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Development of low-NOx combustor of micro gas turbine firing ammonia gas

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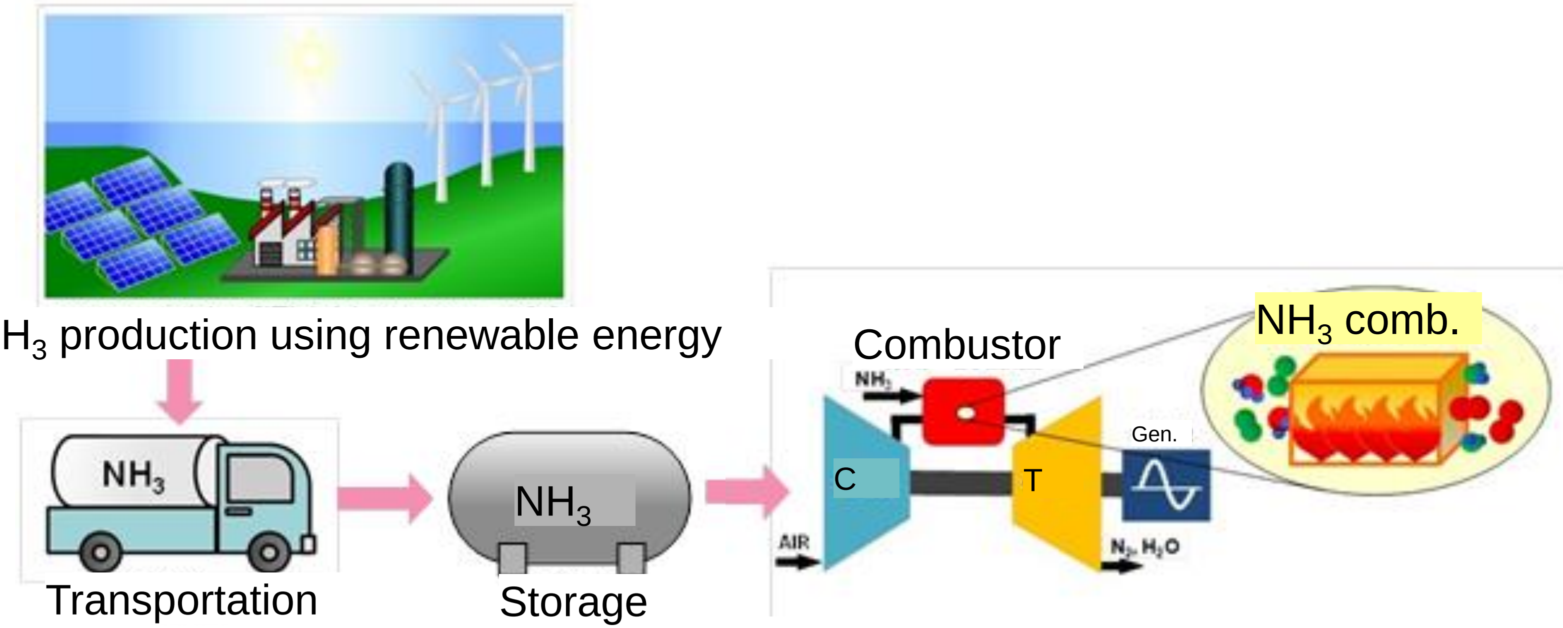
Contents

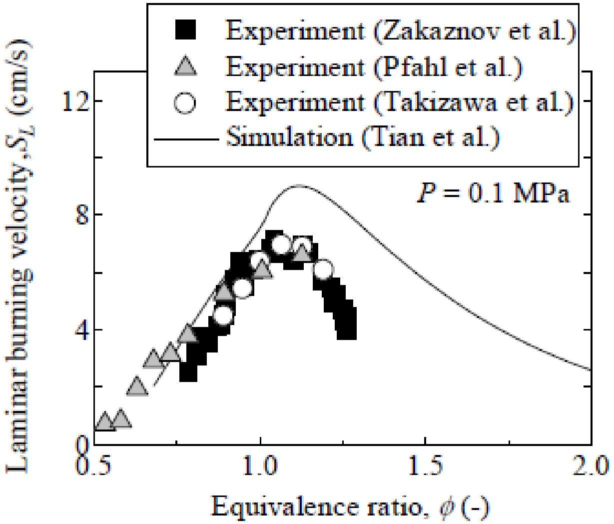
- Introduction
- Development of low NOx combustor
  - Combustor test rig
  - Combustion technique
  - Modify combustor
  - Results: Case 0 to 4
- Summary

NH_3 as a hydrogen energy carrier

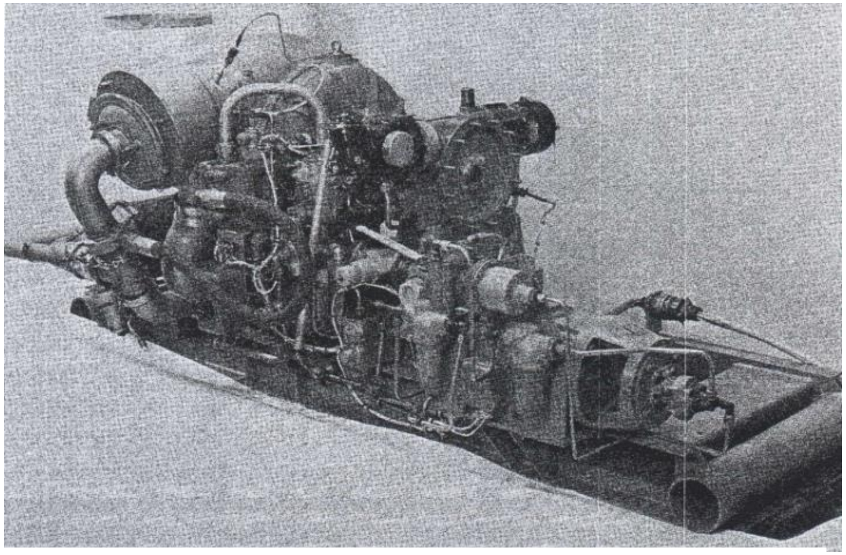


- To protect against global warming, a massive influx of renewable energy is expected.
- Although hydrogen is a renewable media, its storage and transportation in large quantity have some problems.
- Ammonia, however, is a hydrogen energy carrier and carbon-free fuel, and its storage and transportation technology is already established.
- As ammonia utilization, ammonia combustion and ammonia fuel cell are expected.

NH_3-air combustion



S_L of NH_3-air laminar premixed flame (Hayakawa,2015)



Solar model T-350 engine (Solar, *Final Technical Report*, DA-44-009-AMC-824, 1968)

- NH_3-air combustion is difficult because the laminar burning velocity is much lower than that of conventional hydrocarbon fuels.
- In 1967, Pratt examined an NH_3-fired gas-turbine combustor, and concluded that combustion efficiencies were unacceptably low.
- Verkamp showed that the pre-cracking of NH_3 and the additives improved the flame stability
- Because of those difficulties, the research and development of NH_3-fueled gas turbines were abandoned, and it has not been retried until recently.

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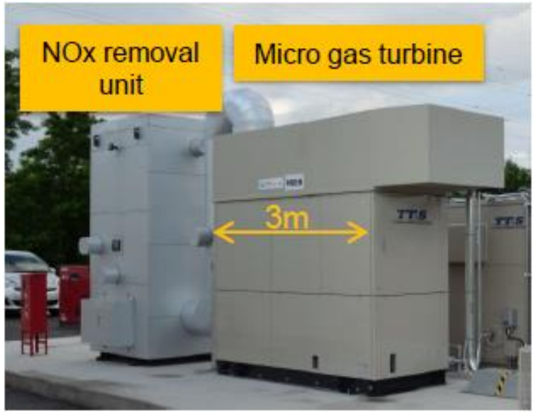
Recent work of NH_3 fueled gas turbine

NH_3-air combustion gas turbine (Evans, 2013)



NH_3-kerosene-air micro gas turbine in our institute (AIST)

- Recent demand for hydrogen energy carrier revives the interest of NH_3 fuel.
- Evans proposed NH_3-air combustion gas turbine using pre-cracked NH_3.
- Valera tested NH_3-CH_4-air gas turbine combustors.
- AIST successfully performed ammonia-kerosene co-fired gas turbine power generation in 2014, and ammonia-fired gas turbine power generation in 2015.
- It is very important to focus on high combustion efficiency and low NOx emission, because combustion efficiency had been unacceptably low in the 1960s.
- AIST demonstrated ammonia-fired gas turbine power generation without any additives to enhance flame stability of ammonia combustion. Instead, AIST used a regenerator-heated, diffusion-combustion gas turbine combustor.

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Fukushima Renewable Energy Institute, AIST (FREA)

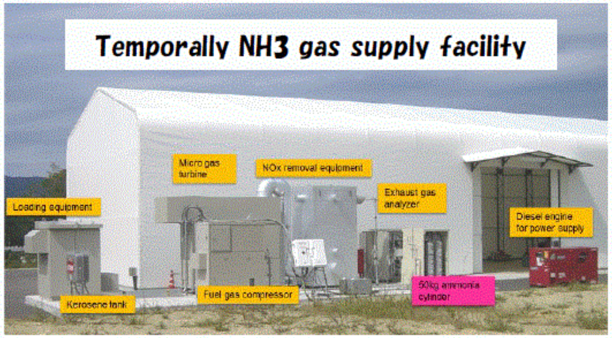
opened in April, 2014 at Fukushima prefecture

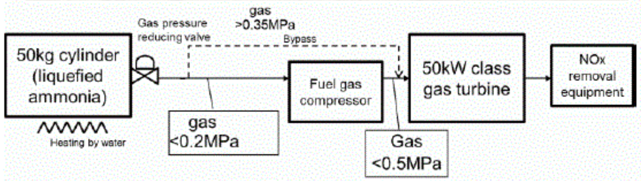
Renewable Energy Research Center

- Energy Network Team
- Photovoltaic Power Team
- Hydrogen Energy Carrier Team
- Geothermal Energy Team
- Wind Power Team
- Shallow Geothermal and Hydrogeology Team

Progress of ammonia gas turbine in AIST

Phase I :
NH3-Keosene Combustion
FY 2013-2014

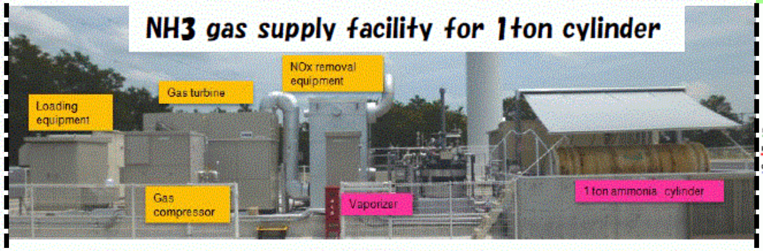


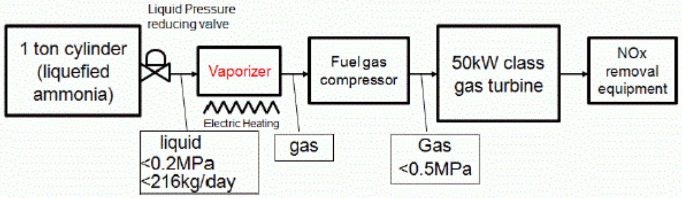


21kW power generation was achieved with about 30% decrease of kerosene by supplying ammonia gas.

Ammonia gas supply to the NOx removal equipment can decrease NOx emission very well.

Phase II :
NH3 Combustion
CH4-NH3 Combustion
FY 2015



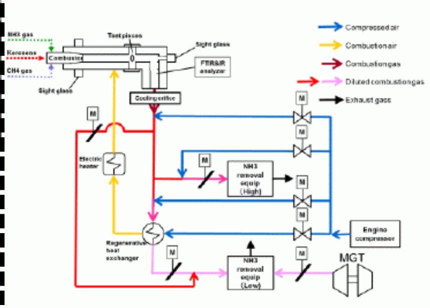


41.8kW power generation firing ammonia gas was achieved.
Goal : CO_2 free Power Station

41.8kW power generation co-firing of methane and ammonia gas was achieved.
Goal : NH3 cofiring at Power Station firing natural gas

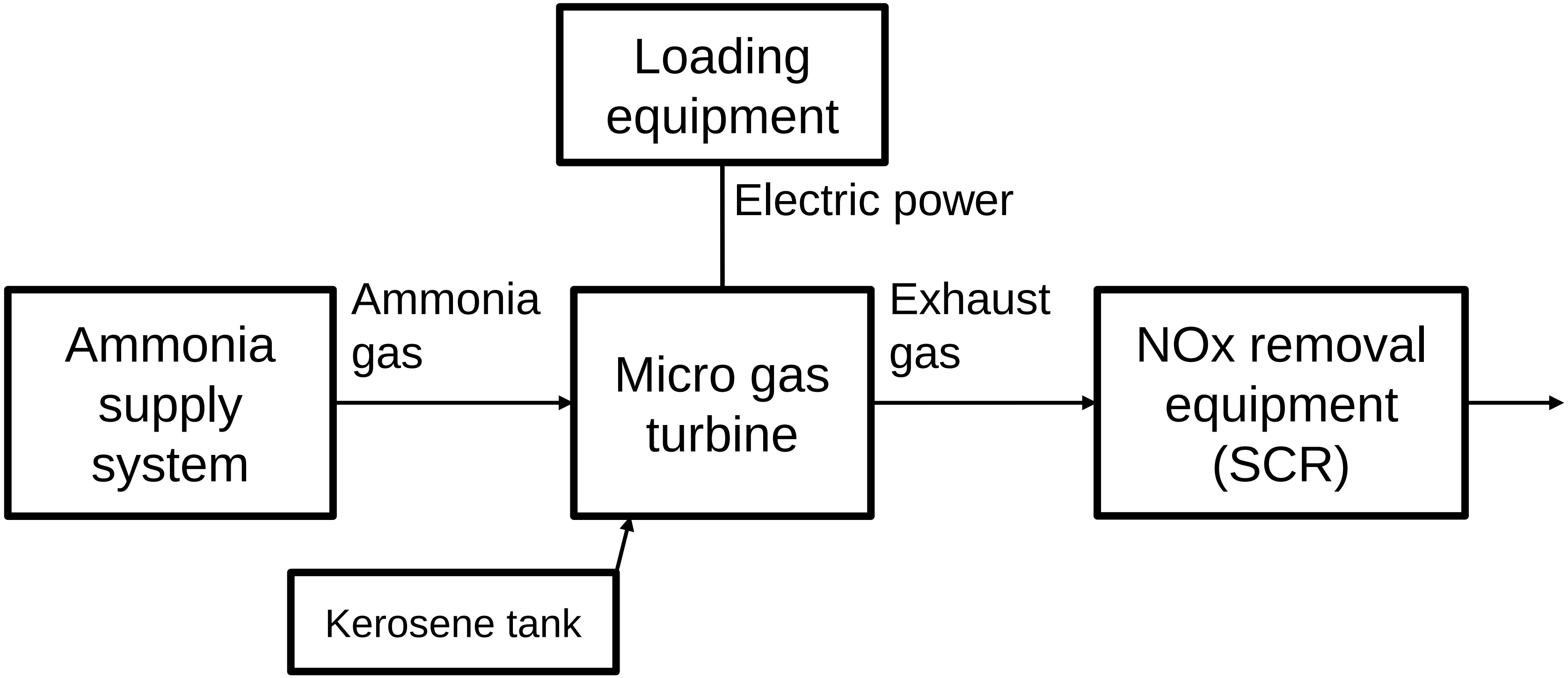
Phase III :
Combustor Test Rig
CFD
FY 2016 -

Start of combustion test by Combustor Test Rig



Development of low NOx combustor by cooperation with Tohoku university

Power generation system



- Power generation system consists of a micro gas turbine, a ammonia supply system, a NOx removal equipment, and a loading equipment.

Gas turbine power generation Micro gas turbine

Table 1 Specification of micro gas turbine

Company	Toyota Turbine and Systems Inc.
Gas turbine model	TPC50RA
Rated electric power output	50 kW
Voltage	200 V
Frequency	50/60 Hz
Soundproofing	below 70 dB
Size	W 3250 mm x D 1000 mm x H 2600 mm
Weight	2530 kg
Engine model	TG051R
Engine type	Regenerative cycle, Single shaft
Compressor	Centrifugal one-stage
Turbine	Radial one-stage
Rotating speed	80000 rpm
Fuel	Kerosene
Fuel consumption	Max. 21.1 L/h
Burning air volume	1370 Nm^3/h
Exhaust gas temperature	271 °C

- A 50 kW-class micro gas turbine with regenerator was selected.
- The kerosene-firing combustor was replaced by a bi-fuel prototype combustor co-firing kerosene and ammonia.
- Diffusion combustion was used to ensure flame stability.

Contents

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Phase 3

- Combustor Test Rig
- FY 2016-
- Development of low NOx combustor by cooperation with Tohoku University

- The drawback of the AIST's facility is that it requires a large-size selective catalytic reduction (SCR) to decrease the high concentrations of NOx.
- To increase the scale and number of NH_3 combustion gas-turbine power plants, it is necessary to develop low-NOx combustion technology because large scale SCR and large numbers of SCR systems are essential without the development of low NOx gas-turbine combustors.

Test conditions of combustor test rig

Table 2 Specification of combustor test rig

Rotating speed	75000 rpm
Electric power output	43 kW
Rated air flow of combustor	1256 Nm^3/h
Rated methane flow	291 L/min
Rated ammonia flow	731 L/min
Combustor inlet temperature	595 ℃
Combustor inlet pressure	210 kPa
Highest temperature	1300 ℃

Table 1 NH_3–air combustion condition

	NH_3 Target	NH_3 L/min	CH_4 L/min	LHV kJ/s	Air m^3/h
NH_3 ratio=1	600	600	0	142	1256
	700	700	0	165	
	800	800	0	189	
	900	900	0	212	
	1000	1000	0	236	
Larger than NH_3 supply	1100	1000	40	260	
	1200	1000	80	283	
	1300	1000	120	307	
	1400	1000	160	331	

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Combustion technique: Rich-lean two-stage combustion

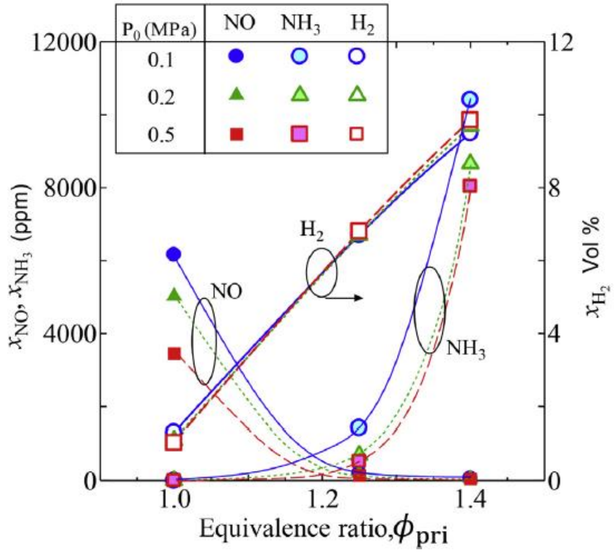

Fig. 8 — STAE of NO, NH_3, and H_2 of NH_3/air premixed flames without secondary air injection in terms of P_0 and ϕ_{pri}.

Source: K.D.K.A.Somarathne, *Int. J. Hydrogen Energy* (2017)

- It was found at Tohoku Univ. that rich-lean two-stage combustion method and a control of equivalence ratio of the primary combustion zone to around the value of 1.1 to 1.2 significantly decreases NO emissions in gas-turbine swirl combustor.

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Contents

Modifications applied to the combustor

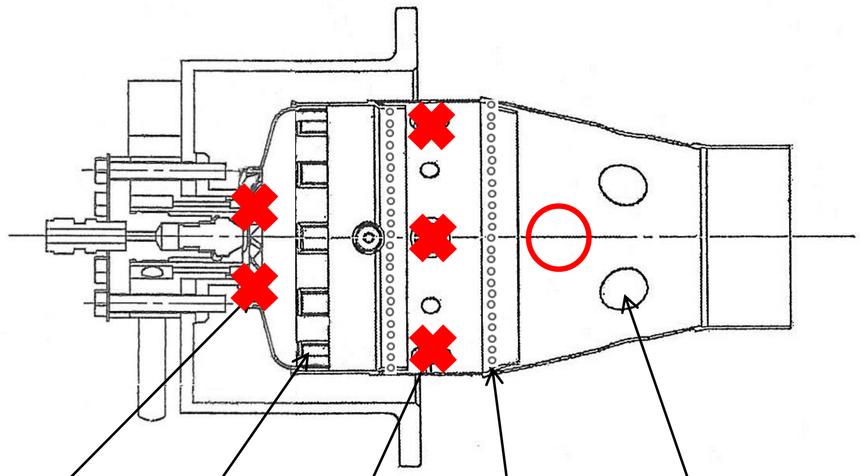


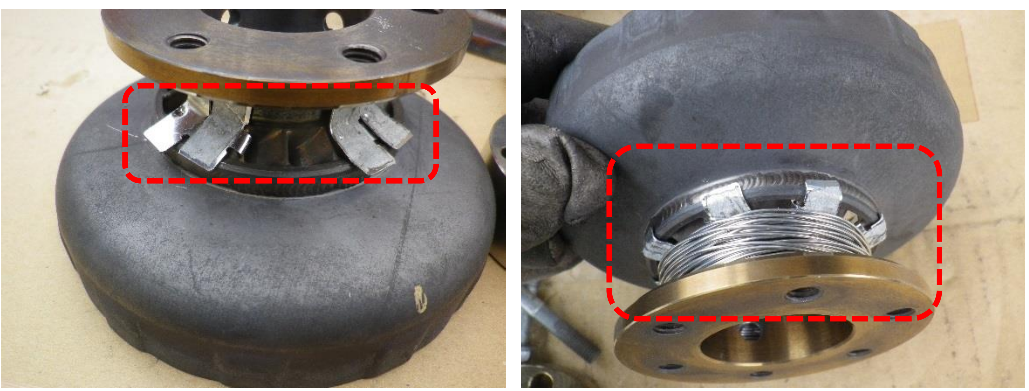
Table 1 Configuration of the combustor.

	Primary dilution holes	Area of air swirler	Sleeve-fitting gap area	Small cooling holes	Area of secondary dilution holes	Fuel/Oxidizer
Case 0	With	1	With	With	1	CH4+NH3/Air
Case 1	Without	1	With	With	1.4	CH4+NH3/Air
Case 2	Without	1	With	With	2	CH4+NH3/Air
Case 3	Without	0.5	With	With	1.4	CH4+NH3/Air
Case 4	Without	1	With	Without	2	CH4+NH3/Air

How to modify the combustor

Fill the holes of the primary combustion zone.

Open the holes of the secondary dilution zone by drill.



Halved the area of air swirler by stainless hook or wire reel.

Contents

- Introduction
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  - Combustor test rig
  - Combustion technique
  - Modify combustor
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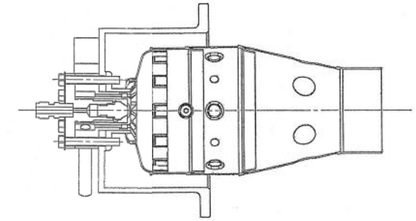
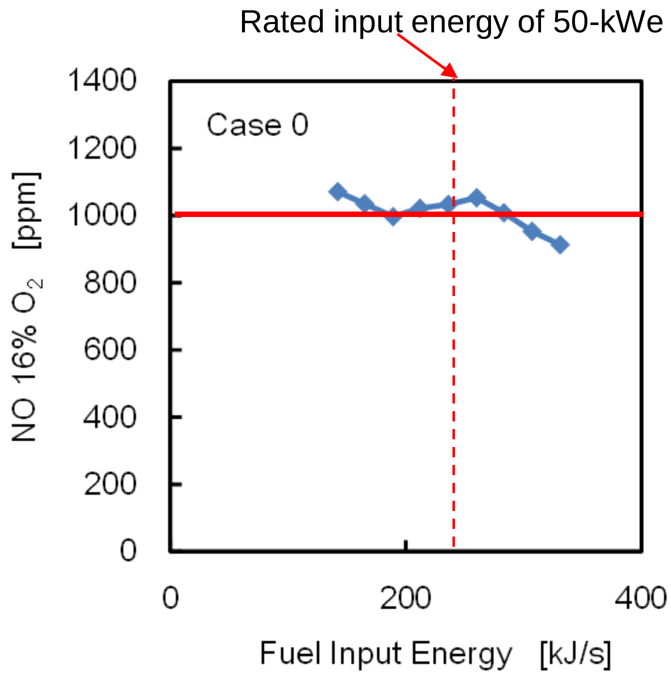
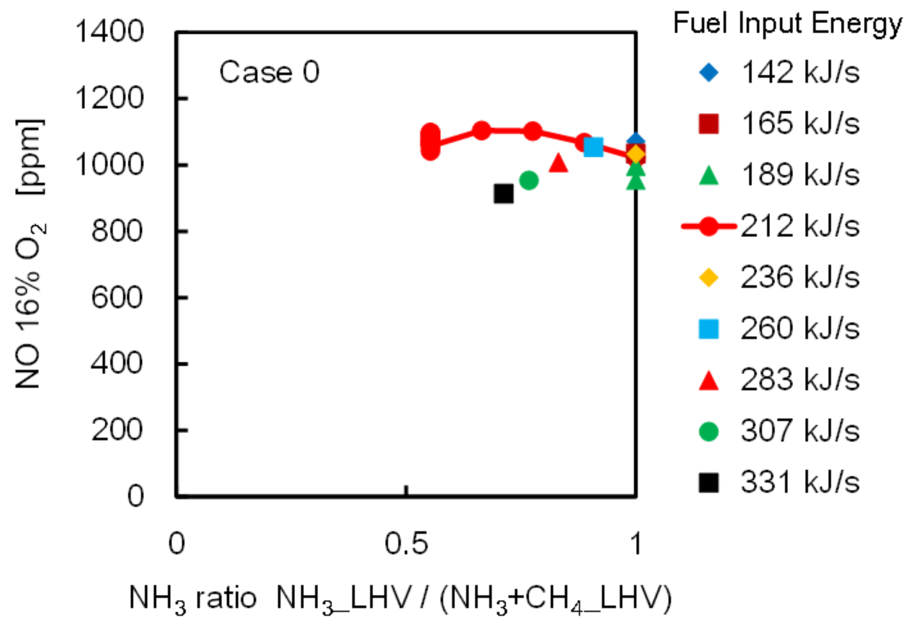
- Summary

Case 0 (base case)

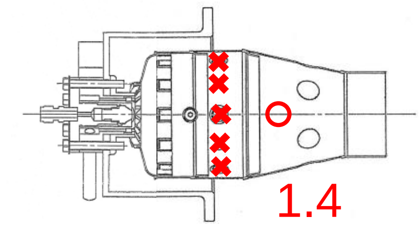


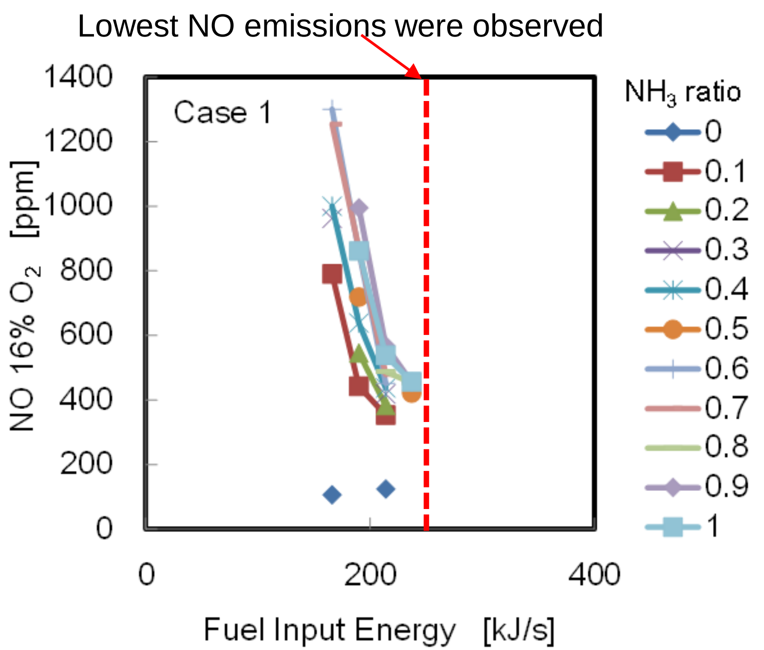


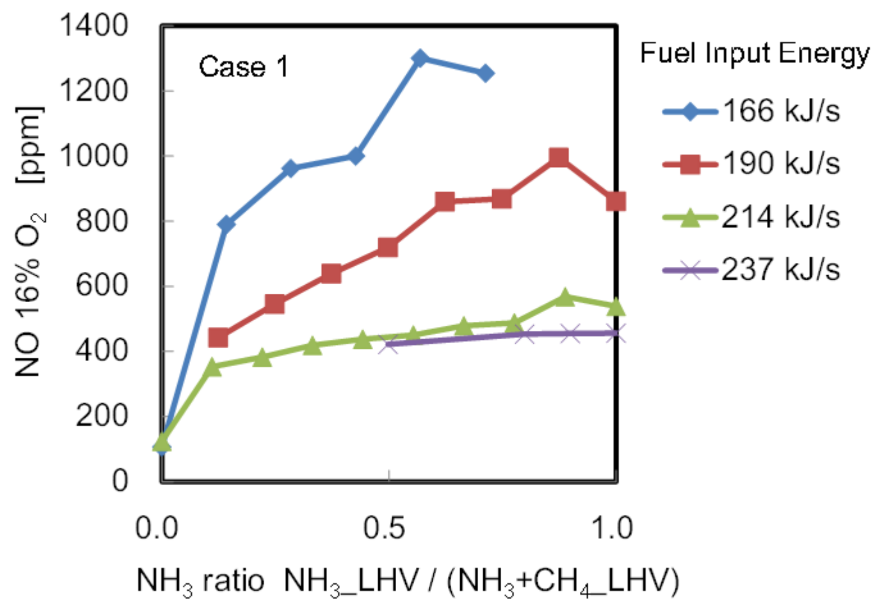


- Case 0 is base case of the original combustor.
- NO emission is flat 1000 ppm in the range of 142 to 330 kJ/s of fuel input energy.

Case 1

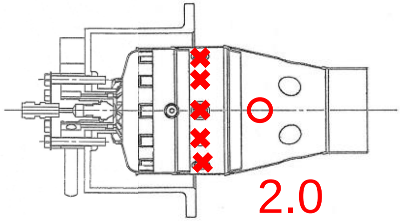




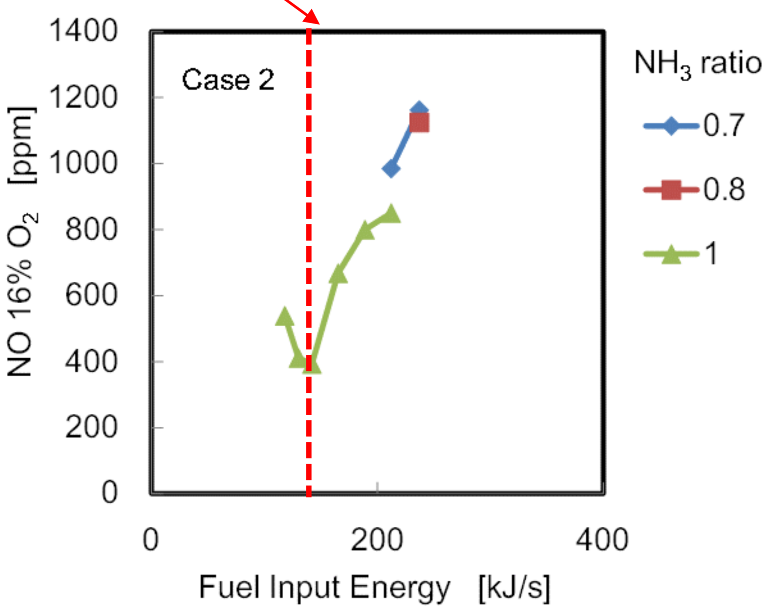


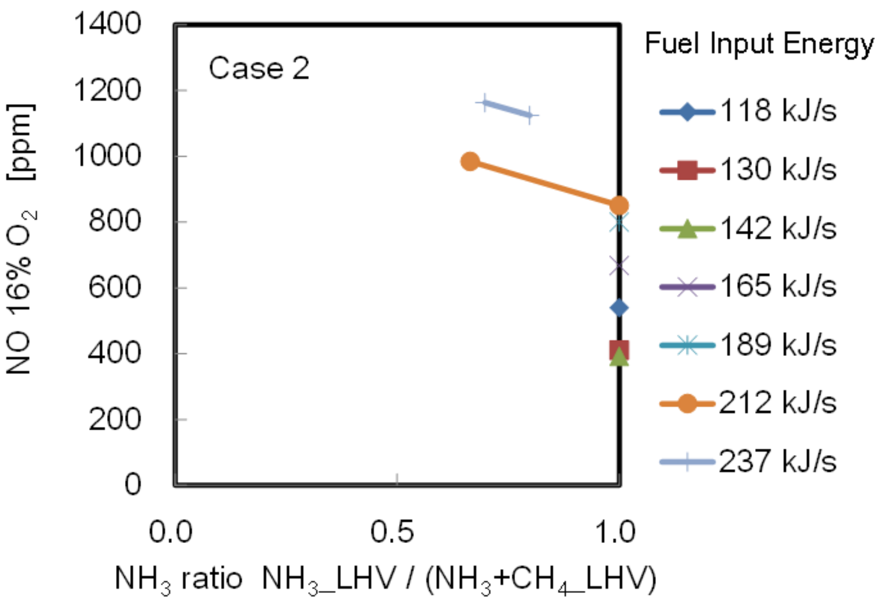
- Case 1 is without the primary dilution holes and the areas of the secondary dilution holes were modified to 1.4X.
- The lowest NO emissions were observed at the point higher than the highest NH_3 fuel energy.

Case 2



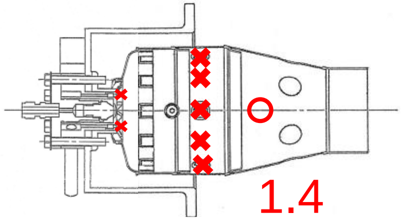
Lowest NO emissions were observed

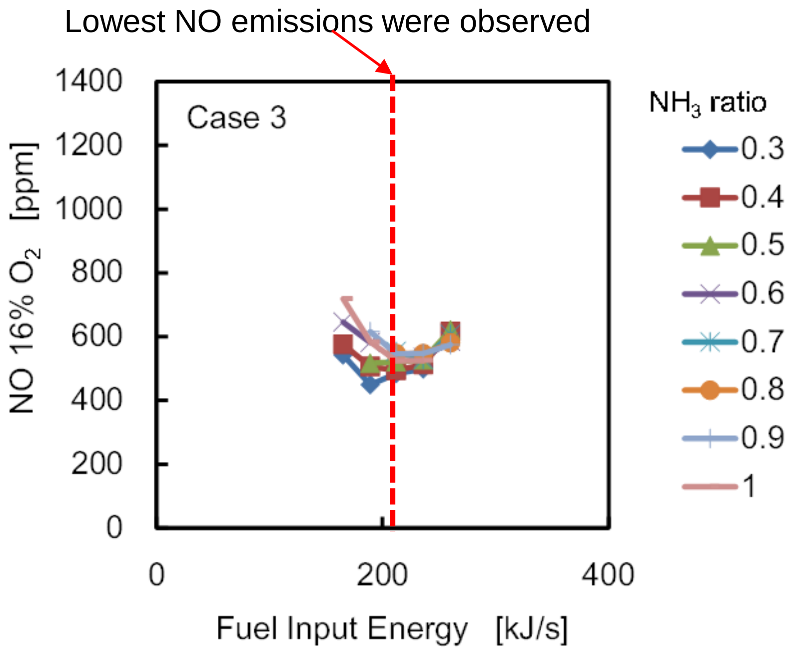


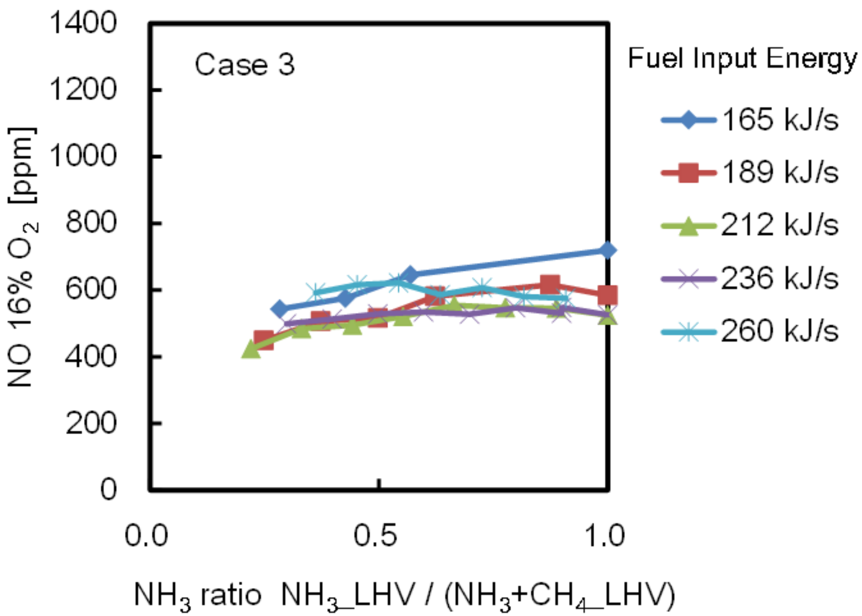


- Case 2 is when without the primary dilution holes and the areas of the secondary dilution holes were modified to 2.0X.
- The lowest NO emissions were observed at a fuel energy of 140 kJ/s.

Case 3

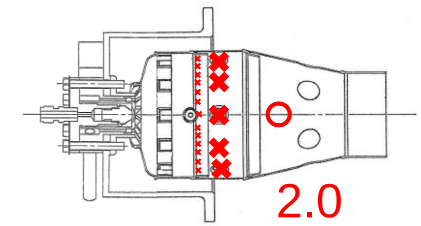


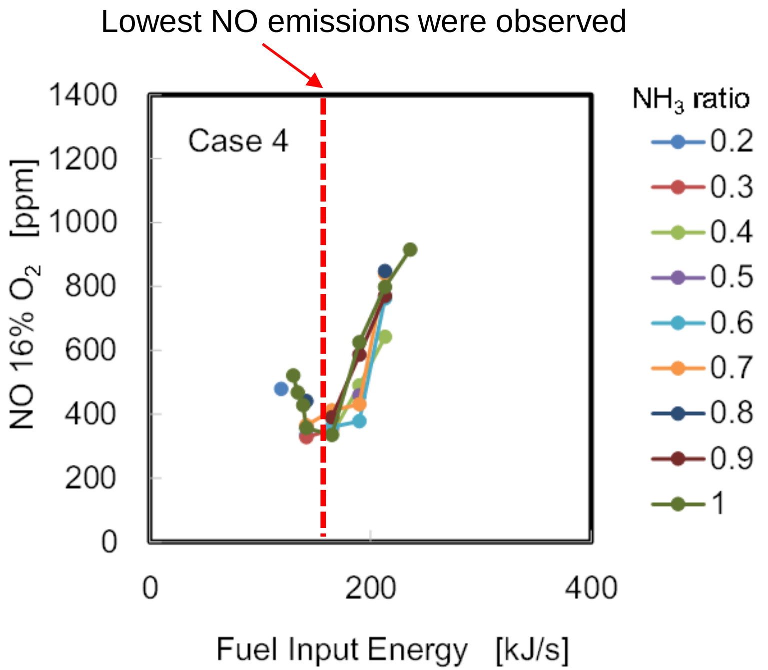


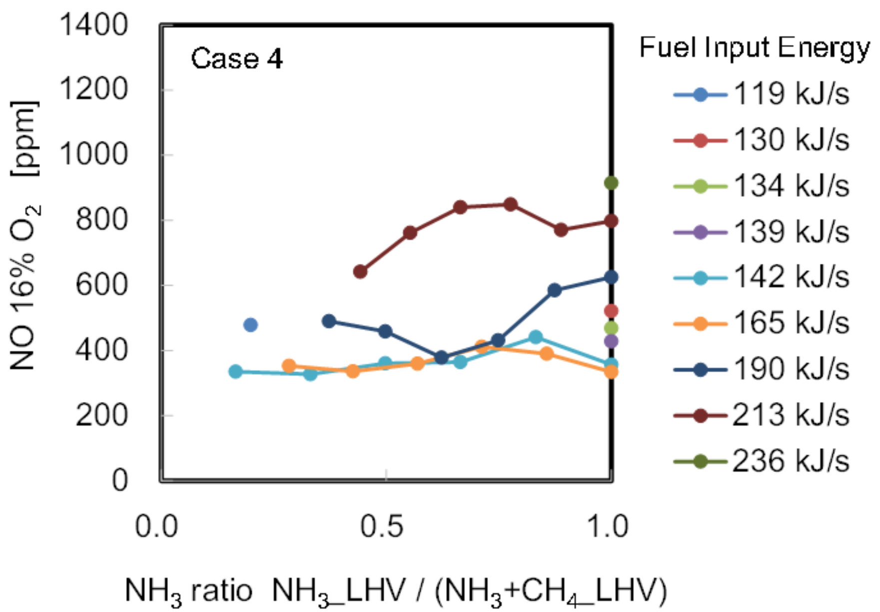


- Case 3 is when without the primary dilution holes, the area of the air swirler was halved, and the area of the secondary dilution hole was modified to 1.4X.
- The fuel energy where the lowest NO emissions were observed was lower than that in case 1.

Case 4







- Case 4 is when without the primary dilution holes, small cooling holes were absent, and the area of the secondary dilution holes were modified to 2.0X.
- The lowest NO emissions was lower than that in case 2.

Contents

- Introduction
- Development of low NOx combustor
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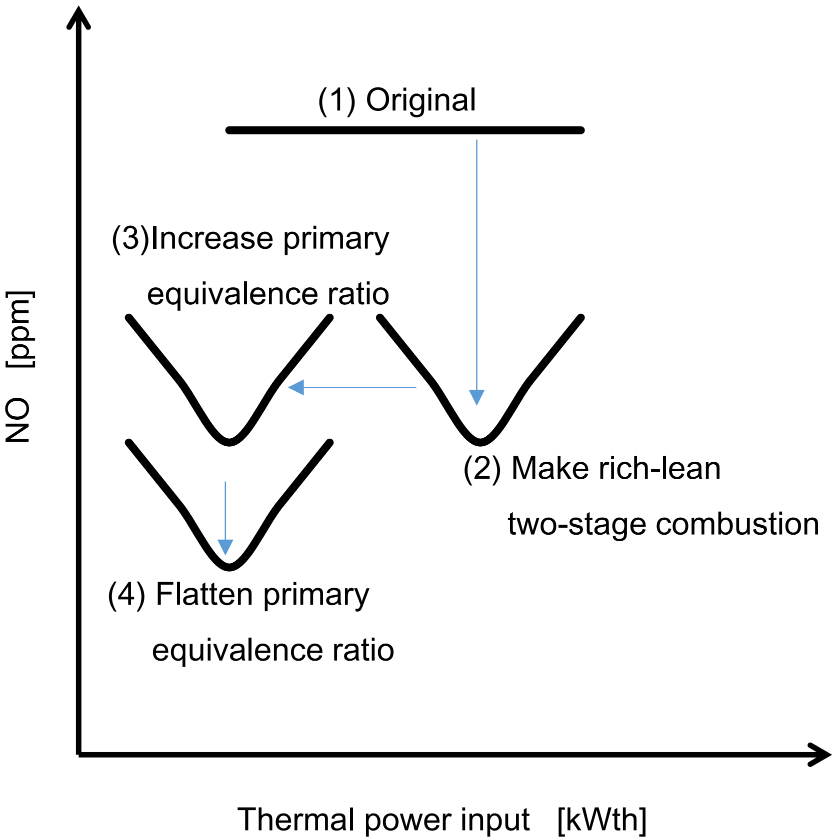
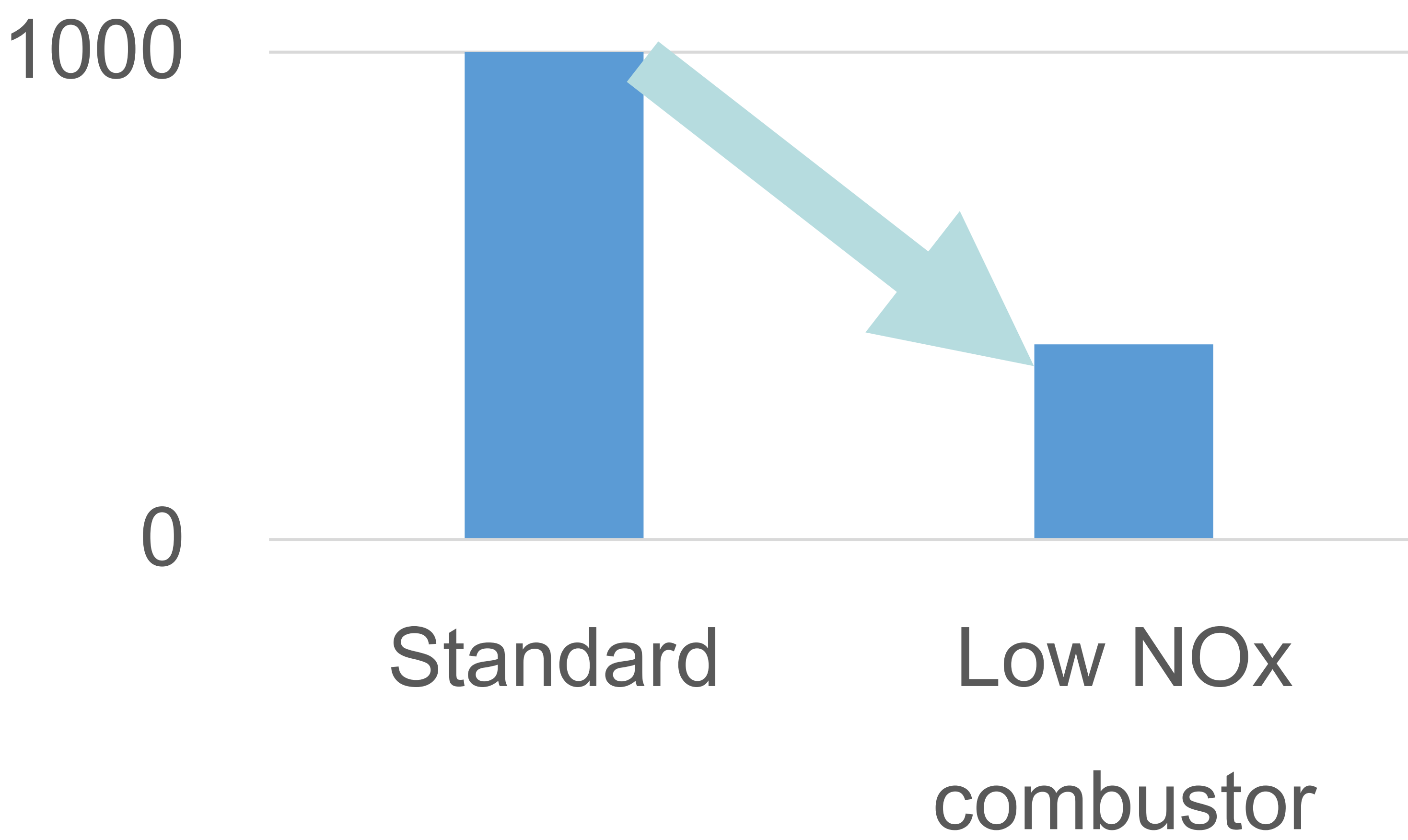
  - Combustion technique
  - Modify combustor
  - Results: Case 0 to 4
- Summary

Summary



- These modifications were intended to increase the equivalence ratio of primary combustion zone.
- With increase of the primary equivalence ratio, valley of NO emission of the modified combustor was observed in the range of fuel input energy of 140 to 236 kJ/s.
- Combustor test rig results show that rich-lean two-stage combustion technique has the ability of low-NOx combustion.

Low NOx Combustor



Acknowledgement

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Thank you for your attention !!

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