



The 6<sup>th</sup> International Conference on Applied Energy – ICAE 2014-863

# Experimental and Numerical Study of the Micromix Combustion Principle Applied for Hydrogen and Hydrogen-Rich Syngas as Fuel with Increased Energy Density for Industrial Gas Turbine Applications

H. H.-W. Funke<sup>a\*</sup>, J. Dickhoff<sup>a</sup>, J. Keinz<sup>a</sup>, A. Haj Ayed<sup>b</sup>, A. Parente<sup>c</sup>, P. Hendrick<sup>c</sup>

<sup>a</sup>Aachen University of Applied Sciences, Hohenstaufenallee 6, D-52064 Aachen, Germany

<sup>b</sup>B&B-AGEMA GmbH, Jülicher Str. 338, D-52070 Aachen, Germany

<sup>c</sup>Université Libre de Bruxelles, Avenue F. D. Roosevelt 50, B-1050 Bruxelles, Belgium

## Abstract

The Dry Low NO<sub>x</sub> (DLN) Micromix combustion principle with increased energy density is adapted for the industrial gas turbine APU GTCP 36-300 using hydrogen and hydrogen-rich syngas with a composition of 90 %-Vol. hydrogen (H<sub>2</sub>) and 10 %-Vol. carbon-monoxide (CO). Experimental and numerical studies of several combustor geometries for hydrogen and syngas show the successful advance of the DLN Micromix combustion from pure hydrogen to hydrogen-rich syngas. The impact of the different fuel properties on the combustion principle and aerodynamic flame stabilization design laws, flow field, flame structure and emission characteristics is investigated by numerical analysis using a hybrid Eddy Break Up combustion model and validated against experimental results.

© 2014 The Authors. Published by Elsevier Ltd.  
Selection and/or peer-review under responsibility of ICAE

*Keywords:* Micromix; Hydrogen; Syngas; NO<sub>x</sub>; Emission Reduction; Jet in Cross-Flow

## 1. Introduction

The research on renewable energy sources is focused on the reduction of greenhouse gas emissions – in particular CO<sub>2</sub> and NO<sub>x</sub>. Therefore, hydrogen-based gas turbine systems may play an important role, if the fuel is produced from renewable and sustainable energy sources like wind- and solar-power or derived from biomass. As a bridge, H<sub>2</sub>-rich syngas, produced by coal and biomass gasification, is used in IGCC power plants. Especially in combination with the carbon capture technology these plants afford an environmental-friendly, renewable, hydrogen-based energy supply. Nevertheless, the combustion of H<sub>2</sub>-rich gases is still a very challenging task. By the use of conventional Dry Low NO<sub>x</sub> (DLN) combustors with syngas the risk of flashbacks as well as the NO<sub>x</sub> values increase. Thus, the development of DLN H<sub>2</sub>

\* Corresponding author. Tel.: +49 241 6009 52387; fax: +49 241 6009 52360  
E-mail address: [funke@fh-aachen.de](mailto:funke@fh-aachen.de)

combustion technologies is indispensable. The Micromix principle developed at Aachen University of Applied Sciences overcomes the issues of conventional DLN combustion technologies. A miniaturized non-premixed combustion keeps the residence time of  $\text{NO}_x$  forming reactants short and avoids the danger of flashbacks. For pure hydrogen the technology has shown great potential in terms of  $\text{NO}_x$  reduction for industrial gas turbine applications [1], [2]. Now the current scope of research intends to increase the energy density of Micromix combustors fueled with  $\text{H}_2$  and  $\text{H}_2$ -rich syngas.

### Nomenclature

$BR$	blockage ratio
$c$	velocity
$d_{fuel}$	diameter of fuel injector nozzle
$d$	inner dimension of air guiding panel (index: <i>AGP</i> ) and burner segment (index: <i>H2Seg</i> )
$D$	outer dimension of air guiding panel (index: <i>AGP</i> ) and burner segment (index: <i>H2Seg</i> )
$ED$	energy density
$LHV$	lower heating value
$\rho$	fluid density
$y$	injection depth of fuel
$y_{crit}$	critical injection depth / position of shearlayer
$Y$	mass fraction

## 2. The Micromix DLN Combustion Principle for $\text{H}_2$ and 90/10 Syngas

The Micromix principle is developed with the major advantages of an inherent safety against flashback and low  $\text{NO}_x$ -emissions ( $<10\text{ppm}_v$ ). The gaseous fuel is injected through small injectors perpendicularly into an air-crossflow. This leads to a fast and intense mixing, which takes place simultaneously to the combustion process. As a result, a miniaturized micro flame develops and anchors at the burner segment edge downstream of the injector nozzle. Multiple micro flames instead of large scale flames lower the residence time of the  $\text{NO}_x$  forming reactants and consequently the averaged molar fraction of  $\text{NO}_x$  can be reduced significantly. For pure hydrogen under gas turbine operational conditions the low  $\text{NO}_x$  capability of the Micromix principle has already been successfully tested in a gas turbine APU GTCP 36-300 [3]. The main influence on the low  $\text{NO}_x$  characteristic can be ascribed to the key design parameters – *blockage ratio*  $BR$  of the air guiding panel *AGP* (Fig. 2) and injection depth  $y$  of the fuel into the oxidizer cross-flow (Fig. 1). 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  $\text{NO}_x$  emission characteristics of the combustion principle as long as the injection depth  $y$  (Fig. 1.b) is not penetrating the shear layer of the *AGP*-Vortex (critical injection depth  $y_{crit}$ ). A recirculation of the fuel/air mixture into the *AGP* vortex leads to raised  $\text{NO}_x$  emissions [4]. Especially for the adaption of the Micromix combustion principle from  $\text{H}_2$  to syngas, these

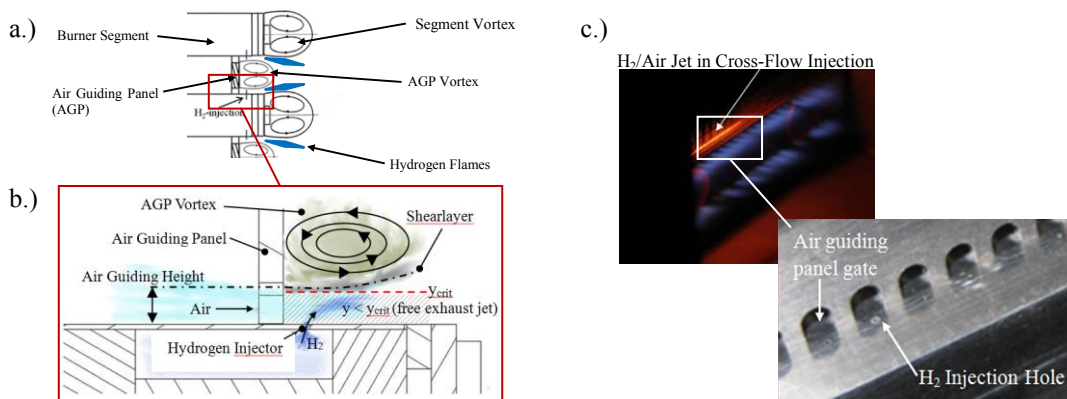


Fig. 1: (a) Aerodynamic flame stabilization; (b) injection depth definition; (c) experimental Micromix hydrogen combustor

phenomena must be considered carefully with respect to the different fuel properties. The investigated syngas mixture consists of 90 %-Vol. H<sub>2</sub> (Y<sub>H2</sub>=0.39) and 10 %-Vol. CO (Y<sub>CO</sub>=0.61). This leads to a lower heating value *LHV* of only 53.29 MJ/kg (*LHV*<sub>H2</sub>=119.95 MJ/kg). For identical thermal power per fuel injector, syngas consequently requires an increased fuel flow.

### 3. Numerical and Experimental Investigation of Micromix 90/10-Syngas Combustors

The impact of the chosen design parameters for the different fuel compositions is investigated using three burner configurations designed with variations of the *BR* and the energy density (*ED*). Fig. 2 shows the strategy for the evaluation of the Micromix combustion principle with hydrogen and syngas at increased energy density. Burner 1 is the basic configuration with a normalized injection depth  $y_1 = 1$  and a normalized blockage ratio of 100% at an energy density of  $ED_1 = 7.74 \text{ MW}/(\text{m}^2 \text{ bar})$ . Burner 2 is used as link between hydrogen and syngas. With an increased H<sub>2</sub> mass flow an injection depth  $y_2$  similar to the one required for syngas combustion is chosen. The necessary adjustment of the shear layer position is done by increasing  $d_{AGP}$ , while  $D_{AGP}$  is kept constant. The resulting blockage ratio is  $BR_2 = BR_3 < BR_1$  and the energy density  $ED_2 = 8.63 \text{ MW}/(\text{m}^2 \text{ bar}) > ED_3 = ED_1 = 7.74 \text{ MW}/(\text{m}^2 \text{ bar})$ . Burner 3 features a comparable injection depth as Burner 2, but it is fueled with the 90/10 mixture of syngas (90/10 SG), which causes an energy density similar to the one of Burner 1.

The experimental and numerical results of the three burner configurations at atmospheric conditions are given in Fig. 3. The corrected NO<sub>x</sub> emissions (@ 15% O<sub>2</sub>) obtained in the experiment are given against the equivalence ratio and compared to the numerical values computed at the design point ( $\Phi = 0.4$ ). Fig. 3.a reveals that the NO<sub>x</sub> emissions for all three burner configurations are in a comparable range below 4 ppm<sub>v</sub> NO<sub>x</sub>. This validates the applied design laws for hydrogen, syngas and increased energy densities. In Fig. 3.a the picture of the established syngas flames at the design point  $\Phi = 0.4$  shows that syngas burns in small micro flames like H<sub>2</sub> (Fig. 1c), maintaining the low NO<sub>x</sub> Micromix character.

The numerical simulation is done by STAR-CCM+™ 7.06. To keep the computational effort in an adequate range an *Eddy Dissipation – Finite Rate* combustion model (kinetic parameters by Fernández-Galisteo et al. [5] and Dryer & Glassman [6]) and the *k-ε*-turbulence model is used on a grid with approx. 0.7 Mio. polyhedral cells. Exemplarily for the results, the temperature distribution for the three burner configurations is shown in Fig. 3b. For all configurations the main reaction zone is attached to the segment vortex, which consequently heats up. Due to the increase in energy density of Burner 2 (C2) compared to Burner 1 (C1), the maximum flame temperature ① is raised and shifted downstream and the high temperature zone ② elongates, despite the air velocity is constant for all configurations. In addition the segment vortex is longer and hotter for C2 increasing slightly the calculated NO<sub>x</sub> emissions shown in Fig. 3a. Due to the change in *BR* for C2 the main flow contributes much more to the vertical separation of the flames (B) and the related change of the cold flow jet length (③, A) compared to C1. The main air flow cools the vortex behind the burner segment when the combustor design allows a lateral flow around the flame [2]. The numerical simulation for syngas also shows a stable and comparable flame structure and averaged outlet temperature as C1. But maximum flame and segment vortex temperature are significantly lower compared to C1 and C2. This is also reflected in the low NO<sub>x</sub> emissions in Fig. 3a.

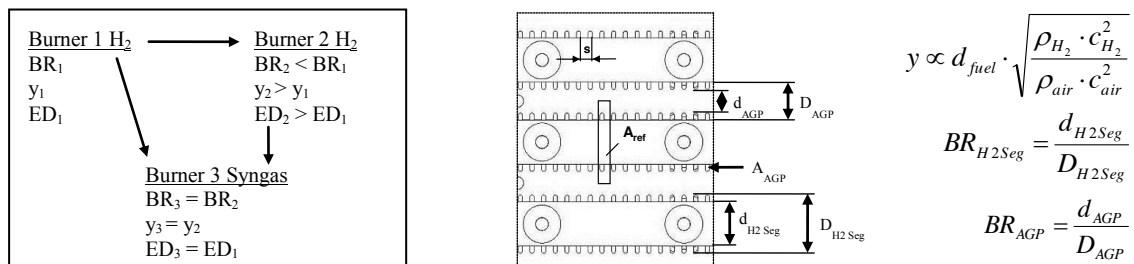


Fig. 2: Investigation flow chart for blockage ratio and energy density variation; definitions

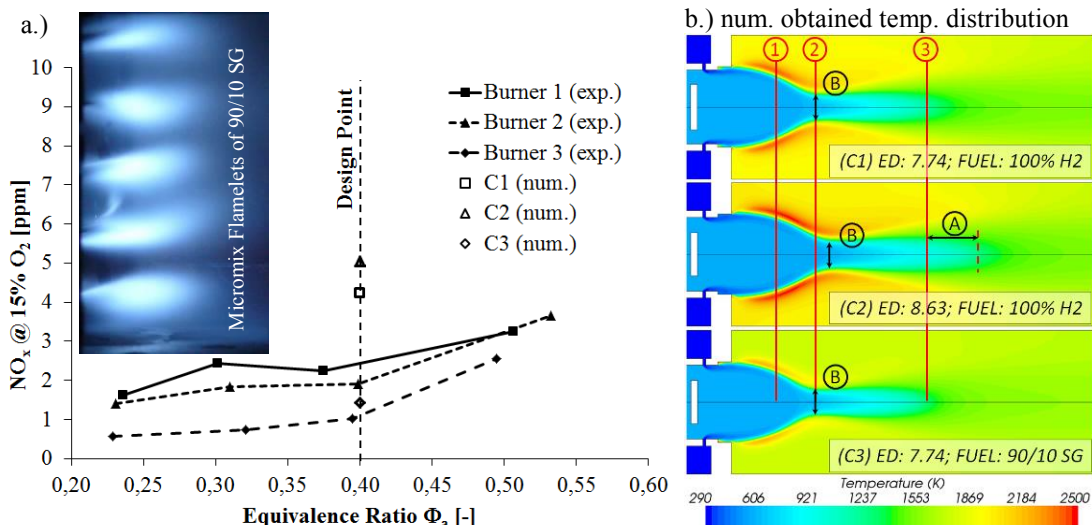


Fig. 3: (a) NO<sub>x</sub> emissions @ 15% O<sub>2</sub> against the equivalence ratio  $\Phi$  of the experimental and numerical investigations also showing the optical flame appearance of 90/10 SG; (b) num. temp. distribution on a cross section for  $\phi = 0.4$  for all three configurations.

#### 4. Conclusion

The experimental and numerical results show that the DLN Micromix principle is capable of using pure H<sub>2</sub> and H<sub>2</sub>-rich syngas maintaining the approved low NO<sub>x</sub> characteristics. The observed Micromix flame structure offers the potential for higher energy density increases and future investigations of fuel flexibility with different syngas compositions. In the full length paper an in-depth analysis of the key design parameters and combustion characteristics using pure H<sub>2</sub> and 90/10 SG is given.

#### References

- [1] Dahl G, Suttrop F. *Engine Control and Low-NO<sub>x</sub> Combustion for Hydrogen Fuelled Aircraft Gas Turbines*. International Journal of Hydrogen Energy; 23(8), pp. 695-704; 1998.
- [2] Funke H. H.-W., Börner S, Keinz J, Kusterer K, Kroniger D, Kitajima J, Kazari M, Horikawa A. *Numerical and experimental characterization of low NO<sub>x</sub> Micromix combustion principle for industrial hydrogen gas turbine applications*. ASME Turbo Expo 2012, GT2012-69421, Copenhagen, DK, 2012.
- [3] Funke H. H.-W., Boerner S, Hendrick P, Recker E, Elsing R. *Development and integration of a scalable low NO<sub>x</sub> combustion chamber for a hydrogen fuelled aero gas turbine*, Progress in propulsion physics vol. 4, 2013
- [4] Funke H. H.-W. et al. *Experimental and Numerical Characterization of the Dry Low NO<sub>x</sub> Micromix Hydrogen Combustion Principle at Increased Energy Density For Industrial Hydrogen Gas Turbine Applications*. ASME Turbo Expo 2013, GT2013-94771, San Antonio/Texas, USA, 2013.
- [5] Fernández-Galisteo D, Sánchez AL, Liñán A, Williams FA. *One-step reduced kinetics for lean hydrogen - air deflagration*. Combustion and Flame, Vol. 156, Issue 5, Pages 985–996, 2009.
- [6] Dryer FL, Glassman I. *High-temperature oxidation of CO and CH<sub>4</sub>*. Symposium (International) on Combustion, Volume 14, Issue 1, Pages 987-1003, 1973.



#### Biography

Prof. Dr.-Ing. H. H.-W. Funke is head of the Institute for “Gas Turbines and Aircraft Engines” at Aachen University of Applied Sciences. His actual research includes low NO<sub>x</sub> Micromix combustion for gaseous fuels in gas turbines, related as turbine control as well as alternative fuels for piston engine propulsion systems.