Development of Ammonia Fuel Conversion Technology for Coal-fired Boilers Aiming for Decarbonized Society

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The Green Growth Strategy to achieve carbon neutrality by 2050 has been established by the Japanese government and sets forth a "roadmap" for the growth of the fuel ammonia industry. In connection with this, ammonia fuel conversion in coal-fired thermal power generation has been positioned as a future initiative. Mitsubishi Heavy Industries, Ltd. is developing technology for fuel conversion to ammonia for both circular firing and opposed firing systems of coal-fired boilers in response to the needs of various customers in Japan and overseas. This paper reports the completion of the development of ammonia single-fuel burners and the prospect of their application to actual boilers, and provides an outline of the modification plans of a boiler plant for ammonia fuel conversion.

1. Introduction

Mitsubishi Heavy Industries, Ltd. (hereinafter referred to as MHI) has declared its intention to achieve carbon neutrality by 2040 (MISSION NET ZERO) and seeks carbon neutrality of the existing infrastructure. To achieve this carbon neutrality in thermal power generation, reducing CO_2 emissions from coal-fired boilers is important. In this context, fuel conversion to ammonia, which does not emit CO_2 even when burned, has been attracting attention.

The Green Innovation Fund Project aims to establish a fuel ammonia supply chain that integrates fuel ammonia supply and demand and promotes the development of technology that will enable 50% or more ammonia fuel conversion in coal-fired power plants, which is needed to introduce 30 million tons of ammonia annually in Japan by 2050.

In order to meet the diverse needs of various customers for ammonia utilization, development of liquid-firing and gas-firing ammonia single-fuel burners that can be used for both circular firing and opposed firing boilers has been completed, and the prospect of application in actual boilers has been achieved. In addition, a plan for boiler plant modification using the developed ammonia single-fuel burners has been established. The above topics are reported in this paper.

2. Ammonia fuel conversion concept

2.1 Concept of ammonia single-fuel burner that enables 50% or more fuel conversion

A previous report described a two-stage electric furnace test in which coal and ammonia were premixed. As a result, NOx increased as the ammonia combustion rate increased, and a maximum ammonia combustion rate of 50% was achieved. In addition, NOx sensitivity to the air ratio increased during ammonia combustion.

On the other hand, by burning coal and ammonia in separate (single-fuel) burners in a small-scale combustion test, the air ratio for each fuel could be easily optimized and NOx could be suppressed even when the ammonia combustion ratio was increased. [(1)]

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Based on these results, a method to install ammonia single-fuel burners separately from coal burners and burn the fuel in the boiler furnace was adopted. Burners on multiple stages are installed in the boiler in the vertical direction. By changing the number of stages installed on the ammonia burners, fuel conversions from a low-rate conversion, such as 20%, to a high-rate conversion, such as 50% or more, became possible. This method also allows for easy control of the air ratio of each burner, thus better results in terms of NOx reduction are expected compared to combustion of coal and ammonia in the same burner.

Furthermore, a burner structure that enables switching the existing coal burners and start-up oil burners to ammonia single-fuel burners has been devised based on the premise that, while at the stage where the use of fuel ammonia is still expanding, rated output and environmental performance of coal single-fuel operations are still needed even after burner modification.

2.2 Ammonia single-fuel burner for each firing system

(1) Circular firing system

For circular firing boilers, the function of an ammonia single-fuel burner was added to the start-up oil burner. For liquid-firing, a liquid ammonia spray nozzle was placed in the start-up oil burner section. For gas-firing, a flat head nozzle, which is widely used in MHI gas-firing burners, was installed (**Figure 1**(a)). The ammonia burner is sandwiched between the coal burners, and when burning coal and ammonia in neighboring burners, the coal flames and ammonia flames are in close proximity. Therefore, while taking into account the influence of mutual flames on ignition and NOx characteristics, a performance evaluation during the combustion test was carried out with both coal and ammonia burners burning.

(2) Opposed firing system

For opposed firing boilers, the function of an ammonia single-fuel burner was added to the coal burner. Ammonia is a gas at normal temperature and pressure, so liquid ammonia injected from the nozzle immediately vaporizes in the boiler furnace. Therefore, a multi-spud nozzle structure was used for liquid-firing, which has already been demonstrated in existing gas firing burners. Also for gas-firing, as with liquid-firing, the existing gas firing burner structure was used. Both liquid-firing and gas-firing burners were optimized for ammonia combustion in terms of the number of injection holes, injection angle, and jet velocity (Figure 1(b)). Since the distance between the burners of opposed firing boilers is far and stable ignition and flame stabilization are essential for a single ammonia burner, a performance evaluation in the combustion test was carried out under ammonia single-fuel combustion conditions.

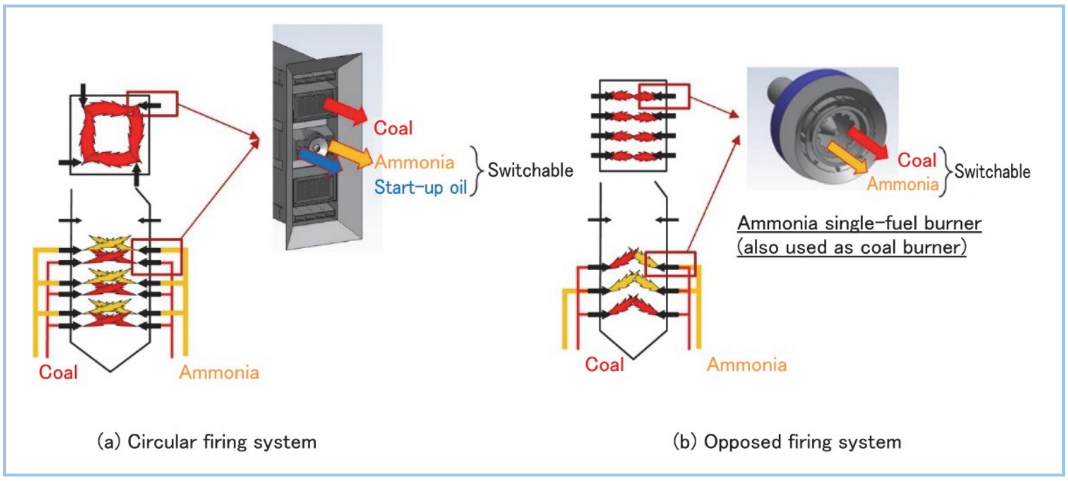

Figure 1 50% or more ammonia combustion burner patterns for two combustion systems and ammonia single-fuel burners

3. Performance verification of ammonia single-fuel burners by combustion test

3.1 Combustion test equipment

For ammonia combustion tests, the ammonia supply equipment was installed under a project commissioned by the New Energy and Industrial Technology Development Organization (NEDO)

(**Figure 2**(a)). This equipment can supply liquid directly with a liquid feed pump and gas with a vaporizer, and can be used for both liquid-firing and gas-firing tests. Combustion tests were conducted using MHI's 0.5 t/h combustion test furnace (rated heat input: 3.7 MWth) (Figure 2(b)) and 4 t/h combustion test furnace (rated heat input: 23 MWth) (Figure 2(c)). A performance evaluation was conducted using the 0.5 t/h furnace, and based on the results, the basic structure and operating conditions of the burner were selected. Next, using the 4 t/h furnace, which can perform combustion tests with full-scale burners equivalent to the actual burner, an evaluation of the combustion performance of the scale-up burner was carried out, and burner specifications for the actual burner were determined.

(a) Ammonia supply equipment (b) 0.5 t/h furnace (c) 4 t/h furnace

Figure 2 External appearance of combustion test equipment

3.2 Combustion test results

(1) Burner combustion test for circular firing system

As previously reported, combustion tests were carried out using the 0.5 t/h furnace at a 55% ammonia combustion ratio to coal. Both unburned ammonia and nitrous oxide (N_2O) with high global warming potentials at the furnace outlet were below the instrument detection limit (ammonia: less than 0.2 ppm, N_2O: less than 0.4 ppm). In addition, NOx and unburned combustible in ash could be suppressed to the same level or lower than those produced during coal single-fuel combustion in both cases of liquid-firing and gas-firing burners. (2)

This report presents the results of the actual scale liquid-firing tests using the 4 t/h furnace. The ammonia combustion rate in these tests was set at 55%, the same as in the 0.5 t/h furnace tests. In addition to the liquid ammonia spray nozzle type, which exhibited the best combustion performance in the 0.5 t/h furnace, several spray nozzle types were developed using computational fluid dynamics (hereinafter referred to as CFD) to further improve combustion performance, and their performance was evaluated through combustion tests. Measurement results of NOx and unburned combustible in ash are shown in **Figure 3**. Nozzle D exhibited the best performance, with a reduction of both NOx and unburned combustible in ash by approximately 30% compared to coal single-fuel combustion.

As described in the previous report, early completion of vaporization by accelerating the dispersion of liquid ammonia spray is important to control NOx in liquid-firing. (2) On the other hand, since the spray nozzle and coal burner are located close to each other, flow of liquid ammonia spray into the coal flames inhibits coal ignition and the amount of unburned combustible in ash increases in the case of nozzles A, C, etc., which aimed for wide-angle dispersion. Simultaneously satisfying both the speed of spray dispersion and the suppression of flow into coal flames was found to be important in the suppression of both NOx and unburned combustible in ash. Unburned ammonia and N_2O at the furnace outlet were below the lower limit of instrument detection, regardless of which nozzle was used.

In consideration of actual operation, the load of coal, ammonia, and of both burners were reduced in a step-wise manner from 100% to 75% then 50%, in order to confirm ignition stability and combustion performance of liquid ammonia at a partial load, and the effect on combustion performance was evaluated. Flame state at 100% and 50% load is shown in **Figure 4**. Even at 50% load, the flame detection signal and exhaust gas properties were stable, and unburned ammonia and N_2O were below the lower limit of instrument detection. NOx emissions were lower than those for coal single-fuel combustion at each load, remained at the same level as those at 100% load, and exhibited good combustion performance.

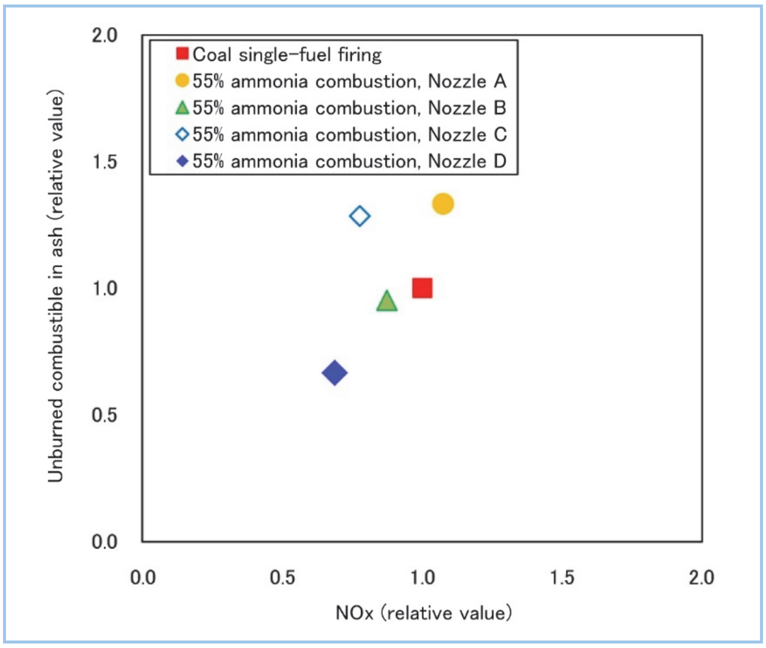

Figure 3 Properties of NOx and unburned combustible in ash in liquid-firing combustion test using 4 t/h furnace

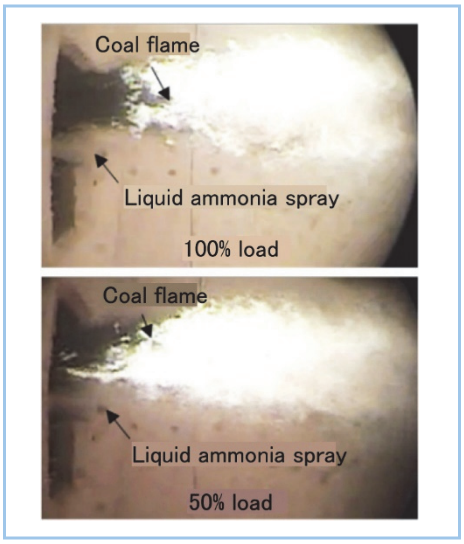

Figure 4 Flame state during partial load operation

(2) Burner combustion test for opposed firing system

The previous report described liquid-firing and gas-firing single-fuel combustion tests using the 0.5 t/h furnace, and actual-scale liquid-firing single-fuel combustion tests using the 4 t/h furnace. The results showed that ammonia was completely burned and NOx could be suppressed to the same level or lower than that of coal single-fuel combustion for both liquid-firing and gas-firing burners. [2]

This report presents liquid-firing single-fuel partial-load tests using the 4 t/h furnace, taking into account actual operation. In these tests, the liquid ammonia spray nozzle that reduced NOx the most at 100% load was used, and the effect on ignitability was evaluated as burner load was reduced. Flame conditions at each load are shown in **Figure 5**. As shown in the figure, flame formation near the burner was possible even at 65% load, and the flame detection signal and exhaust gas properties were stable during combustion.

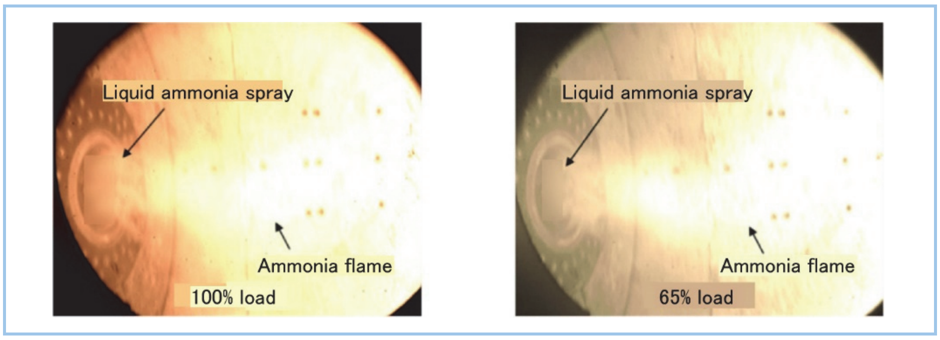

Figure 5 Flame state during partial load liquid ammonia single-fuel combustion

(3) Effect of ammonia combustion on coal combustion ash

There were concerns that combustion of coal and ammonia would result in residual ammonia compounds in the coal ash, and that ash flowability would deteriorate due to changes in ash particle shape caused by the decrease in combustion temperature. Therefore, ash samples were collected from coal single-fuel combustion and 55% ammonia combustion during the combustion tests. Then, chemical analyses such as ion chromatography, X-ray diffraction, and total organic carbon measurement were conducted to detect the presence of various ammonia compounds in the ash. As a result, no ammonia-derived compounds were detected in either sample, and no difference in properties was observed. All ammonia compounds have a low melting point and therefore it is assumed that they decompose in the high temperature environment in the furnace and do not remain in the combustion ash.

In addition, ash particle shape of both samples was observed using a field emission scanning electron microscope (FE-SEM) (**Figure 6**). In both the case of coal single-fuel combustion and the case of ammonia combustion, many spherical particles were observed, and no significant difference was observed between the two samples. Ash particles melt and become spherical when they reach a certain temperature. However, the ash particle shape was not strongly affected by the reduction in flame temperature caused by ammonia combustion since the coal and ammonia were burned at separate burners, and as a result, the effect on the ash particle shape is assumed to be small.

Based on the above, the effect of ammonia combustion on coal combustion ash is considered to be small, and no problems are anticipated. However, since this evaluation was made using combustion ash samples from a combustion test, collecting combustion ash samples from actual equipment is needed for a definitive comparative evaluation.

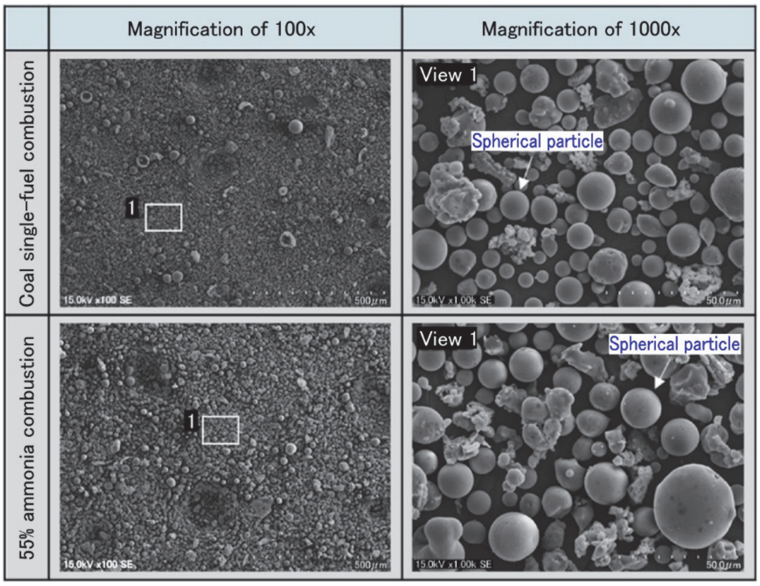

Figure 6 FE-SEM analysis of coal combustion ash produced during coal single-fuel combustion and ammonia combustion

(4) Evaluation of nitriding characteristics of burner candidate materials

There was concern that the ammonia burner component material would be nitrided and its surface hardness would increase due to high-concentration ammonia, resulting in a decrease in toughness. Therefore, nitriding exposure tests simulating the gas composition and metal temperature environment of the burner surface under operating conditions were conducted to evaluate nitriding characteristics of burner component materials. External appearance of the test apparatus is shown in **Figure 7**(a).

In this test, component material samples were kept at a predetermined temperature in an electric furnace and exposed to an ammonia gas mixture simulating the operating environment of an actual furnace for a certain period of time. Sample texture was observed to evaluate the presence or absence of nitriding. Materials tested were high-chromium cast steel, austenitic stainless steel, and low-chromium steel, which may be used as a burner material. An example of the texture observation results of the component material samples is shown in Figure 7(b). In the case of low-chromium steel, a nitrided layer formed entirely over the surface layer. On the other hand, in the case of austenitic stainless steel, a nitrided layer only formed locally, and in the case of high-chromium cast steel, no nitrided layer was detected. It is considered that the higher the chromium content, the more stable the passivation film formed on the surface of the material, thereby increasing the nitriding inhibition effect.

A database of nitriding characteristics of component materials was constructed by conducting the same tests while varying temperature and mixed gas compositions. For parts that may contact high concentrations of ammonia, the material with high nitriding resistance will be used.

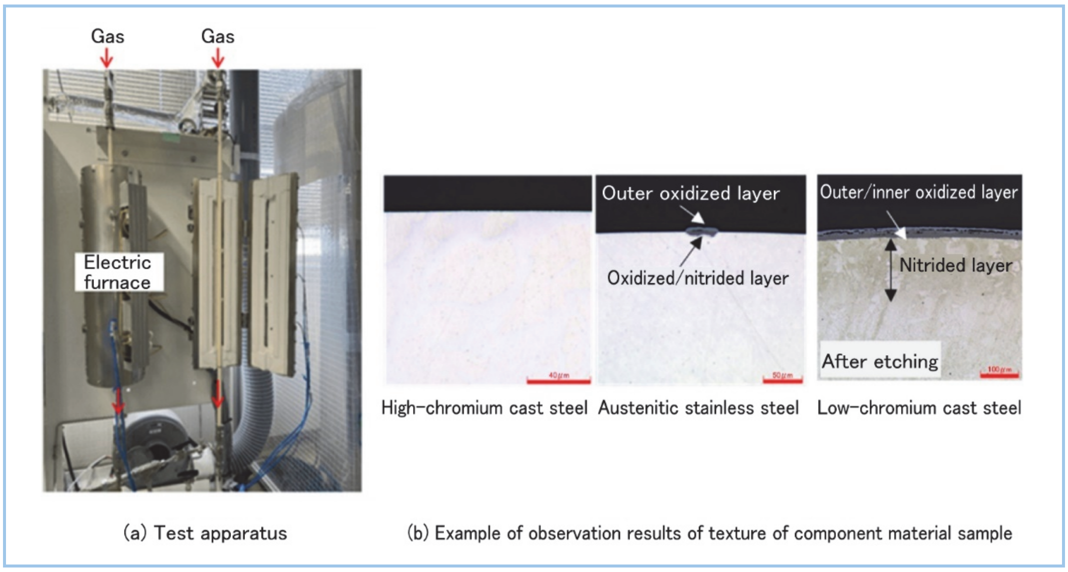

Figure 7 Nitriding test apparatus and example of observation results of texture of component material sample

4. Evaluation of actual boiler performance using combustion CFD

According to the previous report, when the combustion CFD analysis of opposed firing system liquid-firing and gas-firing burners was applied to actual boilers, both burners were found to suppress NOx and unburned loss to the same level as coal single-fuel combustion and application to actual boilers was considered feasible. [2]

This report presents the results of the combustion CFD-based performance evaluation of circular firing system liquid-firing and gas-firing burners when applied to actual boilers. The analysis targeted an existing commercial large-capacity circular firing system coal-fired boiler, which has six stages of coal burners and three stages of start-up oil burners between the coal burners. Application of the developed burners, both liquid-firing and gas-firing, to the start-up oil burners was simulated. The ammonia combustion ratio was set to 55% in both cases. The distribution of gas temperature, NOx concentration, and ammonia concentration in the furnace in the longitudinal center cross sections of the burners on the front side of the boiler wall is shown in **Figure 8**. From the results, no unburned ammonia was observed at the furnace outlet, and ammonia was completely burned in both cases of liquid-firing and gas-firing. Distribution of NOx and ammonia concentrations indicated that ammonia combustion was completed in the burner section, and that although NOx is generated in the burner section, it was almost completely reduced in the reduction atmosphere up to the additional air input section. As shown in **Figure 9**, NOx at the outlet of the furnace was lower than that for coal single-fuel combustion, and the unburned loss was at the same level. As described above, circular firing system liquid-firing and gas-firing burners also satisfied the specified performance in combustion tests and good combustion performance was observed in actual-boiler combustion CFD analysis, demonstrating feasibility of use in actual boilers.

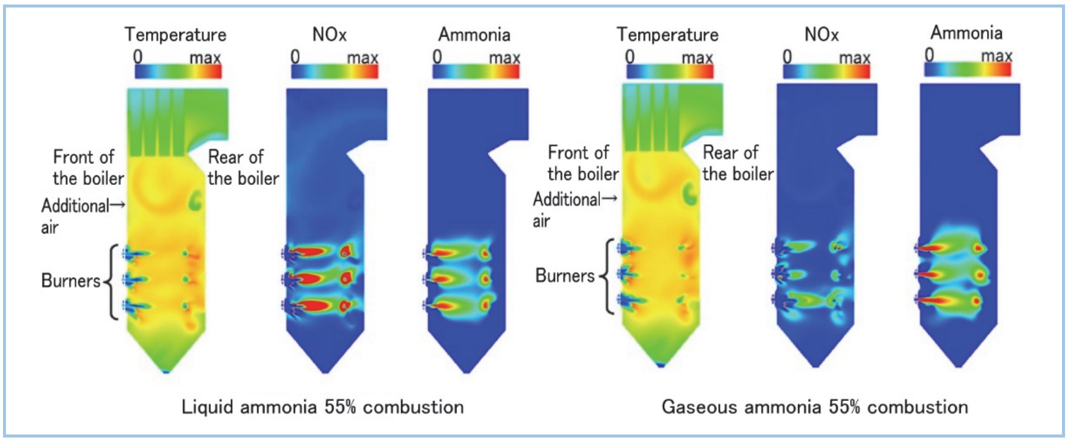

Figure 8　Circular firing system / Results of actual-boiler combustion CFD analysis

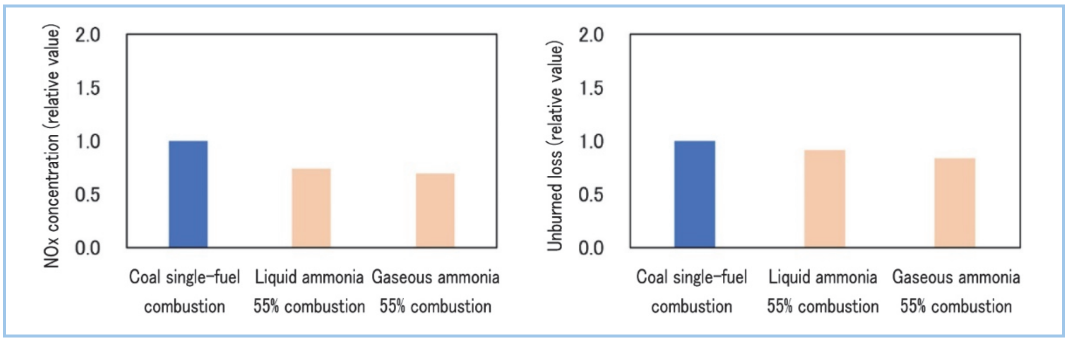

Figure 9　Circular firing system / Combustion performance of actual-boiler ammonia 55% combustion

5. Boiler plant modification plan

5.1　Boiler plant modification plan for ammonia fuel conversion

In order to modify existing coal-fired boilers with ammonia fuel conversion rate over 50%, the burners and boiler modification plan, boiler performance, operation control, auxiliary equipment modification plan, safety measures, etc. are studied for both opposed firing and circular firing systems. There are two types of fuel ammonia combustion systems: gas-firing and liquid-firing. The boiler plant modification plan adopted gas-firing, which is advantageous in terms of operating costs, including fuel cost.

An overview of modifications to the existing coal-fired boiler for ammonia fuel conversion is shown in **Figure 10**. The modification policy is to make effective use of existing equipment, reduce modification costs, and minimize unit shut-down periods. Problems in operation caused by conditions such as certain types of coal, certain atmospheric temperatures, etc., are dealt with by setting operational restrictions, thereby avoiding large-scale modifications to the boiler pressure parts, major auxiliary equipment, and flue gas treatment system. The boiler design requirements are as follows.

- Set the target NOx at the boiler outlet to a value at the same level during coal combustion.
- Design of the ammonia combustion system to have the capacity to achieve the rated load even when the fuel of the power generation facility is converted to 50% ammonia.

- Maintain the ability of coal combustion operation even after modification for ammonia fuel conversion.
- Minimize the scope of modifications and additional installations.
- The plant start-up and shut-down procedure is not changed from the existing plant, using auxiliary fuel in the same manner as the existing plant. Switching to/from ammonia-fired operation shall be performed from/to coal combustion operation.
- Provide leakage prevention measures for fuel ammonia gas piping. In addition, instruments shall be able to promptly detect gas leaks. The leaked gas is not allowed to accumulate, and abatement measures shall be implemented.
- Supply auxiliary steam from the boiler to fuel ammonia heater in the fuel supply system.

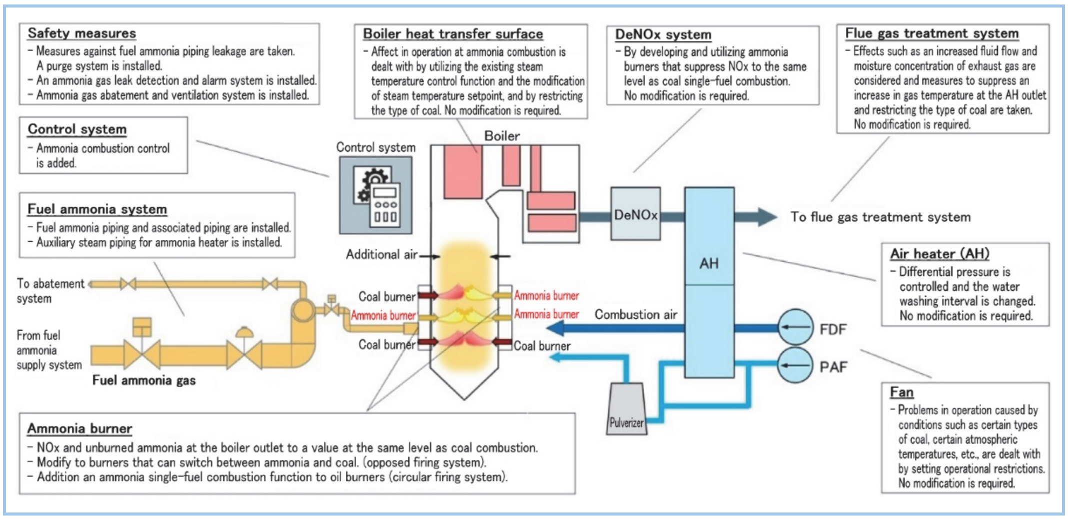

Figure 10 Overview of boiler modification for ammonia fuel conversion

5.2 Fuel ammonia piping and safety measures

Fuel ammonia is fed to the ammonia burners through the flow meter, the shut-off valve, and the control valve. A purge system is designed to replace ammonia in the piping with nitrogen and air at plant start-up and/or shut-down. Ammonia vent gas is planned to be directed to the abatement system. For reliable system isolation, double block and bleed valves are adopted.

The fuel ammonia piping route is based on the existing piping arrangement, and is confirmed that there are no major obstructions and that accessibility is ensured through an on-site survey. And the fuel ammonia piping is planned considering boiler steel frame support beams which can support piping and permit the additional piping load. The piping arrangement of the fuel ammonia is shown in **Figure 11**.

In order to install additional system which handles a large amount of ammonia as fuel, the basic safety design policy is determined for the purpose of ensuring the safety for the neighboring inhabitants and the workers in the power plant. The ammonia combustion system is designed with emphasis on leakage prevention measures and fire and explosion prevention measures.

As countermeasures against ammonia gas leakage, safety measures based on the concept of multiple protection are established by setting step-by-step safety measures: First, "leakage prevention measures" to prevent leakage, followed by "leak spread prevention measures" to prepare for an ammonia leakage, and then "damage prevention measures" to minimize damage after a leakage has occurred. Measures taken at each stage are outlined below.

- Leakage prevention measures
  Since ammonia is a toxic gas, appropriate material selection, corrosion countermeasures, seismic design, and piping connection design are carried out to prevent leakage. Piping and fittings are basically welded.
- Leak spread prevention measures
  If the ammonia gas leakage occurs, promptly detecting the leakage at an early stage and implementing measures to prevent the spread of the leak are essential. The ammonia gas detection and alarm system, diffusion protection screen around areas where leakage may occur, and a fuel shut-off function are installed to prevent the spread of a leak. The diffusion

protection screens are added to the ventilation system, which also serve as an ammonia abatement measure described below. And the ammonia gas detectors are placed inside the screen to enable early detection of leaks.

- Damage prevention measures
  Since ammonia is a flammable gas, explosion-proof and static electricity prevention measures are taken to prevent fire and explosion. In addition, since ammonia is a toxic gas, installation of ventilation system that can safely and quickly abate ammonia is necessary to prevent damage to the human body. Therefore, diffusion protection screens are connected to the ventilation ducts to discharge any leaked gas to the forced draft fan inlet for combustion treatment in the boiler. An overview of the ventilation system is shown in **Figure 12**.

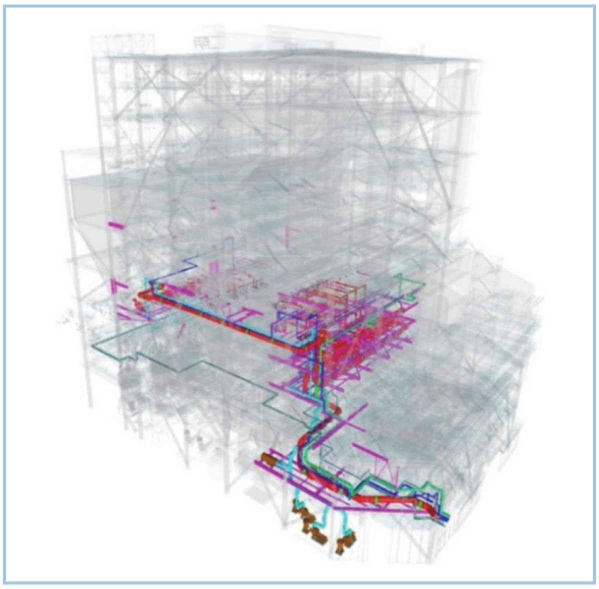

Figure 11　Arrangement of fuel ammonia piping
A case of opposed firing system is shown. Additional piping is indicated by color.

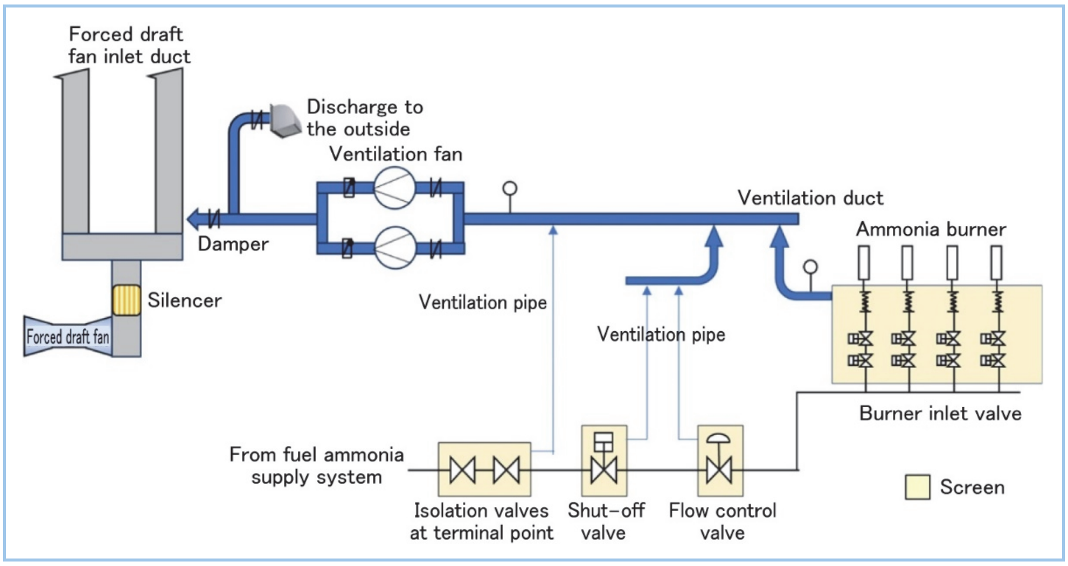

Figure 12　Overview of ammonia abatement and ventilation system

6. Conclusion

MHI has developed ammonia single-fuel burners for ammonia fuel conversion in coal-fired boilers. According to the results of performance evaluation using data obtained from combustion tests and actual-boiler CFD analysis, the prospect of application to actual equipment could be obtained. In addition, an outline of a boiler plant modification plan for 50% or more ammonia fuel conversion and safety measures for handling ammonia as fuel have been presented. This fuel conversion technology can also be applied to a 20% fuel conversion, which meets the needs of an initial introduction of ammonia, by adjusting the number of modified burner stages.

In the future, MHI will continue to make every effort to respond to the wide range of needs of utility and industrial boilers so that various customers in Japan and overseas can take advantage of fuel ammonia as they work toward carbon neutrality.

This development was conducted under "JPNP21020 Green Innovation Fund Project / Fuel Ammonia Supply Chain Establishment / Ammonia high-ratio co-firing and single-fuel firing for thermal power generation / High-ratio co-firing and single-fuel firing needed for ammonia power generation/ Development and demonstration of high-ratio ammonia co-firing technology (including single-fuel firing technology) in coal-fired boilers / Demonstration project of high-ratio ammonia co-firing in the commercial coal-fired power plants utilizing ammonia single-fuel burners" of the New Energy and Industrial Technology Development Organization (NEDO). [3]

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