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HYDROGEN ROAD OF KAWASAKI - DEVELOPMENT OF INNOVATIVE HYDROGEN COMBUSTION SYSTEMS FOR INDUSTRIAL GAS TURBINES

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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.

Kawasaki Heavy Industries, LTD. (KHI) has research and development projects for future hydrogen societies; production of hydrogen gas, refinement and liquefaction for transportation and storage, and utilization with gas turbines / gas engines for the generation of electricity.

Due to the large difference in the physical properties of hydrogen compared to other fuels such as natural gas (NG), well established gas turbine combustion systems cannot be directly applied for Dry-Low-Emission (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 (MMX) 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 flames. The major advantages of this combustion principle are the inherent safety against flashback (stable flame) and the low NOx-emissions due to a very short residence time of the reactants in the flame region of the micro-flames.

ABBREVIATIONS

AcUAS	Aachen University of Applied Sciences
CGS	Co-Generation System
CHP	combined heat and power
DLE	Dry Low Emission
DLH	Dry Low Hydrogen
MMX	Micro Mix
NG	Natural Gas
NEDO	New Energy and Industrial Technology Development Organization
NO_x	Nitrogen oxide
TPLR	total pressure loss ratio

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 future power generation, especially in Europe. In case of overcoming the new challenges, the gas turbine technology has realistic chances to solidify and expand its role in future power generation. Thus, future gas turbines 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 high fuel flexibility 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 CO2 implying fossil fuels. It represents a possible alternative gas turbine fuel within future low emission and carbon free power generation. Due to the large differences in the physical properties of hydrogen compared to other fuels such as NG, the combustion of hydrogen gases is a very challenging task, especially for the DLE combustion.

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

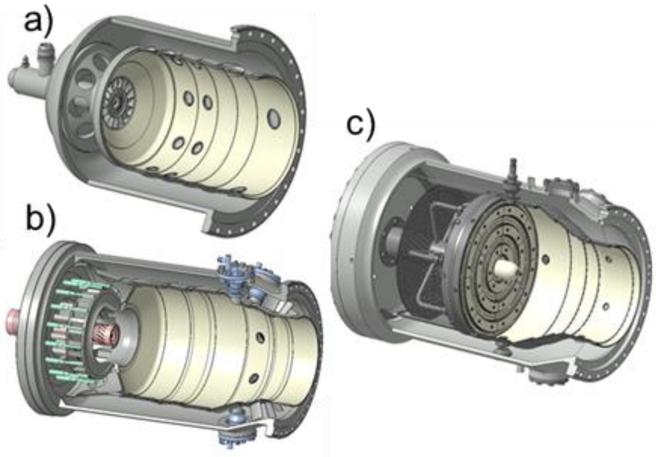


Figure 1: Different hydrogen combustion systems: a) Diffusion-Flame-, b) Supplemental-, c) Micro-Mix-Combustor (MMX)

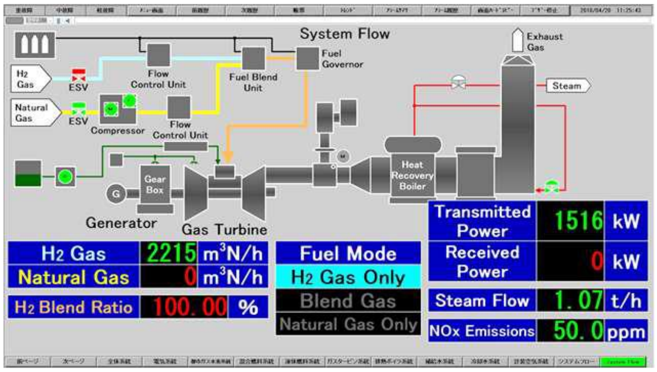
The diffusion flame combustor in Figure 1a can operate with 100% hydrogen and 100% natural gas and also with mixtures of both. Water injection is used to achieve low emissions.

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

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 NO_x emission during 100% hydrogen combustion is 50ppm (16%Vol.O2).

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 conventional 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 0-100% hydrogen. The third mode "H2 Gas Only" is the innovative pure hydrogen fuel mode, as visualized below.



H2 Gas 2215 m^3N/h
Natural Gas 0 m^3N/h
H2 Blend Ratio 100.00 %

Fuel Mode
H2 Gas Only
Blend Gas
Natural Gas Only

Transmitted Power 1516 kW
Received Power 0 kW
Steam Flow 1.07 t/h
NOx Emissions 50.0 ppm

Figure 3: Process controlling interface of Kobe plant

The second development in Figure 1b is the so-called M1A-17 DLH combustor. It based on a conventional DLE combustor with hydrogen injection over the supplemental burner up to 60Vol% 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 NO_x emission can be kept below the 25 ppm (O_2-15%) guaranteed level. This combustor has also been tested successfully at Akashi Works.

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

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.

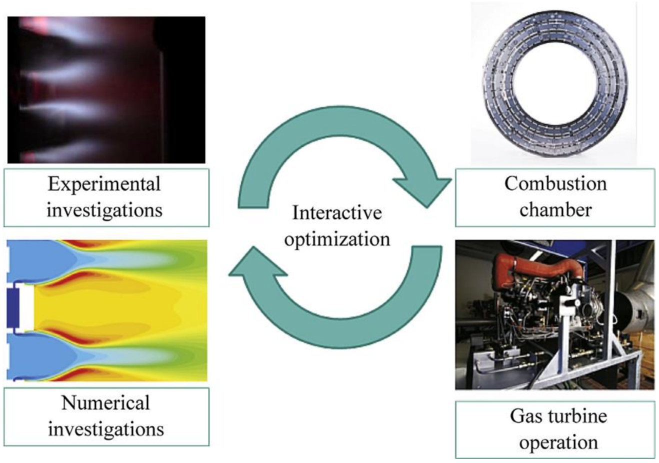


Figure 4: Interactive optimization cycle of Micro-Mix combustor research and development [1]

MICRO-MIX COMBUSTION PRINCIPLE FOR HYDROGEN

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 NO_x-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.

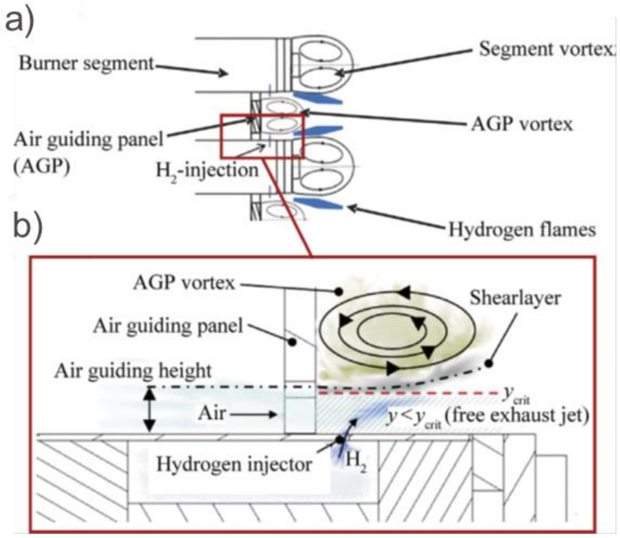


Figure 5: a) Aerodynamic flame stabilization principle and

b) Hydrogen injection depth definition. [10]

A significant reduction in the formation of NO_x 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 NO_x 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 NO_x forming reactants and consequently the averaged molar fraction of NO_x can be reduced significantly.

The first design started with about 1600 miniaturized flames, with fuel injector diameters of 0.3mm. 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 be established to keep the low NO_x characteristics. This was achieved by stepwise increased hole diameter of the H_2-injectors from 0.3mm to 0.45mm, 0.55mm 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.

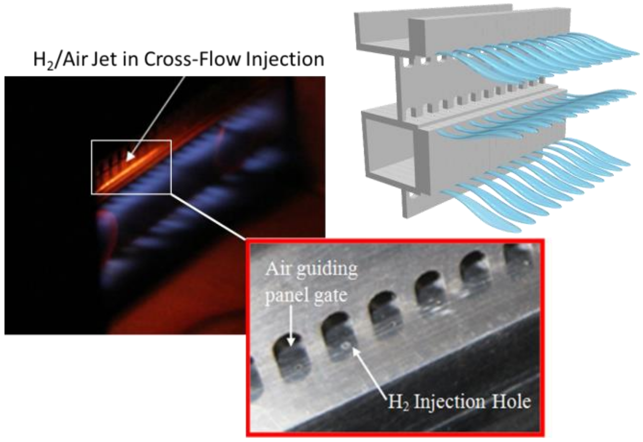


Figure 6: H_2-Micro-Mix test burner [10]

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 1600 flames down to 410 flames. Detailed information is presented in [11].

For pure hydrogen under gas turbine operational conditions the low NO_x 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 hydrogen from the center which is connected via pipes to each ring segment. Each ring segment can be controlled individually depending on the power load.

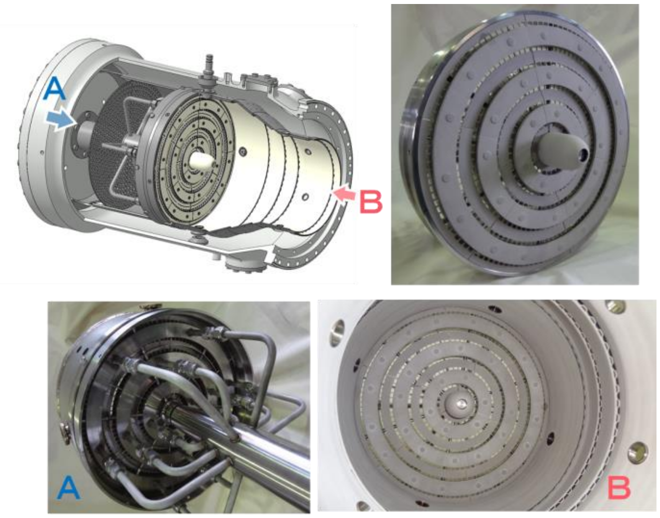


Figure 7: Design of the Micro-Mix combustion burner

Figure 8 shows the NO_x emission and the total pressure loss ratio (TPLR) distribution for two different prototype combustors under operating pressure. From idle to 30% load, the inner hydrogen rings were used and from 30% load to full load, all rings were used. It can be seen, that low NO_x values are also achievable at partial load. The NO_x values are below the project target value of 35ppm over the whole load range only for 0.55MMX. The TPLR project target level is achieved for both configurations.

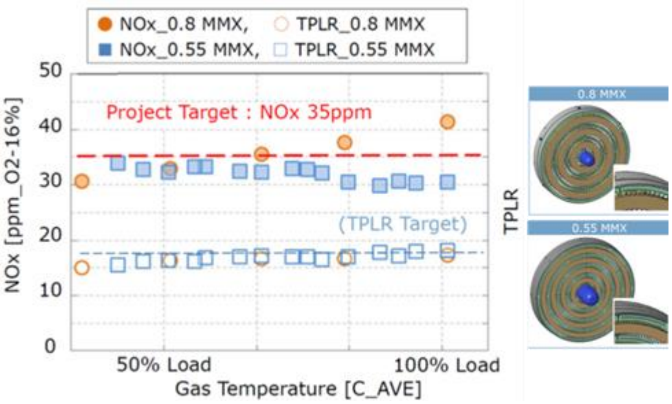


Figure 8: NOx distribution over load for test burner at 2bar

Figure 9 shows an innovative future power plant with combined heat and power (CHP) and integrated renewable energy supply. The system consists of a H2/NG fueled gas turbine with integrated hydrogen production and storage. The surplus energy from the renewable sources such as wind and solar is used for hydrogen production via an electrolyzer. This is temporarily stored and can be used for generating power and heat via the hydrogen gas turbine anytime as needed, with low NO_x emissions and zero carbons.

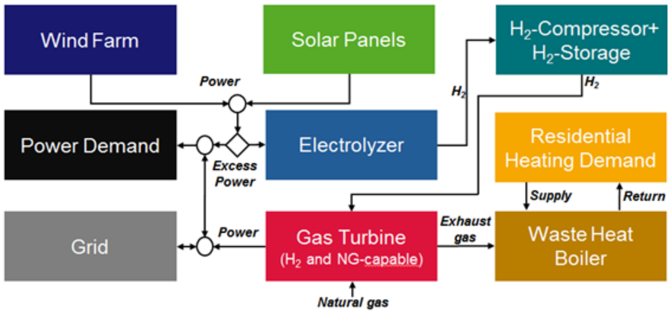


Figure 9: Innovative CHP power plant with renewable energy supply

CONCLUSION

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

In addition, the hydrogen fueled DLE Micro-Mix Prototype combustor has been tested successfully under atmospheric and pressurized conditions and has proven its dry low NO_x ability over a wide operating range. The Micro-Mix combustion principle leads to significantly reduced NO_x emissions due to the miniaturized micro flames with inherent safety against flashback.

For further increase of fuel flexibility of the MMX combustor, H2/NG gas mixtures up to a certain level are under investigation. First operation tests carried out a high potential for admixture of NG up to 40Vol.%.

The MMX-Technology is a technological breakthrough for hydrogen combustion within gas turbines. It ensures, that gas turbines have realistic chances to solidify and expand their roles in future CHP generation. Thus, with this innovative and unique technology the gas turbine is ready for the upcoming energy transition.

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