Enhancement of fuel flexibility of industrial gas turbines by development of innovative hydrogen combustion systems

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For fuel flexibility enhancement hydrogen represents a possible alternative gas turbine fuel within future low emission power generation, in case of hydrogen production by the use of renewable energy sources such as wind energy or biomass. Kawasaki Heavy Industries, LTD. (KHI) has research and development projects for future hydrogen society; production of hydrogen gas, refinement and liquefaction for transportation and storage, and utilization with gas turbine / gas engine for the generation of electricity. In the development of hydrogen gas turbines, a key technology is the stable and low NO_x hydrogen combustion, especially, Dry Low Emission (DLE) or Dry Low NO_x (DLN) hydrogen combustion. 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 DLE hydrogen combustion. Thus, the development of DLE hydrogen combustion technologies is an essential and challenging task for the future of hydrogen fueled gas turbines. The DLE Micro-Mix combustion principle for hydrogen fuel has been in development for many years 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 flashback and the low NO_x-emissions due to a very short residence time of the reactants in the flame region of the micro-flames.

1. INTRODUCTION

Within the last decade the global demand for renewable energy has increased rapidly, which leads to new challenges for conventional power generation systems. For nuclear and coal power plants it will be very difficult to be part of the power generation in the future, especially in Europe. In case of overcoming the new challenges, the gas turbine technology has realistic chances to solidify and expand its role in the future power generation.

In the past "efficiency" was the only key driver for gas turbine developments. Nowadays, flexible power generation systems and energy storage systems become increasingly more important to fulfill the requirements of the renewable energy market. Thus, the gas turbine in the future must offer more operational flexibilities, such as a higher number of starts, lower emissions at partial load, hot start capability, short start time, low maintenance and flexible in fuel to meet the requirements of the renewable energy market.

To enhance fuel flexibility, hydrogen has great potential as a renewable and sustainable energy source derived from wind or solar power and gasification of biomass and therefore substituting the limited resources of fossil fuels. It represents a possible alternative gas turbine fuel within future low emission power generation, paired with the use of renewable energy sources for its production.

Due to the large differences in the physical properties of hydrogen compared to other fuels such as natural gas, the combustion of hydrogen gases is a very challenging task, especially for the Dry Low Emission (DLE) combustion.

Nevertheless, Kawasaki Heavy Industries overcame these challenges and developed 3 different H2-combustion systems, which are illustrated in **Figure 1**.

The diffusion flame combustor in **Figure 1a** can operate with 100 % hydrogen and 100 % natural gas and also with mixtures of both. Water injection is used to achieve low emissions.

The first gas turbine with this diffusion flame combustor has been used in the project "Development of smart community technology by Utilization of Hydrogen CGS (Co-Generation System)". This project is subsidized by NEDO (New Energy and Industrial Technology Development Organization). The successful commissioning took place on the 19th and 20th of April 2018 in a demonstration plant in Kobe, see **Figure 2**.

Figure 3 shows the process control interface, during the 100 % hydrogen fuel operation mode. The electrical power output is approx. 1,5MW. The amount of measured NOx emission during 100 % hydrogen combustion is 50ppm (16 %Vol. O_2).

In total, three different fuel modes are available at the touch of a button, which leads to very high flexible operation. The first fuel mode "Natural Gas Only" is the con-

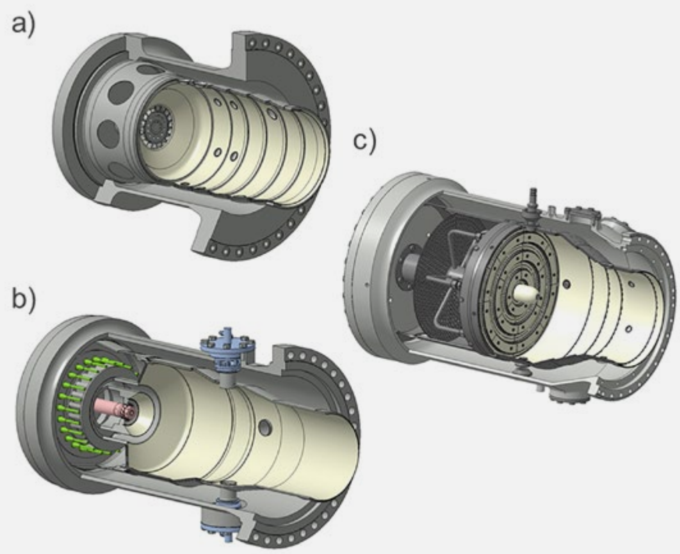

Figure 1: Different hydrogen combustion systems: a) Diffusion flame, b) Supplemental burner, c) Micro-Mix burner (MMX)

Figure 2: World's first pure hydrogen and natural gas demonstration plant in Kobe (Japan)

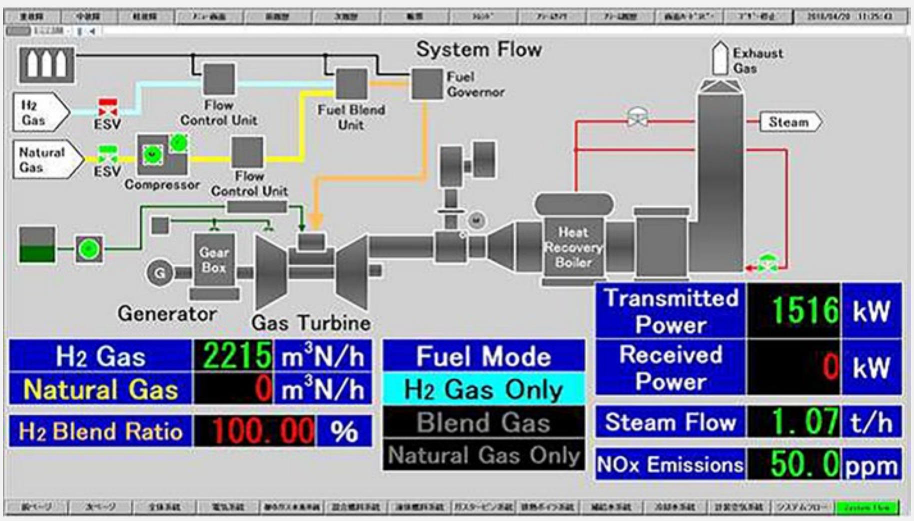

Figure 3: Process controlling interface of Kobe plant

ventional operation with natural gas. The second mode "Blend Gas" is the operation with mixtures ratios of natural gas and hydrogen. The mixture ratio can vary from 1 %-99 % hydrogen. The third mode "H2 Gas Only" is the innovative pure hydrogen fuel mode, as visualized in **Figure 3**.

The second development in **Figure 1b** based on a conventional DLE combustor with hydrogen injection over the supplemental burner up to 60 Vol% hydrogen, which correspond to 30 % of the total thermal input. Basically the DLE combustor of KHI has pilot, main and supplemental burners. Usually natural gas is supplied from the supplemental burners. Within this combustor, it can be switched from natural gas to hydrogen or natural gas and hydrogen mixing gas fuel via the supplemental burner. The NOx emission can be kept below the 25 ppm (O2-15 %) guaranteed level. This combustor has also been tested successfully at Akashi Works.

Using hydrogen in conventional DLE combustors increase the NOx emissions values as well as the risk of flashbacks. The established gas turbine combustion systems cannot be directly applied. Thus, the development of DLE H2 combustion technologies is indispensable for pure hydrogen (100 Vol%) combustion.

Therefore, the innovative Micro-Mix DLE combustion chamber (MMX combustor) **Figure 1c** has been developed by using an interactive optimization cycle including experimental and numerical studies on test burners and full scale combustion chamber investigations. The feasibility is proven in real gas turbine operation, as visualized in **Figure 4**.

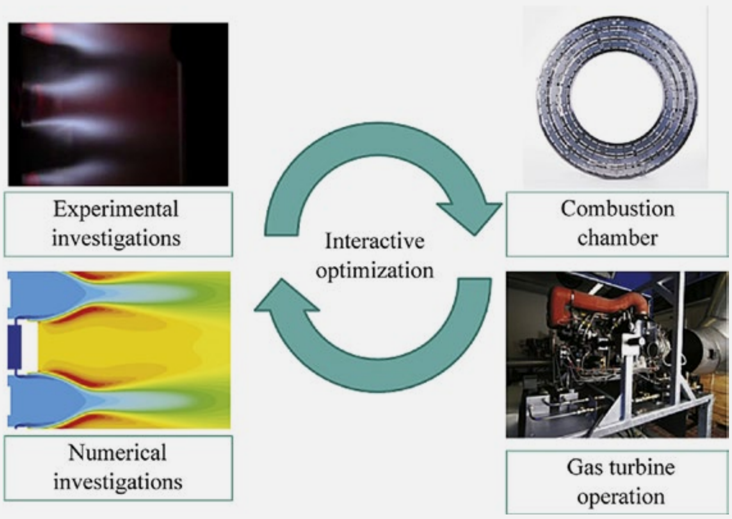

Figure 4: Interactive optimization cycle of Micro-Mix combustor research and development [1]

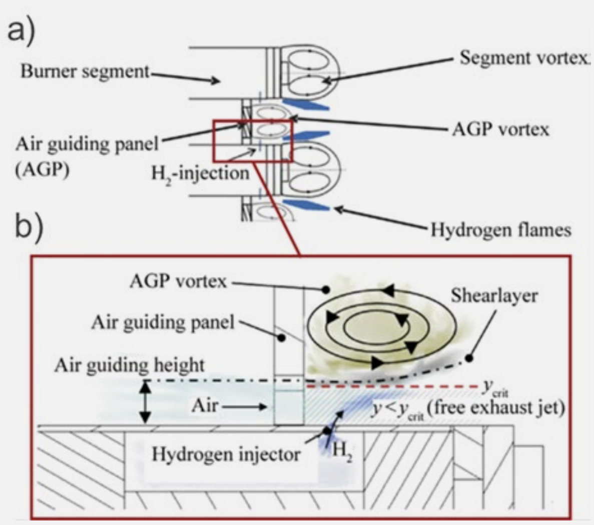

Figure 5: a) Aerodynamic flame stabilization principle b) Hydrogen injection depth definition [10]

2. THE MICRO-MIX COMBUSTION PRINCIPLE FOR H_2

The application of gaseous hydrogen as fuel in gas turbines is being investigated at Aachen University of Applied Sciences (AcUAS) since the European research projects EQHHPP [2] and CRYOPLANE [3] where the low NO_x Micro-Mix hydrogen combustion principle was invented. In 2011 Kawasaki Heavy Industries decided to cooperate with AcUAS and B&B-AGEMA to investigate the ability of the low NO_x Micro-Mix combustion principle with hydrogen for the integration into industrial gas turbines.

In addition, the hydrogen DLE combustor developments, as described in chapter II, were supported by the Council for Science, Technology and Innovation (CSTI), Cross-ministerial Strategic Innovation Promotion Program (SIP), "Energy Carrier" (Funding agency: JST) in 2014 and 2015.

In 2016 and 2017, the MMX combustor developments have been conducted in the NEDO project "Basic Research and Development of Hydrogen Firing Combustor for Gas Turbine".

In several scenarios hydrogen fueled gas turbines, as efficient and reliable power systems, are regarded as an important part in future power plant development processes and greenhouse gas emission reduction [4]. With the application of hydrogen as fuel burned with air, only NO_x emissions result. Former investigations showed that the combustion process has to be modified in order to achieve low NO_x emissions when burning hydrogen [5]. This is the main focus of the Micro-Mix research at Aachen University of Applied Sciences [5, 6, 7, 8], a review of the previous research activities at AcUAS is presented in [9].

Significantly reduced NOx-emissions can be achieved by enhancing the mixing process of reactants and by lowering the residence time of these reactants in the hot flame regions. The Micro-Mix burning principle for gaseous hydrogen fulfills these requirements.

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, as visualized in **Figure 5**.

A significant reduction in the formation of NOx emissions is achieved by miniaturizing the reaction zone creating multiple micro diffusion flames with a usual size of 5-10 mm in length, instead of several large scale flames and by improving the mixing process using the fluid mechanic phenomenon of jets in the crossflow.

Former investigations showed, that the flame anchoring and therewith the NOx formation is mostly dominated by the resulting recirculation zones of the burner geometry [7] and by the momentum flux ratio of the jet in cross-flow [8]. 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.

The first design started with about 1,600 miniaturized flames, with fuel injector diameters of 0.3 mm.

To increase the energy density of a Micro-Mix combustor it is required to increase the power per fuel injector. If the power per injector is to be increased, the required fuel flow per injector must also increase. The established fuel velocity in each single injector is to be maintained as a design parameter and in consequence the injector size must increase. However, the micro flames must still established to keep the low NOx characteristics. This was achieved by stepwise increased hole diameter of the H_2-injectors from 0.3 mm to 0.45 mm, 0.55 mm up to 1.0 mm.

The multiple micro flames at the test burner are visualized in **Figure 6**. The H_2-injection holes and the air guiding panels are also visible.

The power-increase per injector leads to a reduction of manufacturing complexity, because the number of required injectors could be reduced significantly. Within the development and optimization process the number of holes was reduced from 1,600 flames down to 410 flames. Detailed information is presented in [11].

For pure hydrogen under gas turbine operational conditions the low NOx capability of the Micro-Mix principle has already been successfully tested.

Figure 7 shows the prototype combustion chamber and Micro-Mix burner. The Micro-Mix burner with its three ring segments is implemented in a conventional can type combustion chamber. The rings are supplied with H_2 from the center which is connected via pipes to each ring segment. Each ring segment can be controlled individually depending on the power load.

Figure 8 shows the NOx emission (2-15 % corrected values) for the test burner at 2 bar condition. Horizontal axis shows the thermal input; load 100 % means full load (design point) and 0 % means idle conditions. Fuel supply staging is possible. From idle to 30 % load conditions, inner 2 hydrogen rings were used and from 30 % load to full load conditions, all 3 rings were used. It can be seen, that low NOx values are also achieve at partial load. The NOx values are below 20 ppm over the whole load range.

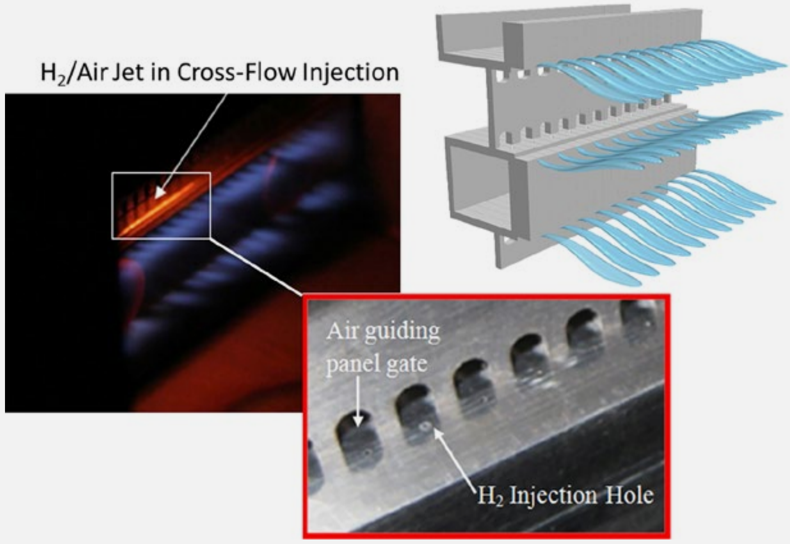

Figure 6: H_2-Micro-Mix test burner [10]

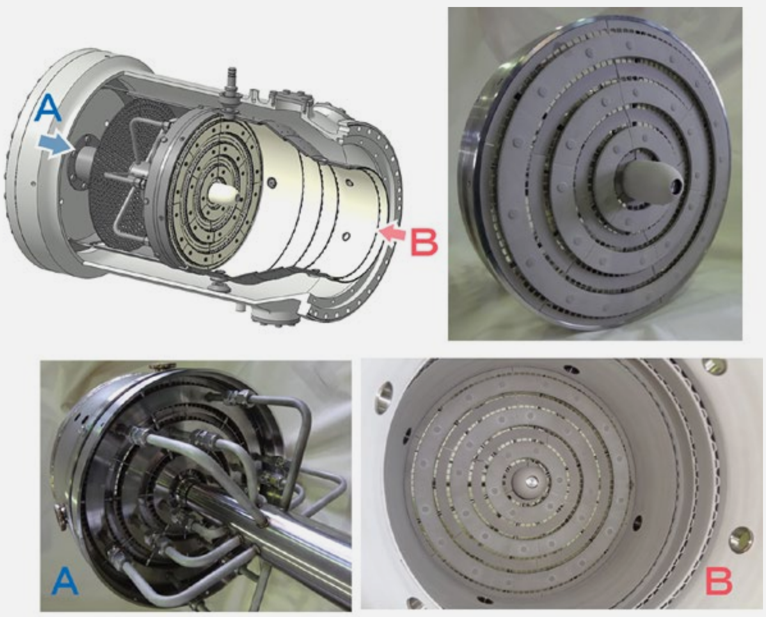

Figure 7: Design of the Micro-Mix combustion burner

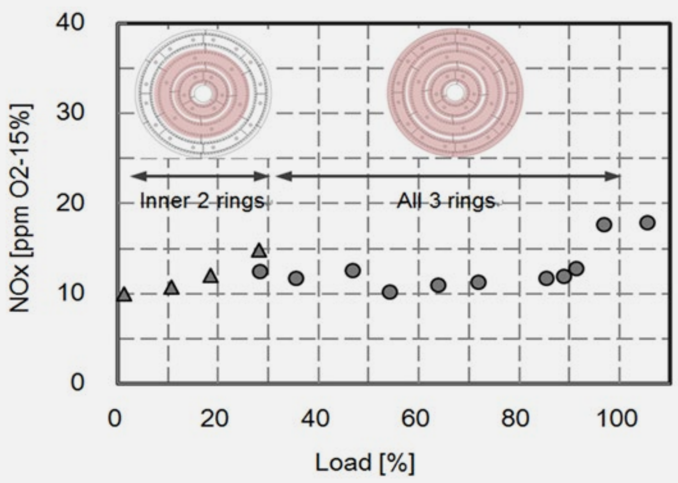

Figure 8: Interactive optimization cycle of Micro-Mix combustor research and development [1]

3. CONCLUSION

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.

In the Kawasaki hydrogen technology developments, hydrogen gas turbine and hydrogen combustion technologies have been developed.

The commissioning of the world's first diffusion flame combustor with 100 % hydrogen fueled gas turbine has been carried out successfully in Kobe, Japan.

In addition, the hydrogen fueled Micro-Mix DLE test burner has been tested successfully under atmospheric and pressurized conditions and has proven its dry low NOx ability over a wide operating range. Numerical investigations with different combustion models revealed the ability of the applied numerical approach to simulate the Micro-Mix combustion and to capture the typical Micro-Mix flame anchoring and structure.

The Micro-Mix combustion principle leads due to the miniaturized micro flames to significantly reduced NOx emissions with inherent safety against flashback.

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