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MICRO GAS TURBINE FIRING AMMONIA

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ABSTRACT

A demonstration test with the aim to show the potential of ammonia-fired power plant is planned using a micro gas turbine. 50kW class turbine system firing kerosene is selected as a base model. A standard combustor is replaced by a prototype combustor which enables a bi fuel supply of kerosene and ammonia gas. Diffusion combustion is employed in the prototype combustor due to its flame stability. Demonstration test firing ammonia gas was achieved using a new facility of large amount of ammonia supply. The gas turbine started firing kerosene and increased its electric power output. After achievement of stable power output, ammonia gas was started to be supplied and its flow rate increased gradually.

41.8kW power output was achieved by firing ammonia gas only. Ammonia gas supply increases NOx in the exhaust gas dramatically. However post-combustion clean-up of the exhaust gas via Selective Catalytic Reduction can reduce NOx successfully.

INTRODUCTION

Global warming is an important issue for human beings. The International Energy Agency (IEA) reported several scenarios of future energy share and global warming [1, 2]. Renewable energies are expected to account for 34% of annual emission reduction between the 6ºC Scenario (6DS) and the 2ºC Scenario (2DS) in 2050. 6DS shows the world is heading with potentially devastating results. Japanese government proposed 26% greenhouse gas cut until 2030.

Energy carrier technology is a key to increase renewable energy share in the primary energy. Japanese government call the year 2015 “the first year of hydrogen society”, many hydrogen refueling stations opened for fuel cell vehicles in Japan. Hydrogen storage and transportation systems using hydrogen carrier are important issue for hydrogen society. Ammonia is one of the candidates of the future hydrogen carriers.

Ammonia, NH_3 consists of nitrogen and hydrogen. Ammonia includes 17.6wt% of hydrogen. The Haber–Bosch process is the main industrial procedure to produce ammonia.

$$N_2 + 3\,H_2 \rightarrow 2\,NH_3 \quad (\Delta H = -92.4\ \mathrm{kJ{\bullet}mol^{-1}})$$

Ammonia can be produced from hydrogen and nitrogen, and ammonia can be cracked hydrogen and nitrogen at high temperature. Ammonia is carbon-free combustible material as the same way as hydrogen. Higher heat value of liquid ammonia is not high but it is as almost same as that of methanol.

$$2\,NH_3 + 3/2O_2 \rightarrow N_2 + 3\,H_2O \quad (\Delta H = -382.6\mathrm{kJ{\bullet}mol^{-1}})$$

Therefore energy density of liquid ammonia is higher than batteries. Ammonia is a common industrial chemical and its mass storage and mass transportation technology is practical.

Usage of ammonia as a fuel is not new idea. Ammonia was co-fired with other fuels in 1940s. In 1960s, the X-15 rocket plane set speed and altitude records powered by ammonia. A gas turbine engine firing ammonia gas was developed. The Solar Model T-350 gas turbine was used as a base engine by changing the combustor to an ammonia vapor combustor or a catalytic combustor [3, 4]. Values of measured combustion efficiency were unacceptably low for gas turbine operation. In 1970s pollution problem became big issue. However exhaust gas of ammonia combustor includes much nitrogen oxide because ammonia is nitrogen-containing fuel. It was difficult to overcome the NOx issue. Recently ammonia used for Selective Catalytic Reduction (SCR) system for NOx reduction of exhaust gas of engines. NOx issue of ammonia engine has become solvable problem. Recently development of ammonia fueled vehicle and ammonia fueled power plant have started in several countries [5].

Japanese government starts the project of researches and developments focusing on energy carriers in 2013. Ammonia has become one of the attractive energy carriers. The Japan Science and Technology Agency (JST) supports R&D project of energy carriers including ammonia. This project includes ammonia production and ammonia utilization. R&D of ammonia gas combustion is planned for power generation, automobile and industrial furnace. Especially gas turbine power generation is important to use ammonia gas effectively. Since most of thermal power stations have ammonia supply facility for NOx reduction system, thermal power stations have potential to handle ammonia as fuel. Therefore it is reasonable scenario to remodel combustors of gas turbine power plant to bi-fuel combustors firing fossil fuel and ammonia or hydrogen. AIST has been responsible for the demonstration of gas turbine firing ammonia to show the potential of ammonia as fuel. As the first step of the project, AIST tried to demonstrate a small gas turbine firing ammonia gas with kerosene to obtain the knowhow concerning to ammonia gas handling and combustion of ammonia. AIST succeeded 21 kW of power generation by combustion of kerosene with 30% ammonia in a 50kW class gas turbine [6]. Ammonia gas supply increases NOx in the exhaust gas dramatically. However ammonia gas supply to the catalyst can decrease NOx very well. Then demonstration test firing ammonia gas was achieved using a new facility of large amount of ammonia supply. This paper report the details of this first success of the ammonia firing gas turbine operation without cracking device of ammonia.

EXPERIMENTAL APPARATUS

A 50kW class micro gas turbine was selected as the base engine of ammonia fueled gas turbine. The specification of this gas turbine is shown in table 1. Its standard swirl combustor is replaced by a prototype swirl combustor which enables a bi-fuel supply of kerosene and gas fuel as shown in figure 1. Diffusion combustion is employed in the prototype combustor due to its flame stability. A conventional swirl injector for kerosene is set in the center of the combustor inlet. Ammonia gas is supplied from 12 holes outside of the kerosene injector. Since the laminar burning velocity of ammonia is lower than that of methane gas, air flow rate in the combustor was decreased using bypasses of air flow by making 6 large holes in the combustor liner.

Outline of ammonia fuel supply and gas turbine

50kW class gas turbine needs about 200kW of fuel input (about 17kg//h of ammonia gas) in the case that 25% of thermal efficiency. Latent heat of vaporization is about 6% of higher heating value. Over 12kW of heat is necessary for evaporation of ammonia supply for 50kW class gas turbine. Hence planed ammonia supply facility includes 1 ton gas cylinder and vaporizer as shown in figure 2. A gas cylinder of ammonia is

Table 1 Specification of base micro gas turbine

Manufacturer	Toyota Turbine and System Inc. (TTS)
Cycle	Regenerative cycle
Shaft	Single shaft
Compressor	Centrifugal one-stage
Turbine	Radial one-stage
Rotating Speed	80,000rpm
Electric Power Output	50kW
Fuel	Kerosene
Combustor	Single can, Diffusion combustion

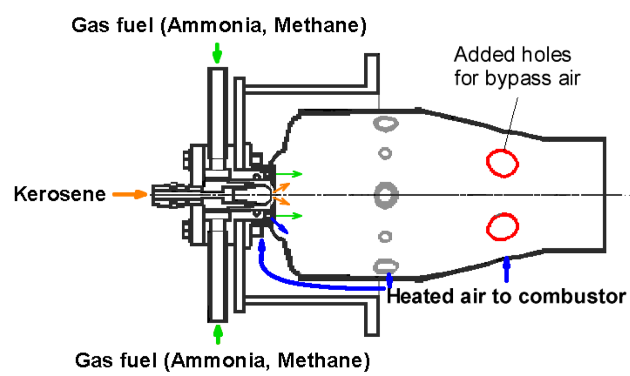


Figure 1 Prototype bi-fuel combustor

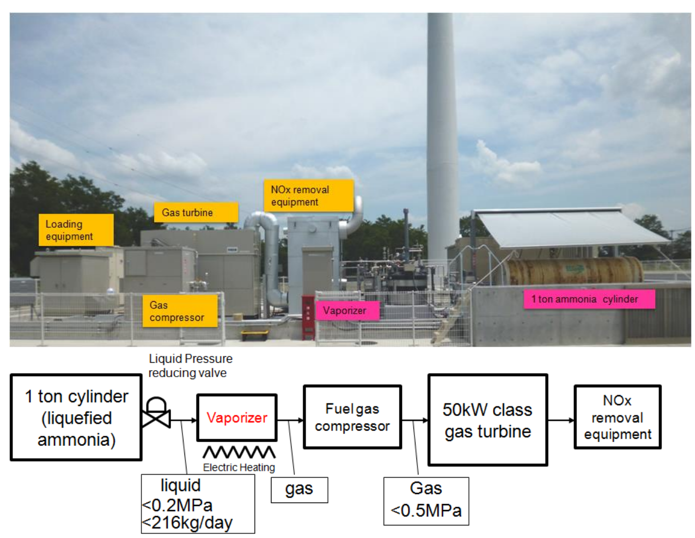


Figure 2 Ammonia supply facility and a micro gas turbine

not allowed to heat using an electric heater directly by Japanese law. Therefore liquid ammonia is supplied from 1 ton gas cylinder and evaporates by vaporizer using hot water. Fuel gas compressor compresses ammonia gas to over 0.5MPa and compressed ammonia gas supplied to a gas turbine. Exhaust gas of a gas turbine passes through NOx removal equipment and is emitted. Nitrogen gas cylinder connected to ammonia gas line for purging. Fuel gas compressor is made by TTS. Gas sealing parts are replaced for ammonia supply.

A methane gas supply facility is also prepared for basic research of natural gas-ammonia co-firing. As the first step, methane gas is mixed to pressurized ammonia gas near the gas fuel inlet of the prototype combustor.

Operation sequence

An electric fuel controller is also remodeled for control of ammonia gas and methane gas. Table 2 shows the combustor operation sequences for methane-ammonia co-firing and ammonia firing. At the starting-up of the micro gas turbine is fueled by kerosene. After the warming up of the gas turbine, the target value of the electric power output increase gradually from 0 to over 20kW. Then the gas fuel valve opens gradually around 25kW of electric power output. Since the target value of the electric power output is fixed, kerosene supply decrease with increase fuel gas supply. After stopping the kerosene supply, the target value of the electric power output and rotating speed etc are set to the test condition. The turbine outlet temperature and the combustor inlet temperature are checked to stability of the operation and to keep the temperature of the recuperator properly.

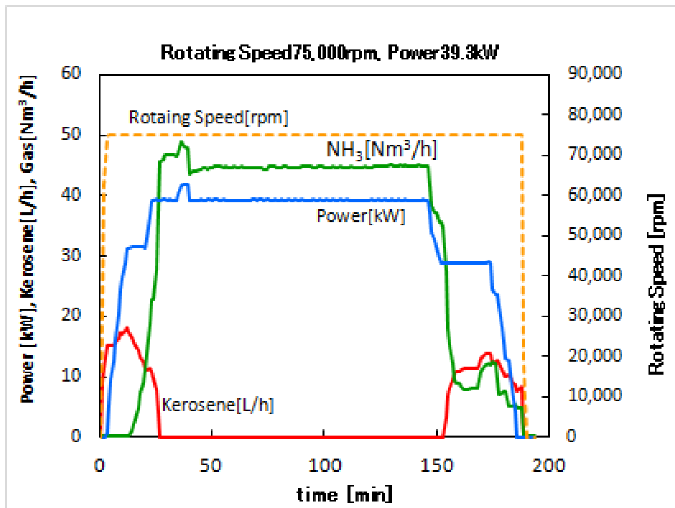
Table 2 Combustor operation sequence

CH4-NH3 combustion		NH3 combustion	
Procedure	Fuel	Procedure	Fuel
Start-up	Kerosene	Start-up	Kerosene
Increasing electric output	Kerosene	Increasing electric output	Kerosene
Opening fuel gas valve	Kerosene +CH4	Opening fuel gas valve	Kerosene +NH3
Stopping Kerosene supply	CH4	Stopping Kerosene supply	NH3
Starting NH3 supply	CH4+NH3		

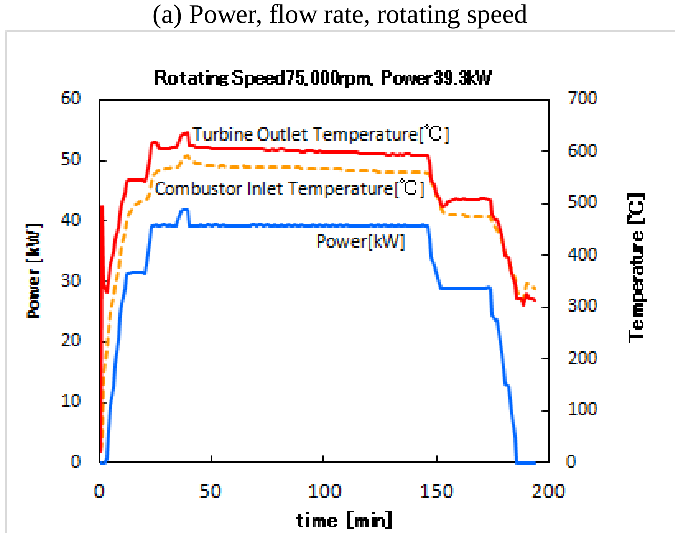
RESULTS

Trial of ammonia firing operation

Figure 3 shows the trial of the ammonia firing operation. At starting-up, the rotating increased until 75,000rpm. Then the electric power output increased until 31.5kW and started ammonia supply. After the combustor inlet temperature reached to 500ºC, the electric power output increased until 39.3kW and kerosene supply was stopped. 39.3kW of electric power output was succeeded with only ammonia firing. Although the 41.7kW of electric power output was tried, the turbine outlet temperature reached to the limitation that is 630ºC and electric power output was decreased. Combustor Inlet temperature and turbine outlet temperature decreased slightly and ammonia flow rate increased slightly with time. This tendency was caused atmospheric temperature change in the evening.

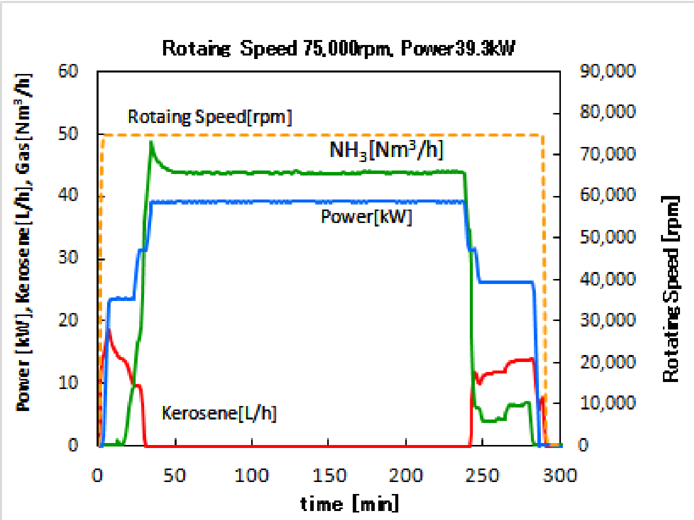


(a) Power, flow rate, rotating speed

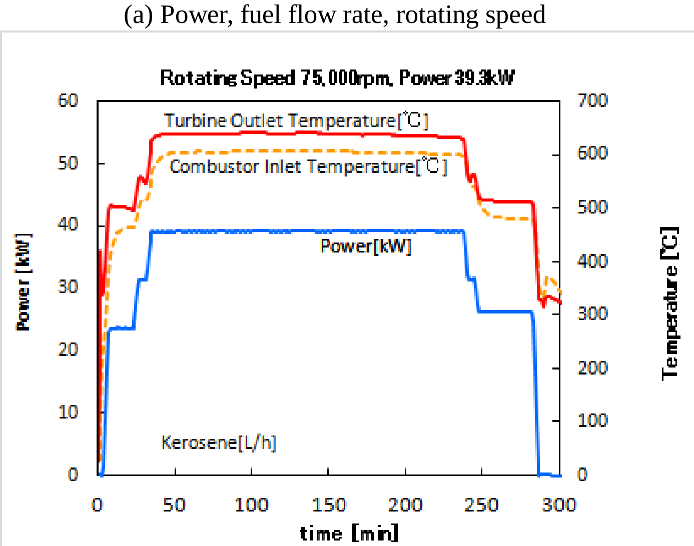


(b) Power, temperature

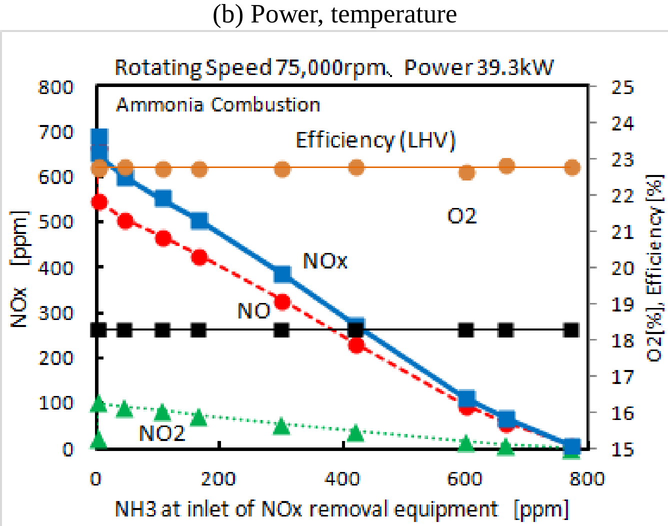
Figure 3 Ammonia firing operation in April.



(a) Power, fuel flow rate, rotating speed



(b) Power, temperature



(c) Exhaust gas, efficiengy

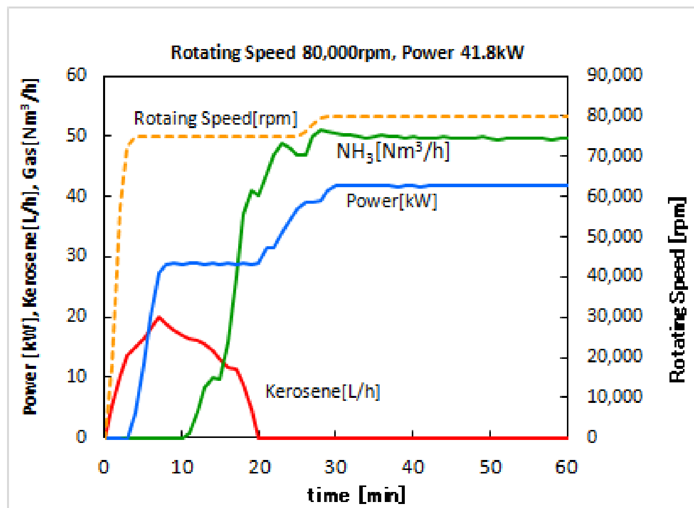
Figure 4 Ammonia firing operation in June

Emission and efficiency of ammonia firing operation

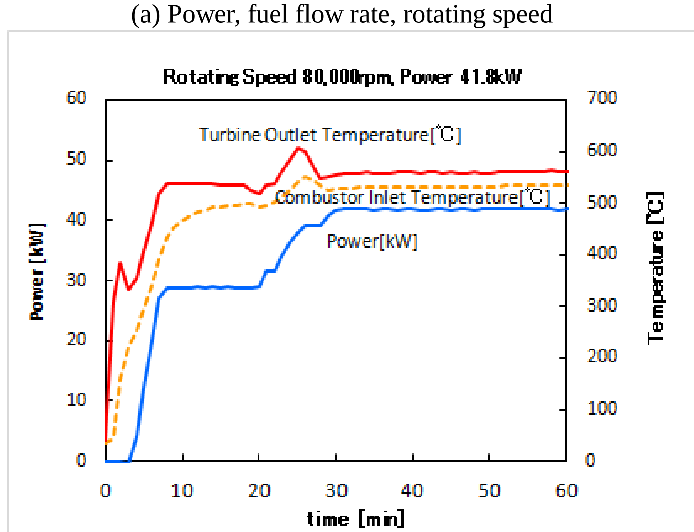
Figure 4 shows the ammonia firing operation for the exhaust gas analysis in the day time. Ammonia gas flow rate includes ammonia gas that was added to the exhaust gas for NOx removal. Although ammonia gas for NOx removal increased with time, increase of ammonia gas flow rate was not obviously. NOx, here summation of NO and NO_2, is about 700ppm and O_2 concentration was 18.3%. Ammonia gas added to the exhaust gas decrease NOx emission. When added ammonia gas to the exhaust gas was 700ppm, its amount was only about 2% of total ammonia gas. The efficiency base on lower heating value (LHV) was almost stable. Turbine outlet temperature was around 630°C that is the upper limit.

Increase of electric power output

To increase the electric power output, combustion gas flow rate should be increased instead of increase of turbine inlet temperature. Hence increase of air flow rate is tried by increase



(a) Power, fuel flow rate, rotating speed



(b) Power, temperature

Figure 5 Ammonia firing operation in July of rotating speed. Figure 5 shows the ammonia firing operation at 80,000rpm. From the starting-up to 36.7kW of electric power output, the operation sequence was similar to figure 4. Increase of rotating speed decrease turbine inlet temperature obviously. Then 41.8kW of electric power output is achieved.

Trial of methane-ammonia firing operation

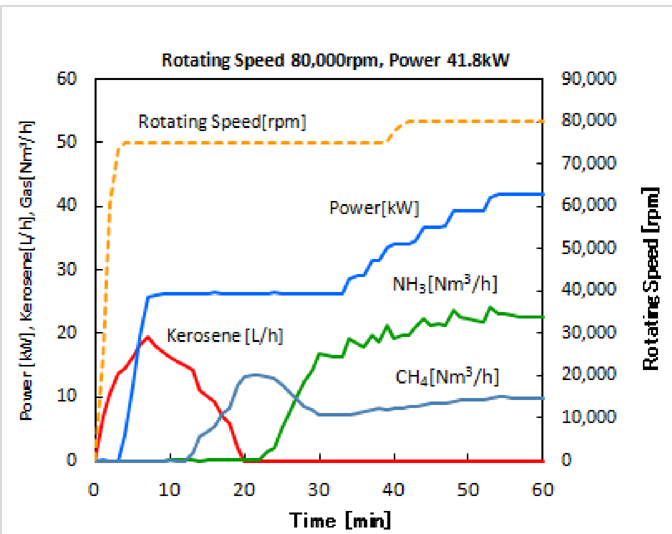
Methane-ammonia firing operation was tried as shown in figure 6. The ratio of methane and ammonia was tried to keep 1:2.5. In this case, lower heating value of methane is as almost same as that of ammonia. 41.8kW of electric power generation was achieved. This fact means that commercial natural gas firing gas turbine have a potential to be converted to natural gas ammonia firing gas turbine by remodeling of combustor, fuel control system and NOx removal equipment. Turbine outlet temperature is higher than that in the case of ammonia firing.

Figure 7 show the comparison of NOx emission. Ammonia gas supply increases NOx in the exhaust gas dramatically. NOx concentration in the exhaust gas in the ammonia firing operation exceeded 550ppm (1100ppm at 15%O_2). NOx emission in the ammonia firing operation is lower than that in the methane-ammonia firing. This fact means the NOx emission can be reduced by improvement of the combustor. However NOx removal equipment can reduce NOx concentration below 10ppm (20ppm at 15%O_2). That is post-combustion clean-up of the exhaust gas via SCR can reduce NOx successfully.

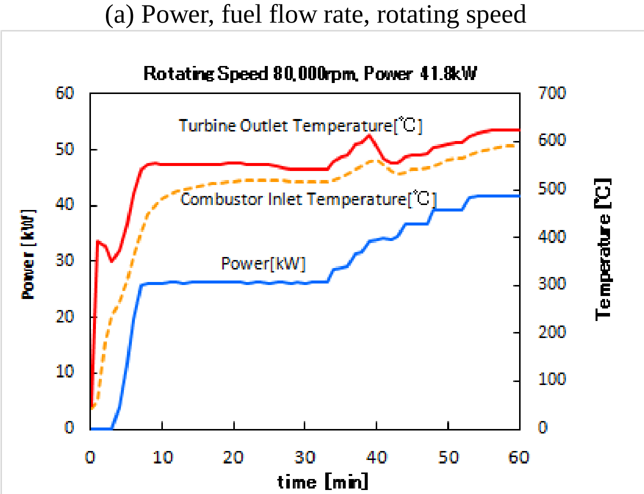
SUMMARY

50kW class micro gas turbine firing kerosene was remodeled for power output firing ammonia. A standard combustor is replaced with a prototype combustor which enables a bi-fuel supply of kerosene and gas fuel. Large amount ammonia supply was achieved with 1ton gas cylinder.

1. 41.8kW power output was achieved in ammonia firing operation.
2. 41.8kW power output was achieved in methane-ammonia firing operation.

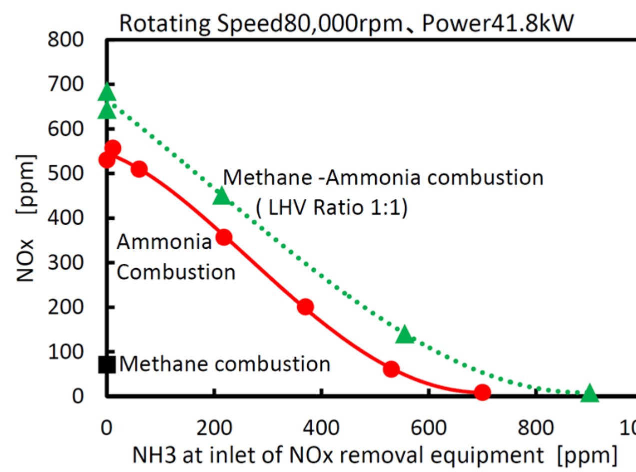


(a) Power, fuel flow rate, rotating speed

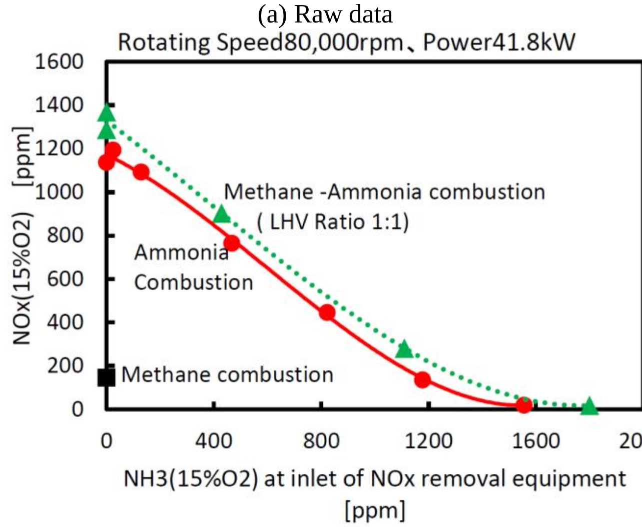


(b) Power, temperature

Figure 6 Methane-ammonia firing operation



(a) Raw data



(b) 15%O_2

Figure 7 NOx emission at exit of NOx removal equipment

3. Although NOx concentration in the exhaust gas of ammonia combustion exceeded 550ppm (1100ppm at 15%O_2), NOx removal equipment can reduce NOx concentration below 10ppm (20ppm at 15%O_2).

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