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Ammonia-Fueled Power Generation for Energy Transition

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ABSTRACT

Ammonia is gaining attention as an efficient hydrogen energy carrier and a decarbonized fuel. In Japan, the development of technologies to use ammonia as a fuel began in the 2010s, focusing on power generation and industrial heating systems. Today, its application is being explored across various sectors worldwide. For gas turbine power generation, IHI has developed a 2 MW gas turbine capable of operating on 100% liquid ammonia and is conducting long-term durability tests within a power generation package system. The application of this technology to large gas turbines is also underway. In the field of boiler thermal power generation, ammonia co-firing technology with a 20% ammonia fuel ratio has been developed and successfully demonstrated in a 1000 MW commercial power plant. This paper introduces the current status and prospects of ammonia firing power generation technologies.

1. Introduction

Hydrogen is expected to be a promising energy source in a decarbonized society, but its transport and storage characteristics pose a challenge, and necessitating efficient means of transport and storage are needed. Ammonia is gaining attention as a hydrogen energy carrier, due to excellent characteristics for transportation and storage. Compared to liquid hydrogen, liquid ammonia has 1.5 times the energy density per volume (lower heating value (LHV)) and a boiling point of −33.4 °C, which is significantly higher than that of liquefied natural gas (LNG) and liquid hydrogen, as shown in Table 1. This makes it easier to insulate storage containers and allows for long-term storage.

In 2019, approximately 200 million tons of ammonia were produced worldwide, with about 10% transported via maritime routes [1]. Ammonia has diverse applications, such as fertilizers, chemicals, power generation denitrification, and refrigerants. According to demand projections for nitrogen-based sources, ammonia equivalent demand is expected to reach 560 million tons by 2050, driven by growth in power generation and maritime fuel [1]. Ammonia production costs are expected to fall below fossil fuel-based prices by 2050 due to the widespread adoption of renewable energy and reductions in the price of water electrolysis equipment [1].

Ammonia is corrosive and toxic, and its handling risks are well understood, predictable, and manageable, with standards being developed for the various applications. When used as a fuel, the volume increases significantly compared to previous levels, and the utilization pattern shifts from local production for local consumption to large-scale long-distance transportation. This necessitates even safer handling technologies. For example, large-scale storage facilities comparable to LNG requires ammonia corrosion resistant materials [2]. However, while these challenges exist, we have the scale and experience to address them. The greatest challenge is the establishment of technologies to efficiently and safely utilize ammonia as a fuel.

Ammonia's energy applications are categorized into three main areas. The first is its use as marine fuel, where ample space is available for fuel storage and exhaust gas treatment facilities, making it convenient for ammonia firing with existing bunker fuels. The second is its application in "hard-to-abate" sectors such as the steel and chemical industries, where ammonia may be converted back to hydrogen for use. The third is the power generation sector, where the expected fuel consumption the largest, making it essential for the establishment of a global ammonia value chain (Fig. 1 [2]).

In Japan, a national initiative on hydrogen energy carriers was launched by the Cross-Ministerial Strategic Innovation Promotion Program (SIP) by the Cabinet office in 2014 to advance ammonia production and utilization technologies [3]. This project involved collaboration between industry and academia, and extensive

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Table 1
Physical properties of liquefied gas.

Fuel	Boiling point (°C)	Liquid density ($kg·L^{-1}$)	Energy density ((MJ LHV)$·L^{-1}$)	Burning velocity ($m·s^{-1}$)	Adiabatic flame temperature (°C)
Ammonia (LA)	−33.4	0.674	12.5	0.09	1750
Hydrogen (LH)	−253	0.071	8.5	2.91	2120
Methane (LNG)	−162	0.422	21.2	0.37	1970

LA: liquid ammonia; LH: liquid hydrogen.

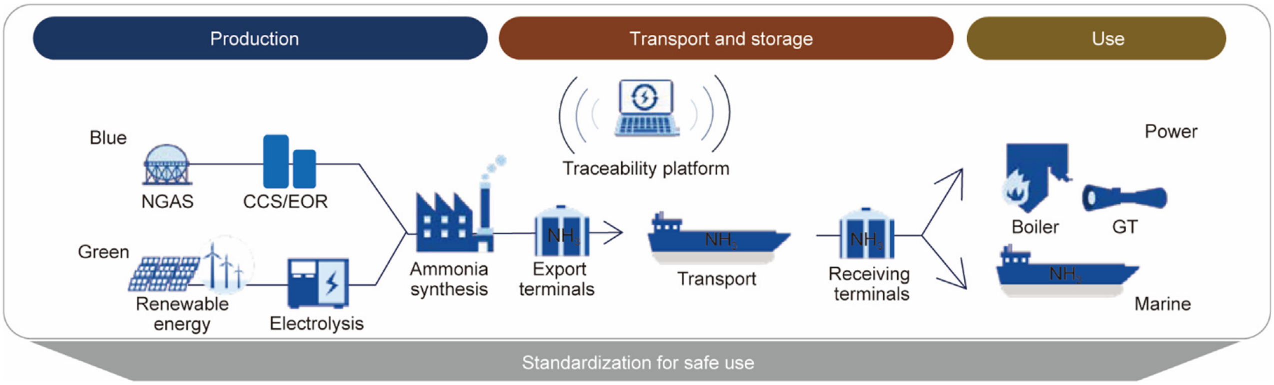

Fig. 1. Ammonia value chain [2]. NGAS: natural gas; CCS: carbon capture and storage; EOR: enhanced oil recovery; GT: gas turbine.

research was conducted on the basic science of ammonia combustion and the development of technologies for using ammonia in various power generation and industrial heating systems. In 2020, the Japanese government set a goal of integrating hydrogen and ammonia into approximately 10% of the total primary energy mix by 2050 as part of its carbon neutrality strategy [4]. Currently, various companies and research institutes are developing practical technologies for implementation under the New Energy and Industrial Technology Development Organization (NEDO) Green Innovation Fund, with a target date of 2030 [5]. IHI has participated in this research and development from the outset, focusing on the development of power generation technologies such as gas turbine, boiler, and internal combustion engine, which are the keys to realizing the ammonia value chain. These technologies entered the demonstration stage in 2024, marking a significant milestone in their practical application. This paper provides an overview of these technologies and discusses prospects.

2. Ammonia combustion characteristics

The adiabatic flame temperature of ammonia is approximately 200 °C lower than that of methane, but it is sufficient for the combustion temperature requirements of thermal power generation equipment. The burning velocity of ammonia is approximately one-fifth that of methane, presenting challenges for combustion stability in gas turbines where the residence time in the combustor is relatively short. Furthermore, NO_x generated by ammonia combustion is mainly fuel-NO_x, which originates from nitrogen in the fuel, rather than thermal-NO_x generated by the oxidation of nitrogen in the air, which is a major difference from hydrocarbon fuels. A significant amount of NO_x is produced under oxidizing and fuel-lean conditions ($\varphi < 1$, where φ is the equivalent ratio of ammonia–air mixture), while minimal NO_x is generated under reducing and fuel-rich conditions ($\varphi > 1$), as shown in Fig. 2 [6]. To mitigate NO_x formation, a two-stage combustion technology has been developed. This approach consists of conducting combustion in a reducing environment in the primary combustion zone, followed by secondary combustion with additional air.

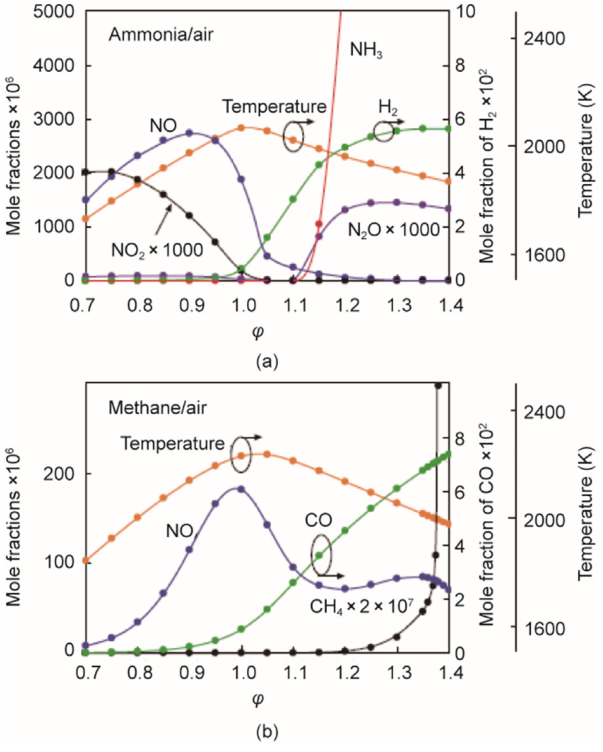

Fig. 2. 1D analysis of premixed flame equivalent ratio versus emissions: (a) ammonia/air flame and (b) methane/air flame [6].

There are three primary methods for supplying ammonia as fuel: liquid, gas, and cracked gas (Fig. 3). Each of these fuel supply methods has advantages and disadvantages, and the most suitable method is selected according to the application. The liquid supply system is simple, requiring a minimal number of components, and allows for quick adjustment of the flow rate. Although the heat of evaporation of liquid ammonia results in energy loss, the latent

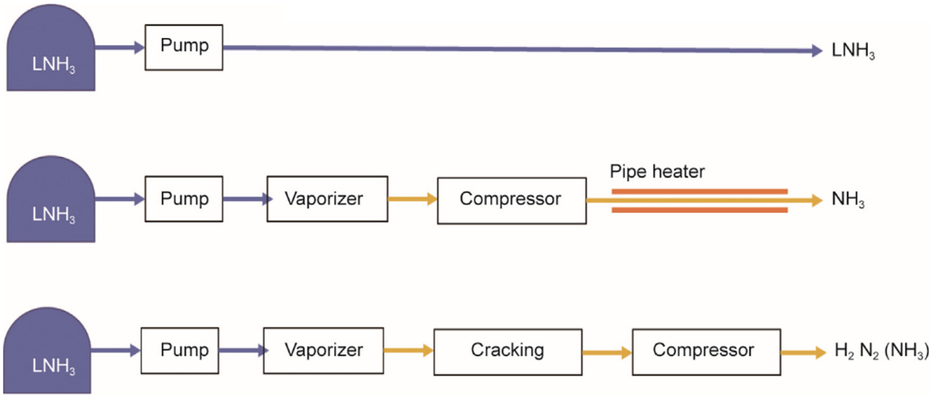

Fig. 3. Various methods of supplying ammonia fuel to combustion facilities. LNH_3: liquified ammonia.

heat of ammonia at atmospheric pressure is equivalent to 7% of the heat of combustion, but at 4 MPa, this percentage decreases by 35%. The gas supply method requires a vaporizer and a heat source. In low-pressure fuel supply systems, such as boilers, seawater can be used as a heat source for vaporization. However, in high-pressure fuel supply systems, such as gas turbines, where the pressure exceeds 4 MPa, the boiling point rises above 80 °C, requiring a heat source with a higher temperature. The ammonia cracking method offers improved combustion stability by utilizing hydrogen cracked from ammonia; however, it is associated with drawbacks such as more complex equipment configuration and slower response times to load changes.

3. Ammonia-firing gas turbine

The world's first successful operation of a 2 MW gas turbine fueled by 100% liquid ammonia has been achieved in ammonia firing gas turbine test facility at IHI Yokohama (Fig. 4 [7]). The ammonia-firing IM270 industrial gas turbine consists of a single-can type combustor, which is a two-stage combustion system burning liquid ammonia, a centrifugal compressor and axial-flow turbine (Fig. 5 [7]). The ammonia-firing gas turbine was started using natural gas, switched to pure ammonia combustion at 50% load, and then increased the fuel supply rate to achieve rated output.

The results of gas turbine exhaust gas from two combustors are shown below. The revised combustor was modified to improve combustion stability by increasing the swirl intensity of the swirl burner and mixing fuel and air more quickly. Fig. 6(a) [7] shows the emissions of nitrous oxide (N_2O) and unburned ammonia at the turbine outlet as the ammonia mixing ratio transitions from natural gas to 100% ammonia combustion under rated condition. Results are shown for both, initial (blue) and improved (orange) combustor designs. The initial combustor emitted N_2O when the ammonia firing ratio exceeded 70%. Due to the increase in N_2O emissions, which has a global warming potential (GWP) of 265 [8], further increases in the ammonia firing ratio did not result in proportional reductions in greenhouse gas (GHG) emissions, as demonstrated in Fig. 6(b) [7]. On the other hand, the improved combustor achieved emissions of unburned ammonia and N_2O below the detection limit of the instruments (1 parts per million (ppm)) across the entire range of operation up to 100% ammonia firing condition. As a result, the GHG emission reduction rate exceeded 99%. Furthermore, NO_x emissions complied with the environmental regulatory standards of Yokohama city through use of a conventional selective catalytic reduction (SCR) NO_x reduction system.

The ammonia-firing IM270 gas turbine package was developed, and its demonstration test has been started at IHI's Aioi Plant from July 2024 with a daily start–stop mode, and as of January 2026, 3000 h of operation has been achieved. This test not only

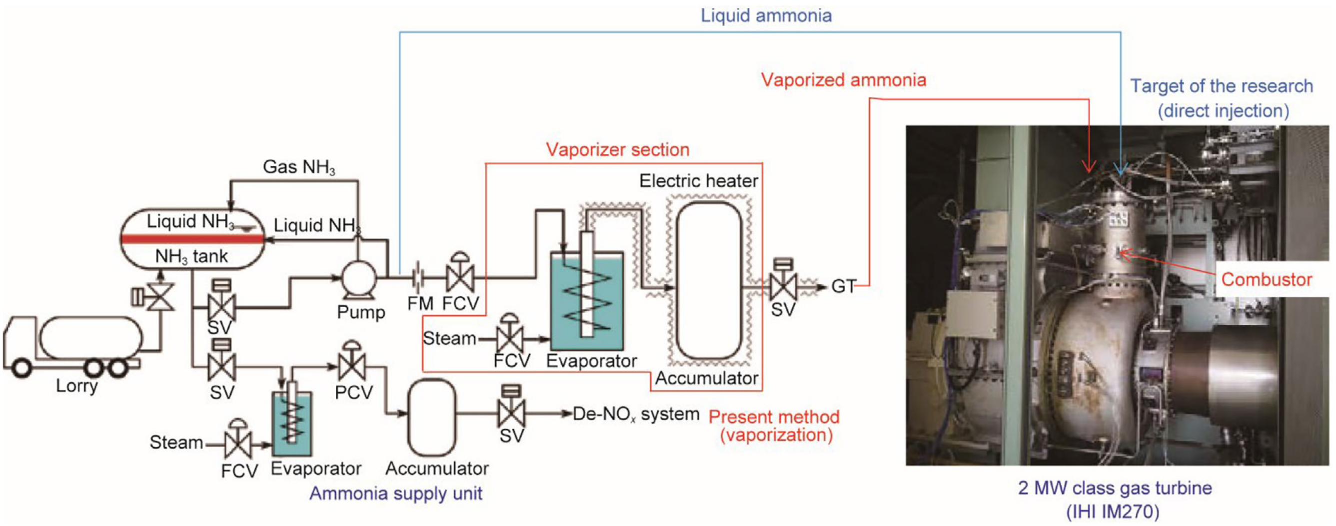

Fig. 4. IM270 single-can combustor gas turbine and ammonia supply systems [7]. SV: shut-off valve; PCV: pressure regulating valve; FCV: flow control valve; FM: flow meter.

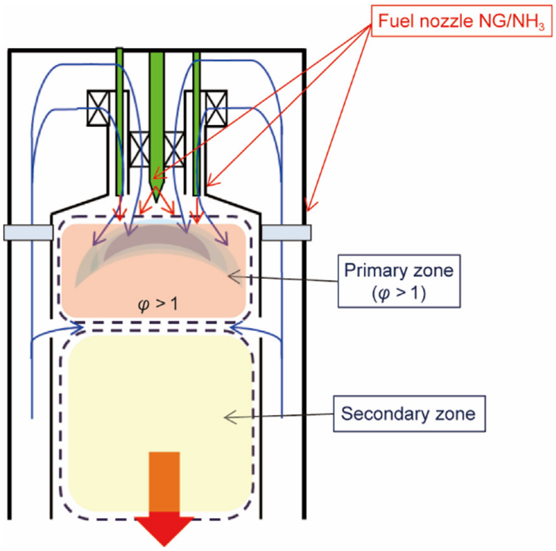

Fig. 5. Schematic of ammonia two-stage combustor of IM270 gas turbine [7].

confirmed the durability of the system, but also successfully evaluated its operational performance through load rejection and load dump tests. In parallel, efforts are underway to scale this technology for larger gas turbines. IHI is collaborating with GE Vernova to develop a 7F-class gas turbine, targeting commercialization by 2030.

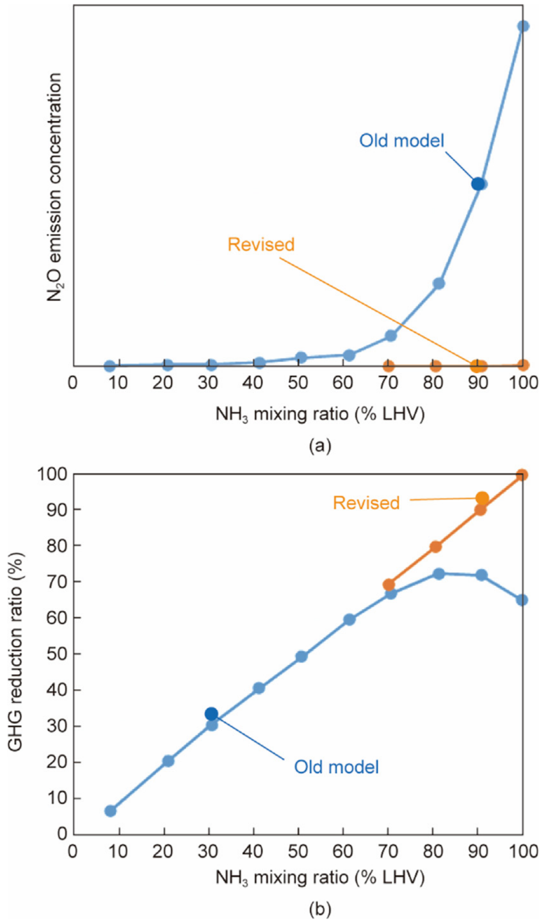

Fig. 6. Ammonia-firing IM270 gas turbine test results [7]: (a) N_2O (nitrous oxide) emission concentration, (b) greenhouse gas (GHG) reduction rate.

4. Ammonia-firing boiler

Coal-fired power generation remains a major energy source in many Asian countries, where numerous plants constructed after 2000 are still operational and have significant remaining lifespans. For a smooth and cost-effective energy transition, the utilization of existing infrastructure represents a pragmatic approach.

4.1. Ammonia-firing pulverized coal (A-PC) burner

A primary technical challenge in ammonia-firing with coal is suppressing NO_x formation without compromising coal combustion performance. The main source of NO_x emission in coal combustion is also nitrogen contained in coal at levels ranging from 0.5% to 3%. To address this challenge, a two-stage combustion method is applied, wherein the primary combustion zone is maintained under reducing conditions, followed by the complete combustion of the remaining coal char in the secondary combustion zone using over-fire air supplied downstream. This approach effectively reduces NO_x emissions by simultaneously.

Boilers typically feature multiple burners, and ammonia-firing can be implemented in two ways: firing ammonia and coal in each burner or using separate burners for ammonia and coal. The former approach was adopted as it allows for straightforward and highly accurate predictions. IHI has many experiences and expertise in predictive technology for evaluating the combustion characteristics of entire boilers based on single burner combustion test results for various fuels. In contrast, when ammonia and coal are fired in separate burners, the results are influenced by the boiler's geometry and burner configuration, requiring case-specific evaluation and optimization, which increases prediction uncertainty.

Fig. 7 [9] shows an image of the flame observed during ammonia firing with a coaxial swirl, pulverized coal burner (A-PC burner) in 1000 MW thermal power boiler furnace. The developed A-PC burner was tested in a 10 MW-scale combustion test facility at IHI Aioi (Fig. 8 [10]). The bituminous coal used in the test had a calorific value of 29 $MJ\cdot kg^{-1}$ (dry basis) and the following composition: proximate analysis (5.2% moisture, 56.2% fixed carbon, 33.0% volatile matter, and 10.8% ash) and ultimate analysis (C: 71.1%, H: 4.6%, N: 1.4%, O: 11.7%, and S: 0.4%). Fig. 9 [10] shows the changes in NO_x emissions and unburned carbon (UC) content in ash with excess air ratio. NO_x decreases as the excess-air ratio decreases, reaches a minimum value, and then increases. UC in ash under 20% ammonia firing conditions were equivalent to those of coal firing conditions. Additionally, no unburned ammonia or nitrous oxide (N_2O) was detected.

4.2. Ammonia-firing thermal power plant

Engineering studies were conducted to retrofit existing boilers thermal power plant for ammonia firing, with the aim of ensuring that the heat absorption rate of the boilers remained within the design margin and that exhaust gas emissions did not exceed current levels. The heat absorption of the boiler furnace under ammonia 20% firing conditions was confirmed within the design margin by network model and computational fluid dynamics (CFD) simulations [11–14]. As shown in Fig. 10 [9], the main retrofit components included A-PC burners and the ammonia fuel supply system, while the existing boiler, exhaust gas treatment system, and pulverized coal feeding system were retained.

A 1000 MW ultra-supercritical pulverized coal boiler (No. 4 unit at JERA's Hekinan Power Plant) was retrofitted for the ammonia 20% firing boiler system, based on the above studies. Fuel ammonia was unloaded from the ship supplied to 2000 m^3 reserve tank

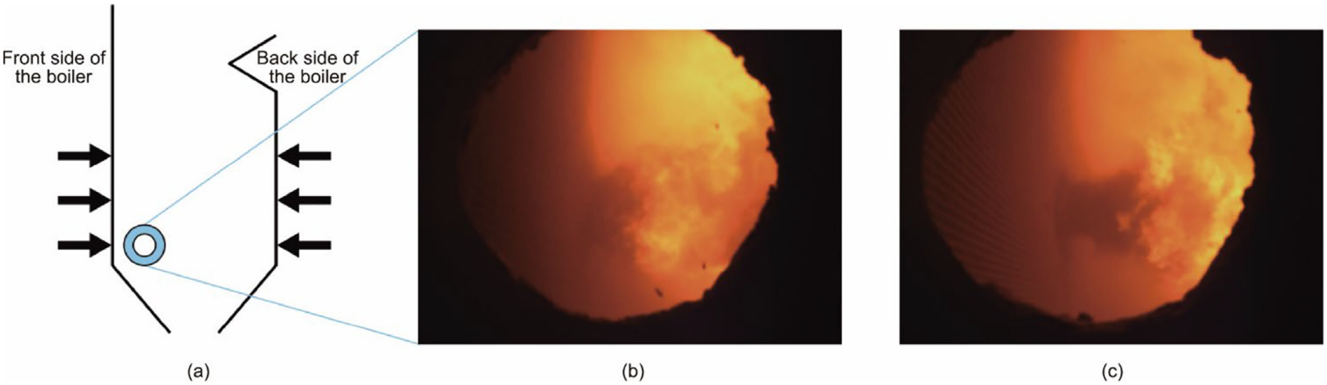

Fig. 7. Comparison of flames between single coal firing and ammonia 20% firing in a 1000 MW thermal power boiler [9]. (a) Photo shooting location (the photos are shot through an inspection window on the right of the lower burner); (b) flame during single coal firing; (c) flame during ammonia 20% firing.

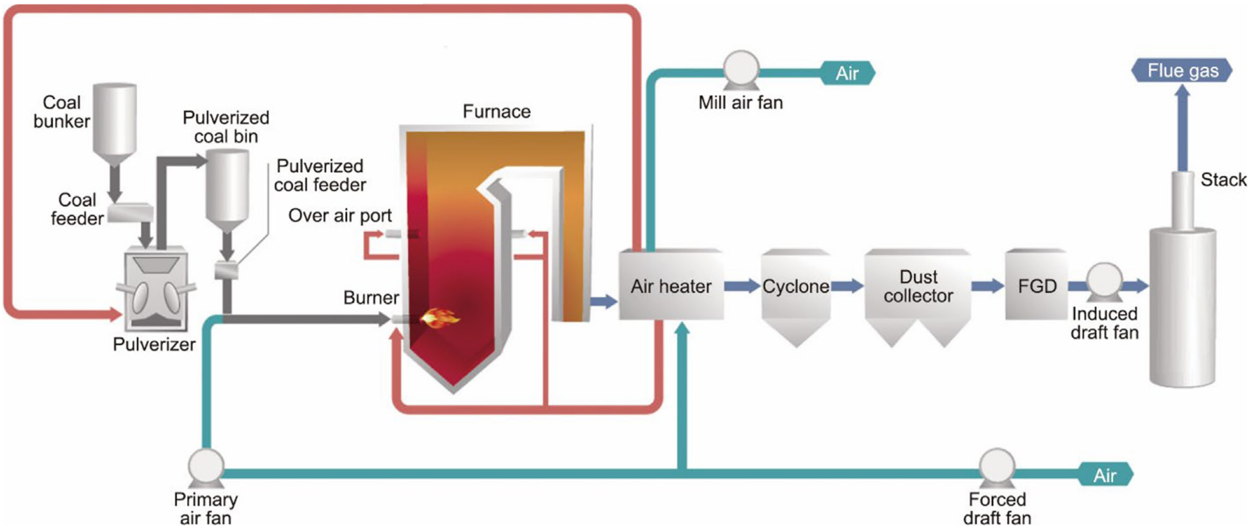

Fig. 8. 10 MW class single burner test furnace (IHI Aioi) [10]. FGD: flue gas desulfurization.

through a 2.4 km pipeline, vaporized by a seawater evaporation facility and fed into 48 A-PC burners installed in the boiler. Metals are known to undergo nitridation due to ammonia, which can lead to damage in some cases. Prior to conducting boiler demonstration tests, a material integrity test was performed using a single fuel nozzle, and no significant nitridation was observed after 1000 h of operation.

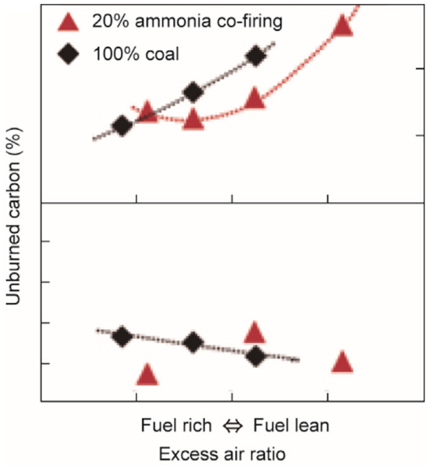

Fig. 9. NO_x emission and unburnt carbon in ash in ammonia 20% firing and coal firing single burner test [10].

The emission results of the ammonia 20% firing boiler test were consistent with those of the single-burner combustion test. CO_2 and SO_x emissions were reduced by approximately 20%, and NO_x emission was equivalent to or lower than those of the coal firing conditions. The UC content in ash was also equivalent, and neither unburned NH_3 nor N_2O was detected within the detection limits of the measurement instruments. Although the furnace heat absorption was initially expected to decrease under 20% ammonia firing due to a reduction in combustion temperature, this effect was offset by the lower ash content, resulting in furnace heat absorption comparable to that of coal-firing operations.

Assuming the annual operation of the power plant under ammonia 20% firing, 500 000 tons of ammonia would be consumed, equivalent to nearly half of Japan's total consumption today, and 1 million tons of CO_2 emission would be avoided. Moreover, to meet diverse customer needs, research and development efforts are underway to adapt ammonia-firing technology for different types of coal and to achieve higher ammonia firing rates exceeding 50%.

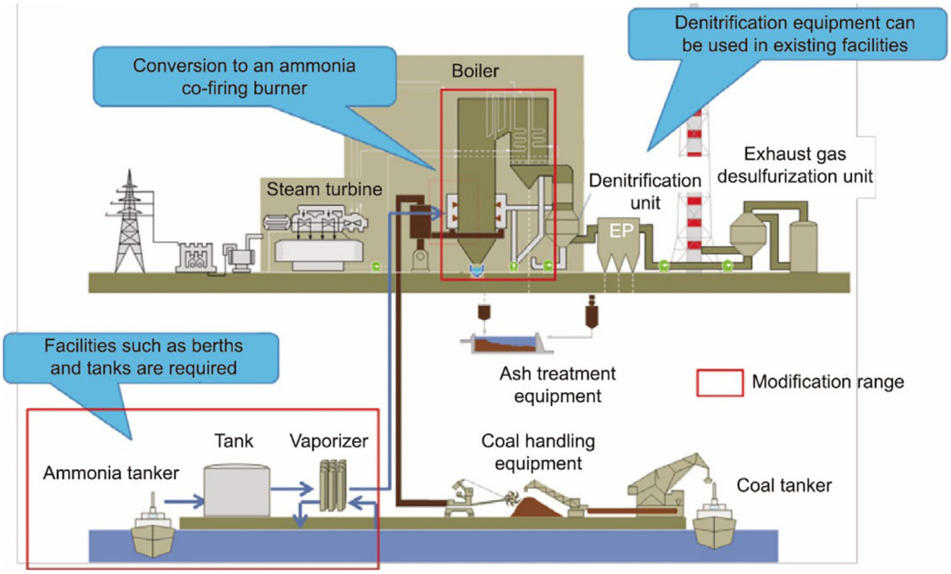

Fig. 10. Retrofitting an ammonia-firing thermal power plant [9].

5. Summary and perspectives

Technological development of ammonia firing engine is advancing in the marine sector as well. Demonstration operations of a tugboat equipped with two ammonia engines developed by IHI Power Systems began in 2024 [15]. The results of these demonstration tests across various applications indicate that ammonia power generation technologies have reached the stage of societal implementation.

For the ammonia value chain to be accepted by society, the following points are crucial. As power plants increasingly adopt ammonia as a fuel, the transition from local production and consumption to global distribution through large-scale transportation and storage systems is anticipated. A more sophisticated safety management system will be needed. Also, standardization of design and operation are important for reliability. Another significant challenge lies in achieving economically viable fuel costs. The cost of renewable energy and water electrolysis equipment, which account for most of the green ammonia production costs, are expected to decrease as they become more widespread. However, further efforts are needed to accelerate these cost reductions.

The energy supply and demand landscape vary significantly across regions, necessitating tailored solutions to address the specific needs of each area. IHI remains committed to collaborating with the partners to establish a robust ammonia value chain, enabling regional decarbonization while contributing to global decarbonization efforts.

CRediT authorship contribution statement

Toshiro Fujimori: Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The author declares the following financial interests/personal relationships which may be considered as potential competing interests: Japan Science and Technology Agency (JST). New Energy and Industrial Technology Development Organization (NEDO).

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