Hydrogen Concentration Measurement in Hydrogen Combustion Gas Turbine Development

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This report introduces the efforts of Kawasaki Heavy Industries for developments of hydrogen-fueled industrial gas turbines and aircraft engines toward the realization of a decarbonized society. In the hydrogen-fueled combustor development, accurate measurement of hydrogen concentration in the exhaust gas will play more important role. Trial measurement results of hydrogen concentration using HORIBA HyEVO-1000, performed in KHI Akashi works, demonstrated favorable accuracy and time response.

Keywords: Hydrogen gas turbine, NOx, unburned hydrogen

Introduction

In the Fifth Strategic Energy Plan[1] in July 2018, it was stated that it is important to promote the development of hydrogen power generation which consumes stable and large amount of hydrogen together with the construction of international hydrogen supply chain. In October 2021, the Sixth Strategic Energy Plan[2] stated that hydrogen and ammonia power generation is one of the powerful options for decarbonizing thermal power generation to achieve carbon neutrality in 2050, and stated that the government will work to overcome technical challenges for hydrogen and ammonia power generation to function as a major supply and regulating force in the power system in 2050.

In addition, in the aircraft field, it was mentioned to promote the development of core technologies such as hydrogen combustors, which will be necessary for the realization of hydrogen aircraft after 2035.

KHI is developing and demonstrating various technologies for the production, transportation, storage and utilization of hydrogen to build an international hydrogen supply chain as shown in Figure 1[3]. Specifically, it is a comprehensive development and demonstration project that liquefies hydrogen produced from brown coal and renewable energy, transports and stores it, and uses it in gas turbines as a fuel to replace hydrocarbon fuels.

This report introduces KHI's efforts in the development of hydrogen combustors for industrial gas turbines and aircraft engines, and describes the measurement of hydrogen gas concentrations required for these developments. Finally, as an example of hydrogen concentration measurement in the development of hydrogen combustors for aircraft engines, the application of the hydrogen gas measuring device HORIBA HyEVO -1000 is introduced.

Challenges of hydrogen combustion

Comparison of combustion characteristics between

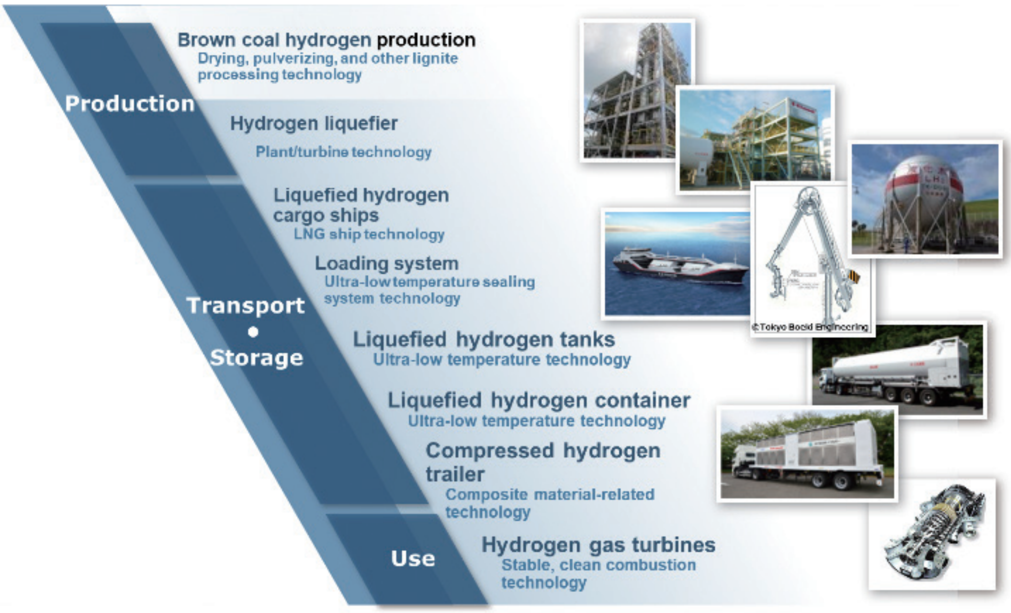

Figure 1 Technology developments for Hydrogen Society in Kawasaki Heavy Industries, Ltd.

hydrogen and methane, a major component of natural gas, and problems specific to hydrogen combustion are shown in Table 1. The maximum combustion speed of hydrogen is faster than that of methane, and the quenching distance is smaller. Therefore, the hydrogen flame tends to get close to the metal parts of the combustor, causing oxidation and damage from overheating. In addition, since hydrogen increases the combustible range, premixed combustion increases the risk of flashback.

Moreover, high combustion speed and flame temperature produce locally hot combustion gas, leading to increased NOx (nitrogen oxides) emissions. Considering these unique combustion characteristics of hydrogen, the development of a combustor with stable combustion of hydrogen and low NOx properties is required.

On the other hand, hydrogen, which is more reactive than conventional hydrocarbon fuels, has the advantage that it is rarely discharged unburned. It has been confirmed in KHI's combustion tests that unburned hydrogen is not generated

Table 1 Combustion characteristics of methane and hydrogen and problems with hydrogen combustion

Combustion characteristics	CH_4	H_2	Hydrogen problems in hydrogen combustion burning rate [m/s]
Combustion speed [m/s] (Stoichiometric mixture ratio, 0.1 MPa)	0.4	2.65	Abnormal combustion (flashback, combustion oscillation)
Quenching distance [mm]	2.2	0.64	Oxidation and damage of metal parts due to overheat
Flammability limit [Vol%]	5~15	4~75	Abnormal combustion (flashback)
Flame temperature [degC] (in the air)	1875	2045	Thermal NOx increase

in the stable combustion state of the gas turbine. However, unburned hydrogen is generated under unstable combustion conditions, rich conditions, and transient conditions such as load changes, ignition and extinguishment. It is important to know whether unburned hydrogen is generated and its concentration in the process of development, because it must be avoided that unburned hydrogen is deposited downstream of the combustor, leading to unintended combustion and explosion.

Micro-mix Hydrogen Combustion Technology and Industrial Gas Turbine Demonstration Test

KHI focused on the micro-mix hydrogen combustion technology which Aachen University Applied Sciences (AcUAS) owns. This technology makes micro hydrogen flames and dry low NOx emissions. In collaboration with B&B-AGEMA, the application to industrial gas turbine combustors was investigated and a conceptual design for the combustor was carried out [4-6].

Figure 2 (a) shows a conceptual diagram of the micro-mix combustion to enable dry low NOx combustion technology, and Figure 2 (b) shows an example of numerical simulation of combustion flow field [7]. Hydrogen is injected through a minute injection hole and rapidly mixed with an orthogonal air jet to form a hydrogen flame. By forming a small hydrogen flame, the generation of the local high temperature region is eliminated and the generation of NOx is suppressed by shortening the reaction time.

In the shear zone behind the hydrogen injection hole and between the recirculation zone formed behind the air

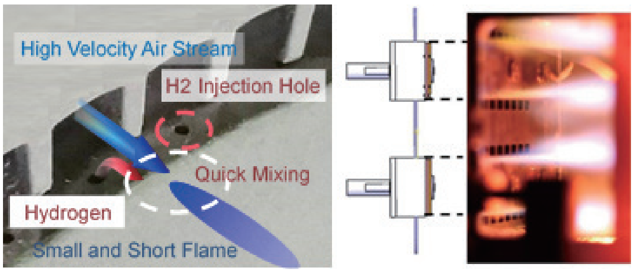

Figure 2(a) Micro-mix hydrogen flame.

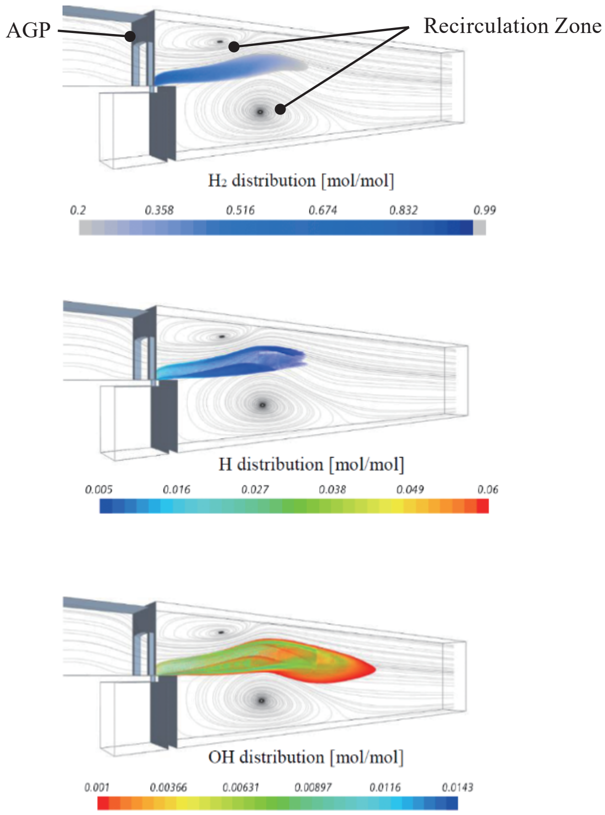

Figure 2(b) Structure of hydrogen flame and flame holding (Examples of CFD analysis).

guiding panel (AGP) and the hydrogen supply unit, OH radicals and H atoms are generated and the hydrogen flame is stabilized. Therefore, the penetration of hydrogen flame into the hydrogen supply unit and flashback to the upstream side of the AGP do not occur.

Industrial gas turbines in KHI use reverse flow can type combustors. Therefore, the rectangular micro-mix burner used in the hydrogen combustion test at AcUAS was formed into a ring shape to fit the shape of the can type combustor. Figure 3 shows the configuration of a combustor equipped with a micro-mix burner module (initial concept stage) [8]. In 2020, KHI succeeded in the technology demonstration test of the world's first dry low-NOx hydrogen combustion gas turbine using a micro-mix burner in a grant project of New Energy and Industrial Technology Development Organization (NEDO)[9].

The move to decarbonize aircraft engines

In recent years, in addition to fuel cells and Sustainable Aviation Fuel (SAF), there has been a growing momentum toward the realization of carbon neutrality in the aviation industry. Since 2020, when Airbus in France started a hydrogen aircraft development project, aiming to start operation in 2035[10], efforts for hydrogen conversion have been intensified in various fields such as engines, aircraft equipment, and infrastructure development in airports.

KHI started development of core technologies for a hydrogen aircraft in fiscal year 2021, which is expected to make a significant contribution to decarbonization as a part of NEDO Green Innovation funding project [11]. The target aircraft has a route distance of 2,000 - 3,000 km and a passenger capacity of about 200 passengers. Combustors and engine fuel systems, liquefied hydrogen fuel tanks and equipment systems, and structural study of airframe will be set as core technologies. Development of each component will be promoted until FY 2028. In the FY 2029 to 2030, KHI will conduct end-to-end ground demonstration tests by integrating them, aiming to demonstrate key technologies for social implementation of hydrogen aircraft.

In the development of combustors for aircraft engines, as well as industrial gas turbines, high environmental compatibility is required, and strict regulations have been

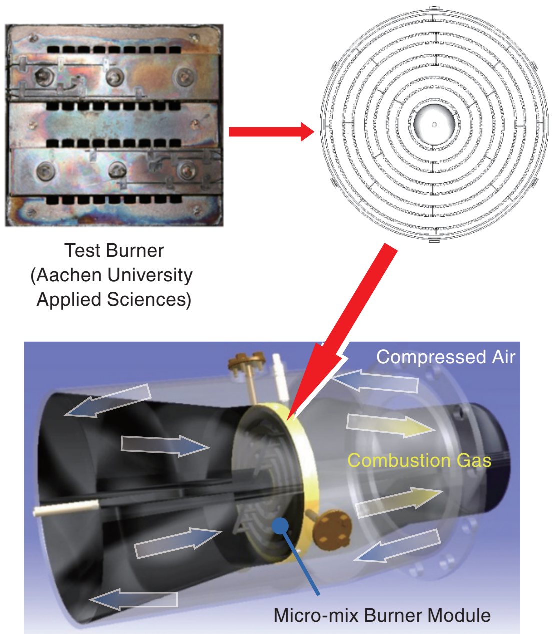

Figure 3 Schematic view of the first conceptual design of hydrogen Dry Low Emission combustor with micro-mix burner module.

established by ICAO (International Civil Aviation Organization). Decarbonizing aviation engines can greatly contribute to reducing environmental impact in terms of CO_2 and smoke, but the generation of NOx and water vapor can not be avoided. In particular, the pressure inside an aircraft engine is higher than that of an industrial gas turbine, making it difficult to reduce NOx emissions. In addition, since the power fluctuation during operation is large and rapid, the development of a combustor that can reduce the emission of harmful substances while keeping up with the changes in combustion conditions will be very important for the practical use of hydrogen aircraft.

Unburned hydrogen concentration measurement in gas turbine combustor development

As mentioned in the introduction, unburned hydrogen is hardly generated if hydrogen burns stably with a wide combustible range. However, when the engine is under low load or the transient state, the unstable combustion tends to occur and causes the generation of unburned hydrogen. In particular, aircraft engines have a risk of generating a large amount of unburned hydrogen temporarily because the air flow rate, pressure, and air excess rate change significantly in a short time compared to industrial gas turbines.

In the development of hydrogen combustors, not only the aforementioned reduction of NOx emissions during stable combustion, but also combustion efficiency above a certain level must be ensured even during low-load and transient operations. Therefore, both responsiveness (about 0.5 seconds) and accuracy (resolution on the order of several ppm) are required for measuring instruments in development tests.

Trial Measurement of unburned hydrogen concentration for aeroengine hydrogen combustor using HyEVO-1000

KHI is planning to introduce the HORIBA HyEVO-1000, which is scheduled to go on sale in 2023, as a device that can measure hydrogen concentration accurately in real time for aviation engine combustors. In preparation for the installation, a trial measurement with a demonstration machine was carried out in December 2022.

Figure 4 shows the appearance of the test apparatus. Hydrogen gas is injected from a fuel nozzle located in the combustor casing through a fuel manifold, and forms flames in an annular inner cylinder called a liner. Exhaust gas is sampled from the combustor outlet and fed through a

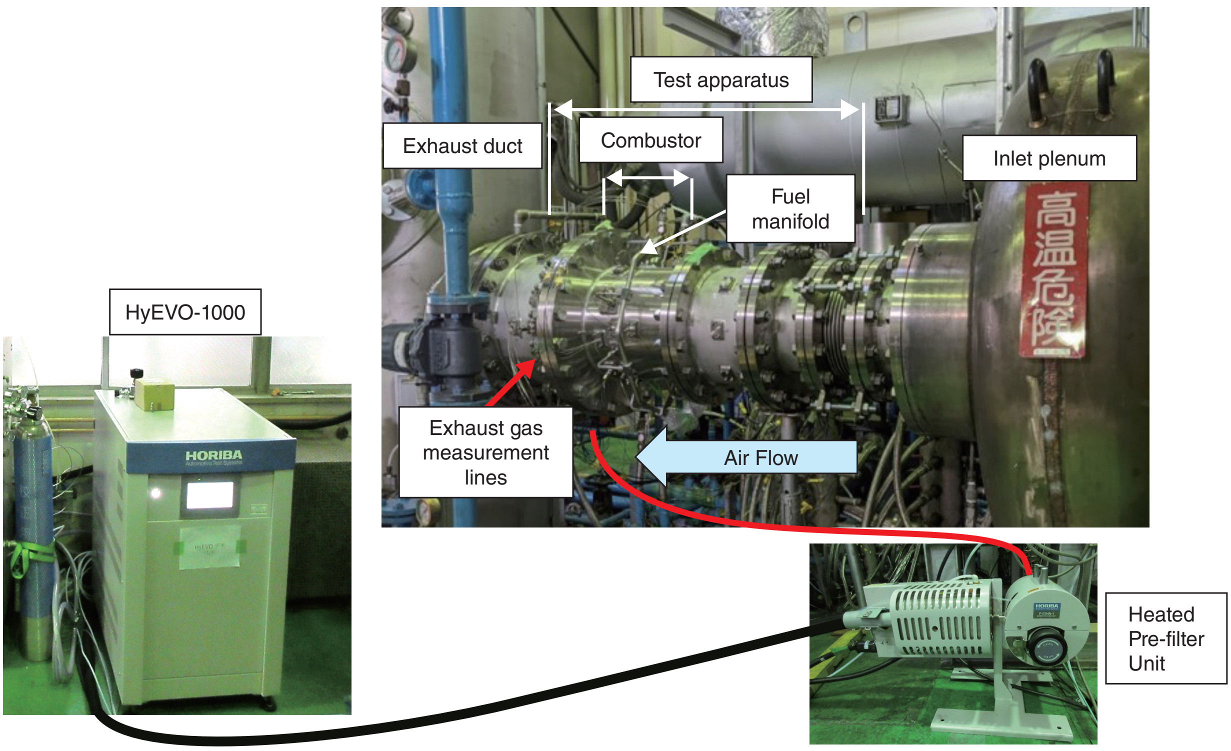

Figure 4 Test apparatus of hydrogen combustor for aeroengine.

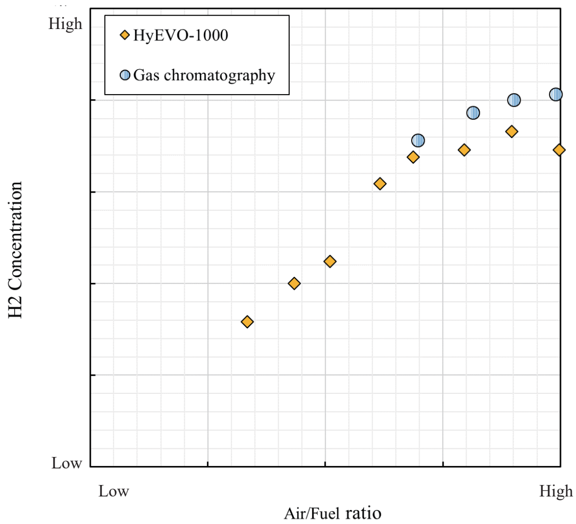

Figure 5 Comparison of hydrogen concentration between HyEVO-1000 and gas chromatography.

heating filter to the densitometer body. To verify the measured data, hydrogen concentration measurements by gas chromatography were also performed in parallel.

Figure 5 shows a comparison of hydrogen concentration measured by HyEVO-1000 with that measured by gas chromatography. In a series of air-fuel ratio conditions, both showed good agreement, and it was confirmed that the hydrogen concentration could be measured accurately. It was also responsive, and the combustion test was carried out smoothly.

Summary

KHI's efforts in the development of hydrogen combustors for industrial and aviation gas turbines are introduced, and the expected role of hydrogen concentration measurement for the development of combustors is described with an introduction of hydrogen concentration measurement examples using HyEVO-1000. It is expected that effective utilization of the high measurement capability not available in conventional measuring instruments will lead to the promotion of development of hydrogen combustors.

Considering that decarbonization by hydrogen utilization will become more active in the future, demand for hydrogen concentration measurement is expected to increase in various fields. From the user's point of view, not only the measurement capability but also the ease of handling and cost of the equipment are important points, and there are much to be expected such as further compactness, quiet structure, and adaptability to flexible operating range. It is expected that if manufacturers and users can cooperate with each other to realize more advanced and easy-to-use measuring instruments, they can greatly contribute to the demonstration of future technologies to reduce environmental impact.

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