy sources for its production, Hydrogen represents a possible alternative gas turbine fuel within future low emission power generation. Due to the large difference in the physical properties of Hydrogen compared to other fuels such as natural gas, well established gas turbine combustion systems cannot be directly applied for Dry Low NOx (DLN) Hydrogen combustion. Thus, the development of DLN combustion technologies is an essential and challenging task for the future of Hydrogen fuelled gas turbines. The DLN Micromix combustion principle for hydrogen fuel has been developed to significantly reduce NOx-emissions. This combustion principle is based on cross-flow mixing of air and gaseous hydrogen which reacts in multiple miniaturized diffusion-type flames. The major advantages of this combustion principle are the inherent safety against flash-back and the low NOx-emissions due to a very short residence time of reactants in the flame region of the micro-flames. The Micromix Combustion technology has been already proven experimentally and numerically for pure Hydrogen fuel operation at different energy density levels. The aim of the present study is to analyze the influence of different geometry parameter variations on the flame structure and the NOx emission and to identify the most relevant design parameters, aiming to provide a physical understanding of the Micromix flame sensitivity to the burner design and identify further optimization potential of this innovative combustion technology while increasing its energy density and making it mature enough for real gas turbine application. The study reveals great optimization potential of the Micromix Combustion technology with respect to the DLN characteristics and gives insight into the impact of geometry modifications on flame structure and NOx emission. This allows to further increase the energy density of the Micromix burners and to integrate this technology in industrial gas turbines.

Keywords: Micromix Combustion; Hydrogen Gas Turbine; DLN combustion; Hydrogen Combustion; High Hydrogen Combustion.

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* Corresponding author.

1. Introduction

Aviation and power generation industry has need of efficient, reliable, safe and low-pollution energy conversion systems in the future. Gas turbines will play a decisive role in long-term high power application scenarios, and hydrogen has great potential as renewable and sustainable energy source derived from wind- or solar power and gasification of biomass substituting the limited resources of fossil fuels [1]. Hydrogen impacts the operation of common gas turbine systems due to its high reactivity requiring combustion chamber modifications to guarantee efficient, stable, safe and low NOx combustion. Besides optimized combustion technology and related exhaust gas emissions, modifications of the gas turbine control and fuel metering system have to be applied to guarantee safe, rapid and precise changes of the engine power settings [2,3,4,5,6,7]. Against this background the Gas Turbine Section of the Department of Aerospace Engineering at Aachen University of Applied Sciences (AcUAS) and B&B-AGEMA GmbH work in the research field of low-emission combustion chamber technologies for hydrogen gas turbines and related topics investigating the complete system integration of combustion chamber, fuel system, engine control software and emission reduction technologies. The hydrogen gas turbine research at AcUAS started during the European projects EQHHPP [8] and CRYOPLANE [9] where the low NOx Micromix Hydrogen combustion principle was invented. When hydrogen is burned as fuel with air, only NOx emissions occur, but [2,3,10,11] have shown that the combustion process has to be modified and optimized in order to achieve low NOx emissions. Because of the large difference in the physical properties of hydrogen compared to other fuels such as kerosene and natural gas, well established gas turbine combustion systems cannot be directly applied for Dry-Low-NOx (DLN) combustion. Thus, the development of DLN hydrogen combustion technologies is an essential and challenging task. The DLN Micromix combustion principle for hydrogen is being developed and optimized for years to significantly reduce NOx-emissions by miniaturizing the combustion zone, reducing the residence time of reactants in the combustion zone, and enhancing the mixing process using a jet in cross-flow design. A review of the previous research activities at AcUAS is presented in [12].

Especially the flame anchoring - mostly dominated by the resulting recirculation zones and vortices within the Micromix burner geometry [10] and by the momentum flux ratio of the jet in cross-flow [11] - is most essential to the Micromix low NOx characteristics. Based on previous investigations a Micromix combustion chamber with about 1600 miniature injectors (Figure 1) was designed for a small size Auxiliary Power Unit APU GTCP 36-300 and successfully tested [13].

The GTCP 36-300 requires about 1.6 MW thermal energy converted to shaft power generating electrical and pneumatic power up to 335 kW. The combustion section consists of an annular reverse flow combustion chamber in which the Micromix combustor is to be integrated.

The Micromix hydrogen combustion research is done using an interactive optimization cycle including experimental and numerical studies on test burners, full scale combustion chamber investigations and the feasibility is proven in real gas turbine operation (Figure 2).

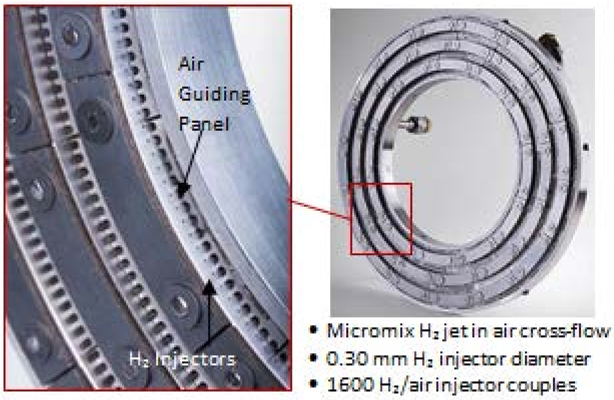

Figure 1: Micromix Prototype Combustor for Gas Turbine Honeywell/Garrett Auxiliary Power Unit APU GTCP 36-300

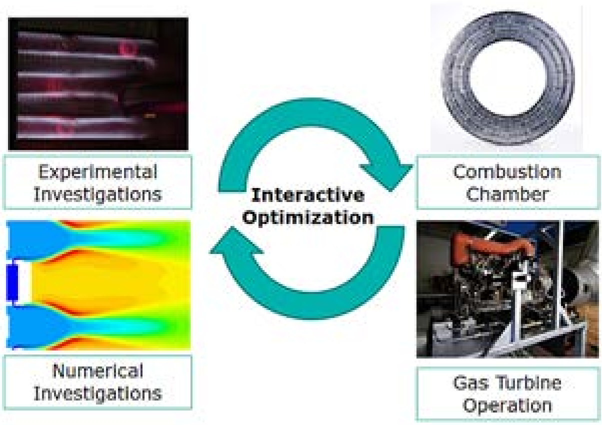

Figure 2: Interactive optimization cycle of Micromix combustor research and development for APU GTCP 36-300

Based on these studies the impact of different geometric parameters on flow field, flame structure and NOx formation are identified and the Micromix combustion principle is continuously optimized.

Within previous studies the influence of combustion modeling and burner design parameters on flow field, temperature distribution and flame structure has been studied for a low energy density burner configuration having a fuel injector diameter of 0.3 mm [14,15]. The study discussed in [15] has shown potential to reduce NOx emission of the burner by controlling lateral cool air flows around the flame, which are established at given geometric parameters. The findings of [15] have been applied to design a high energy density burner with an injector diameter of 1mm (increasing the heat rate per injector by more than 11 times). This burner has been analyzed numerically and experimentally in [16] and has proven low NOx ability at increased energy density.

Within the present study, the impact of further geometric parameter variations of the high energy density Micromix burner (1mm injector diameter) on its flame structure and NO emission is studied numerically in order to reveal possible further optimization potential. The main driver of this study is the fact, that the high energy density of the burners leads to thicker and longer flames that need to be optimized in shape and position to minimize their NOx emissions. Thereby, a variation of the burner head geometry is performed within a geometrically feasible range. 3D CFD simulations of the reacting flow have been performed for the different Micromix burner variations in order to evaluate the resulting flow field, flame structure and NO emissions and understand the influence of the single parametric variations on the complex reactive flow field of the Micromix burner. The observations resulting from this study will reveal optimization potentials of the Micromix combustion technology in terms of NO emissions, especially with regards to increased energy densities.

2. Micromix Hydrogen Combustion

2.1. Micromix Description

Gaseous Hydrogen is injected through miniaturized injectors perpendicularly into an air cross-flow through small air guiding panel (AGP) structures. This leads to a fast and intense mixing, which takes place simultaneously to the combustion process. As a result, miniaturized micro flames develop and anchor at the burner segment edge downstream of the injector nozzle. Multiple micro flames instead of large scale flames lower the residence time of the NOx forming reactants and consequently the averaged molar fraction of NOx can be reduced significantly as has been shown in [6]. The main influence on the low NOx characteristic can be ascribed to the key design parameters blockage ratio BR of the air guiding panel AGP (Figure 3) and injection depth y of the fuel into the oxidizer cross-flow (Figure 3b). The blockage ratio BR is represents the ratio between the air guiding height and the height of the air guiding panel (AGP) (both indicated in Figure 3).

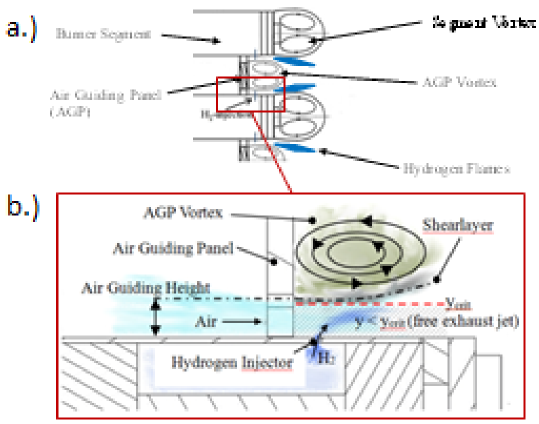

Figure 3: (a) Aerodynamic flame stabilization principle, (b) Hydrogen injection depth definition

The blockage ratio influences shape, position and size of the flame stabilizing vortices downstream of the air guiding panel and the burner segment. The jet-in-cross-flow mixing of fuel and air stabilizes the low NOx emission characteristics of the combustion principle as long as the injection depth y (Figure 3b) is not penetrating the shear layer of the AGP-Vortex (critical injection depth ycrit). A recirculation of the fuel/air mixture into the AGP vortex leads to raised NOx emissions [13].

Within the present study, the air guiding height is kept constant and the height of the air guiding panel is varied, as will be explained in section 3. The injection depth y is kept constant.

2.2. Test Burner Configuration for Numerical Study

The presented numerical study investigates the computational model of the atmospheric test burner with a Hydrogen injector diameter of dH2 =1mm, which has been presented by the authors in [16]. This burner configuration was established by increasing the energy density per fuel injector to more than 11 times, compared to the first developed Micromix burners with an injector size of 0.3 mm, that have been investigated by the authors in [15].

Experimental tests and numerical analyses have been performed for the burner in question at different equivalence ratios and are explained in [16]. Thereby, the Micromix flames were found very stable and well in accordance with the typical Micromix structure, despite of the increased energy density. Figure 4 shows the experimentally observed flame structure at an equivalence ratio of 0.4 (design point).

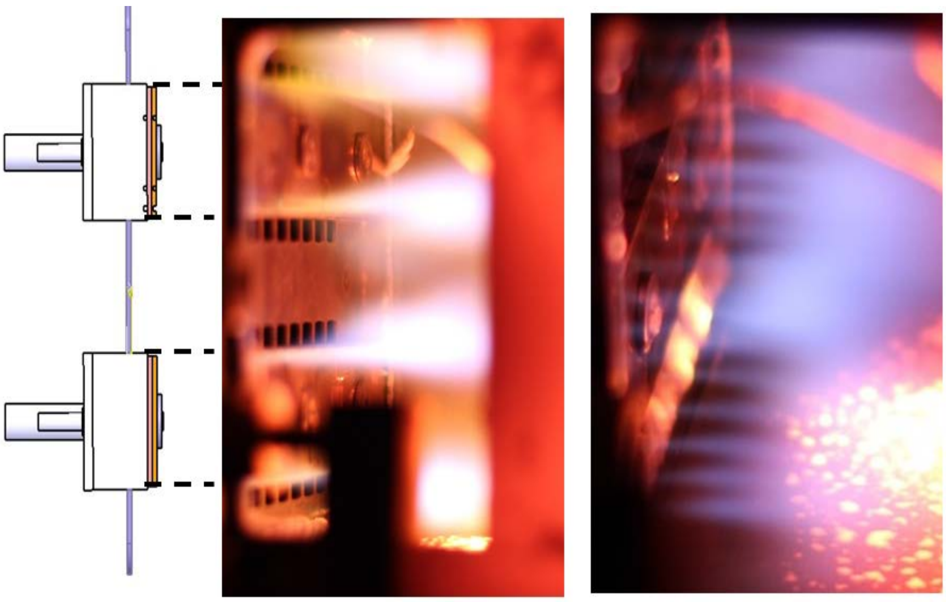

Figure 4: Optical flame appearance of established Micromix flamelets at design point $\Phi = 0.40$ – 1mm injector burner [16]

The corrected NOx emissions (@ 15% O2) obtained experimentally and numerically are given against the equivalence ratio in Figure 5. At the design equivalence ratio of □ = 0.4 the NOx en approx. 2 and calculated to approx. 1.4 ppmv @ 15% O2, which proves the low NOx ability of the Micromix test burner [16].

This burner is considered as reference case within the present study.

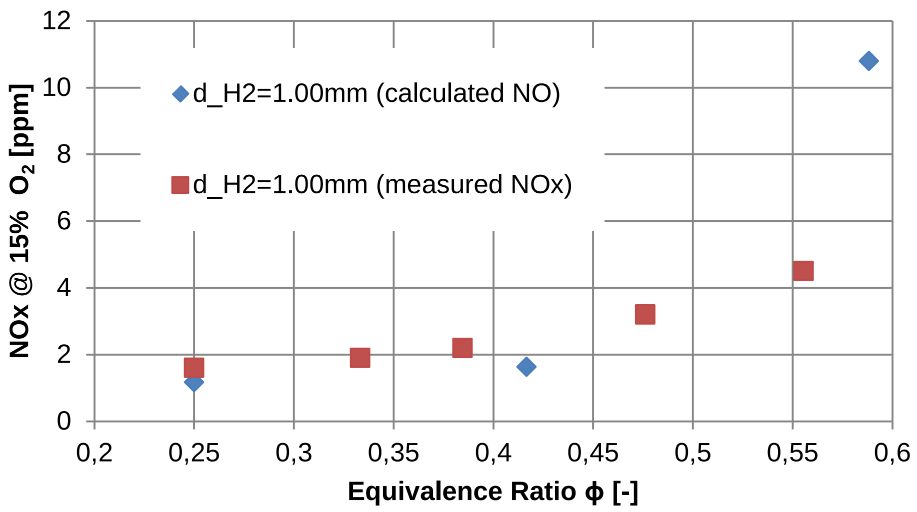

Figure 5: Measured and calculated NOx/NO emissions at different equivalence ratios for the 1mm injector burner [16]

3. Parametric Study & Numerical Exploration

3.1. Simulation Approach

For the numerical simulation of the different burner variations a simplified numerical approach is applied. It uses the 3D numerical simulation of the flow field within the test-burner based on a RANS solver, reduced combustion reaction mechanism and thermal NO formation models to analyze flow-field-structures, temperature distribution, tendencies of flame-anchoring, flame-structure and emission behavior. In this section of the paper, the simplified numerical approach is described, and its application to calculate the reactive flow in the burners is presented. The aim of the numerical analysis is to understand the basic flow phenomena and qualitatively identify tendencies of the different design parameter influences with respect to flow- and flame-structure, and resulting thermal NO emissions. The emission calculation includes only thermal NO, because it is a good and fast indicator of the burner configuration emission behavior and very useful for the numerical prediction of the test-burner emission characteristics prior to testing. Therefore, the calculated NO emissions are expected to be generally slightly below the real values, but provide an excellent qualitative evaluation possibility for the intended numerical design exploration of the high energy density Micromix combustion technology.

3.2. Computational Domain

The numerical analysis has been carried out using a commercial CFD code [17] and has been based on simplified geometric models derived from the different burner configurations to be investigated. The geometric model is shown in Figure 6 and covers a longitudinal burner slice, which makes use of the symmetric nature of the burner in both lateral and vertical directions. The symmetric boundaries along the lateral direction are set on the cross section through the center of one hydrogen injection hole and on the cross section between two hydrogen injection holes, respectively. Along the vertical direction the symmetry planes are set on the center section through one air guiding panel and on the center section through one hydrogen segment. Thus, the slice model contains one half of a hydrogen injection hole and one half of an air guiding gate.

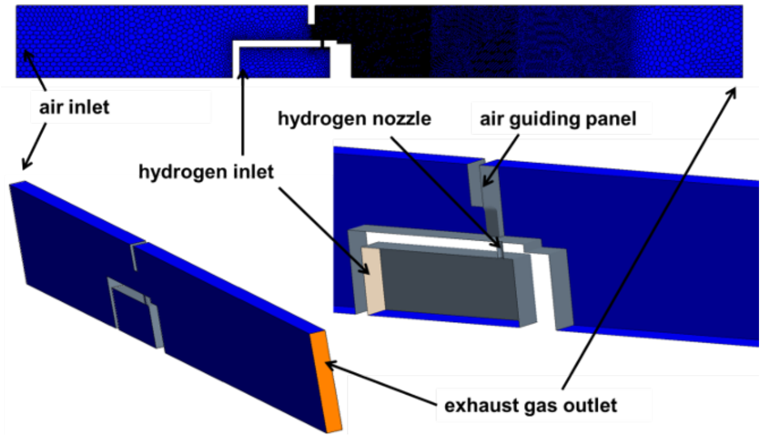

Figure 6: Computational Domain

3D steady RANS calculations have been performed. The realizable k,ε turbulence model with all y+ wall treatment has been applied. The wall treatment is decided depending on the local dimensionless wall distance y+ values. For high y+ values the wall function approach is used. For low y+ values (below or not much larger than 1) no wall function is required, since the boundary layer is well discretized by the numerical mesh. The hydrogen combustion process has been simulated based on a reduced hydrogen combustion reaction model including one step hydrogen combustion reaction, where the reaction rate has been calculated by the hybrid EBU combustion model described in [11]. This model combines the turbulent mixing driven reaction rate and the chemical kinetic reaction rate (finite chemistry). The turbulent mixing driven reaction rate is calculated via the EBU (Eddy Break Up) combustion model formulation, which assumes that reactants are directly burnt after mixing. The chemical kinetic rate is calculated based on the Arrhenius formulation and considers the chemical time scale needed to burn reactants when they are fully mixed. By application of the hybrid EBU approach both reaction rates (turbulent mixing driven rate and chemical kinetic rate) are calculated and compared. The smallest rate is assumed as reaction limiting.

By applying the reduced hydrogen combustion reaction model the calculation time is reduced significantly to 4 days per case and large number of parameter variations can be achieved within a reasonable numerical effort. If detailed hydrogen combustion reaction mechanism was considered, the calculation time would exceed several weeks for the used calculation mesh. The application of the reduced hydrogen combustion reaction model reduced combustion model is found reasonable and sufficiently accurate in quality and quantity as has been found in [16], especially in terms of predicted NOx emissions. Figure 5 shows measured and calculated NOx emissions for the high energy density burner with an injector diameter of 1mm. The calculated values are based on the reduced hydrogen combustion reaction model and show good agreement with the measured values.

Thermal NO formation has been considered by application of the extended Zeldovich NO formation mechanism. A corresponding numerical model is provided by the applied CFD code. Its activation adds NO to the transported species within the solution domain. This allows the evaluation of NO distribution within the reaction zone and the full hot gas path as well as the evaluation of NO concentrations at the burner outlet boundary (calculate the NO emission).

The spatial discretization has been performed using the STAR-CCM+ surface re-mesher and polyhedral mesher resulting in an unstructured polyhedral mesh. The polyhedral cell shape is especially advantageous as it helps minimizing the total number of cells while maintaining mesh resolution quality and thus, helps saving calculation time and cost. Progressive mesh refinement has been performed along the reaction and hot gas zone starting from the hydrogen injection surrounding. There the smallest volume cell size has been selected to get a sufficient resolution inside the mixing and the reaction zone. The refinement process has been performed iteratively within a reference calculation until a mesh independent solution could be obtained. The final mesh includes approx. 900,000 volume cells in total.

3.3. Boundary Conditions

The fuel and the air jet are introduced separately into the burner model via two inlet boundaries as shown in Figure 7. The inlet boundaries are set far enough from the air guiding panel and the fuel injection hole in order to avoid any boundary influence on the key flow phenomena in the mixing and combustion regions. No-slip wall boundaries represent the air guiding panel and the hydrogen segment walls.

Since contact with hot gas is limited to the front surface of the H2 segment and the surfaces surrounding the reaction and exhaust gas zone are symmetry planes, heat transfer from the hot gas into the burner wall has been neglected and has not been considered within the numerical simulations for all burner configurations.

The air and fuel inlet parameters have been defined according to the experimental conditions for the test burner configuration. The air inlet pressure is 1 bar according to the test rig design. The inlet air is preheated to 560 K to simulate the APU inlet condition. The fuel inlet temperature is 300 K.

The fuel mass flow has been selected according to the design operating point ($\Phi = 0.4$).

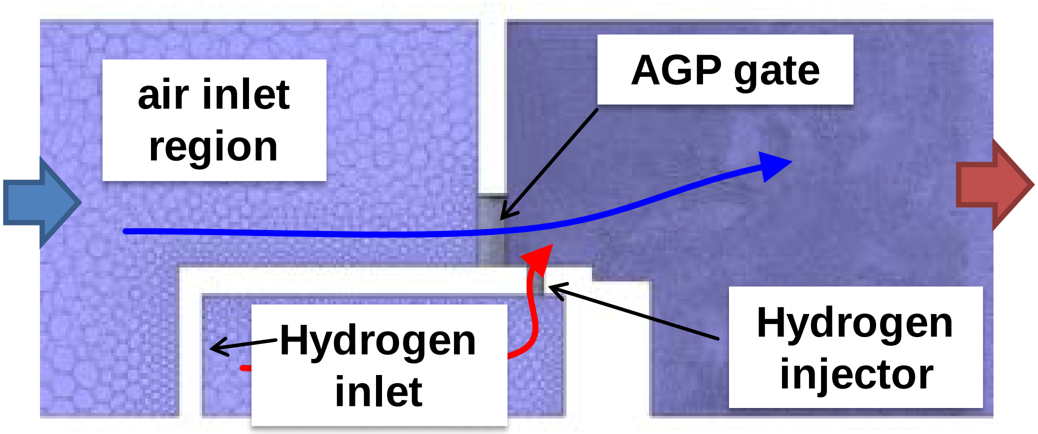

Figure 7: Computational Domain, Close up to fuel injection region

3.4. Numerical Results & Parametric Study

The Micromix burning principle is characterized by distinct reaction zones, anchoring near the edge of the H2 segment and stabilized by the inner and the outer vortex pairs as shown in Figure 8. The inner vortex pair results from the air recirculation downstream the air guiding panel after contraction in the air gate. The outer vortex pair is created by recirculating hot gas downstream the H2 segment. Due to the axial shift in the position of the H2 segment front face and the air guiding panel, an inclined shear layer is established in-between the vortices and combustion reaction takes place and is stabilized along this inter-vortex shear layer.

The structure and orientation of the Micromix flame is depending on the structure of the mentioned shear layer, which is in turn defined by the size, position and intensity of the stabilization vortices.

Figure 9 shows the calculated temperature distribution (bottom part) and the calculated thermal NO mass fraction (top part) in the reference Micromix burner (reference geometry). The Micromix flames are clearly separated from each other and well anchored and stabilized according to the Micromix burning principle.

Looking to the temperature distribution, two peak temperature regions can be distinguished. The first is found along the first flame fragment, which is stabilized in-between the inner and outer recirculation vortices along the inter-vortex shear layer. This zone is thin, but shows a significant temperature gradient across the flame, which is typical for this kind of flames.

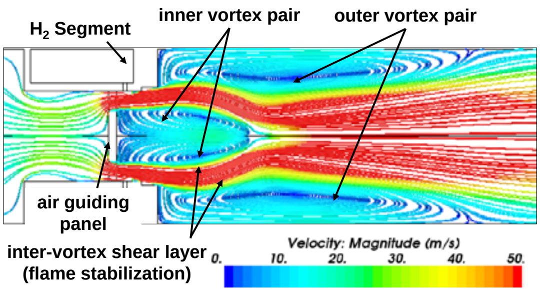

Figure 8: Typical recirculation and vortex structure of the Micromix burning principle

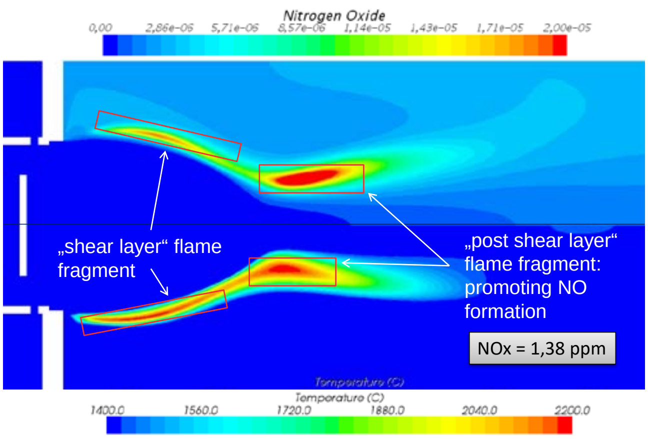

Figure 9: Calculated temperature (bottom) and NO mass fraction (top) distributions for the reference burner (with straight burner head)

The second peak temperature zone is found downstream of the inter-vortex shear layer (as marked in Figure 9). Here, the remaining fuel that was not burnt along the first flame fragment starts to burn and the last heat release of the injected fuel takes place. In this zone, a higher peak temperature is found and the high temperature zone is found thicker than the first fragment, indicating a concentration of heat release.

This flame structure is not typical for the Micromix burning principle, which aims to burn all the injected fuel along the thin inter-vortex shear layer and thus, avoid high fuel concentrations, high temperature peaks and thus, reduce NOx emissions.

This new flame structure is due to the increased energy density of the considered burner (note that the injector size of the burner in question is 1mm, which leads to an 11 times higher energy density compared to the originally invented burner, having an injector size of 0.3 mm). Since the overall burner dimensions are not scaled with the same factor as the injectors (due to combustor integration issues), the length of the inter-vortex shear layer becomes not sufficient to accomplish all the heat release (or to accommodate the whole flame). The fuel that could not be burnt along the shear layer starts to burn further downstream, building the aforementioned second flame fragment.

The calculated NO mass fraction for the reference burner (shown in the top part of Figure 9) reflects the flame structure pretty well and clearly shows two distinct high NO zones: inside the first flame fragment and inside the second flame fragment. Thereby, a clear NO mass fraction peak and concentration is found in the second flame fragment. This means that the new flame structure, which is dividing the flame into a “shear layer” and a “post shear layer” part, has a negative influence on the NOx emission level of the burner. It is expected to reduce the burner’s NOx emissions by reducing the extent of the “post shear layer” part of the flame. This could be achieved by increasing the shear layer length, so that more heat release can take place within the thin “shear layer” part of the flame. A possible measure to achieve this is to modify the burner head geometry by introducing a stepped contour downstream of the Hydrogen injectors as shown in figure 10. This aims to pull the cold recirculation (inner vortex) and the fuel/air mixture jet down and thus increase the size of the inner vortex. This would increase the length of the inter-vortex shear layer and could reduce the “post shear layer” flame fragment.

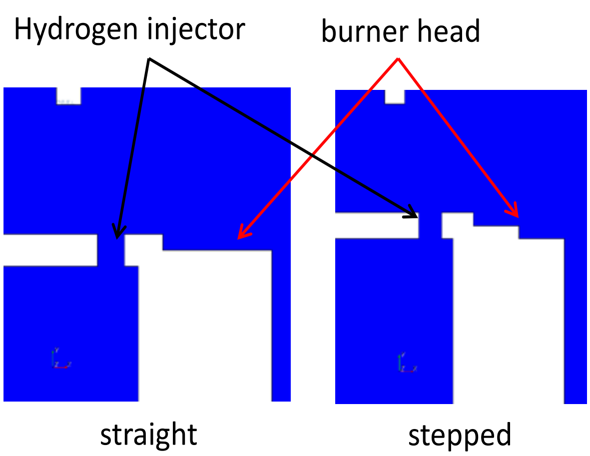

Figure 10: Variation of the burner head geometry: straight, ramped and stepped

Figure 11 shows the calculated temperature distribution for two different stepped burner head configurations in comparison with the baseline configuration (straight).

Following the increase of the step height, the temperature and size of the "post shear layer" flame fragment decrease gradually. Finally, at a step height of 0.8 mm (on each step), the typical and preferred flame structure is obtained, which burns nearly all the fuel within the first (shear layer) flame fragment.

This change in flame structure is achieved thanks to the larger size of the inner recirculation vortex, which provides a longer shear layer with the outer recirculation vortex and gives the flame more space to burn before reaching the "summit" of the inner vortex (see figure 11). This observation is interesting: it means that influencing the inner vortex size by influencing the burner head geometry allows direct control of NO emissions.

Thanks to these improvements in flame structure and heat release zone extent, the total NO emission of the burner has been reduced from 1.38 ppm for the reference geometry to 0,87 ppm, which is an emission reduction by nearly 37 %.

Although both emission values are very low (already at a single digit level), the significant NO emission reduction provides the possibility to increase the energy density further, e.g. when operating at higher pressures or further increasing the fuel injector diameter.

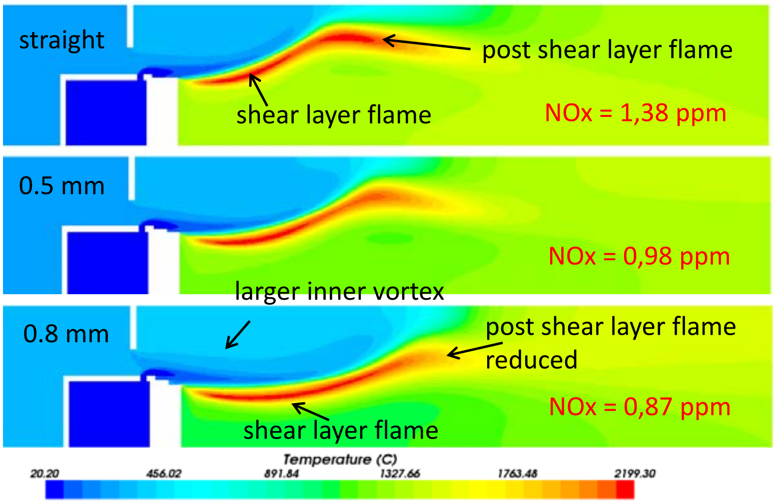

Figure 11: Calculated Temperature Distribution for Straight and Stepped Burner Head Configurations (0.5mm and 0.8 mm step heights)

4. Conclusion

The Micromix test burner with an injector diameter of 1 mm has been tested successfully under atmospheric conditions and has proven its dry low NOx ability over a wide operating range, despite of its increased energy density. Due to the increased energy density, the Micromix flames become thicker, longer and develop a "post shear layer" flame fragment, where NO formation is increased due to higher temperatures.

A parametric study and numerical exploration of the high energy density Micromix burner revealed that it is well possible to positively influence the flame shape by influencing the stabilization vortices. An adequate selection of the burner head geometry allows adjusting the flame length and inter-shear layer length to suppress the NO rich "post shear layer" flame fragment. This has been found to significantly decrease the NO emissions of the burner in question by approx. 37 %. This offers a great potential of further increasing the Micromix energy density while maintaining low NOx emissions. Especially the consideration of elevated pressure conditions (for integration in real gas turbine combustors) leads to thicker and longer Micromix flames. The design of adequate burners for real gas turbine applications can make use of the present findings to balance the design requirements in terms of energy density, manufacturability, stability and emission behavior.

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Nomenclature

A	area (unit: mm^2)
BR	blockage ratio
d	diameter / inner diameter (unit: mm^2)
D	outer diameter (unit: mm^2)
ED	energy density (unit: $MW/(m^2\ bar)$)
$\dot{m}$	mass flow (unit: kg/s)
p	pressure (unit: bar)
T	temperature (unit: K)

Greek letters

Φ	equivalence ratio

Subscripts

3	combustor inlet
4	combustor outlet
AGP	air guiding panel
crit	critical
fuel	fuel / hydrogen
H_2-Seg.	hydrogen burner