Vol. 2, Iss. 3 (2025) 99-108, DOI: 10.61552/JMES.2025.03.001

JMES

Journal of Management and Engineering Sciences

www.jmes.aspur.rs

Hydrogen Integration in Gas Turbines: OEM Innovations and Challenges in Advancing Sustainable Energy Systems

Amr Abbass[a,*]

[a] *University of Idaho, Calgary, Canada.*

Keywords:

Gas Turbine
Hydrogen
OEM
Sustainable Energy

* Corresponding author:

Amr Abbass
E-mail:
calgary732@outlook.com

Received: 21.10.2024.
Revised: 09.12.2024.
Accepted: 13.12.2024.

ABSTRACT

This research analyzes the incorporation of hydrogen as a fuel in gas turbines, highlighting its crucial significance in the shift towards a low-carbon energy framework. Gas turbines operating on hydrogen sustainably stabilize renewable energy systems and diminish greenhouse gas emissions. The research investigates flame stabilization, flashback, thermoacoustic dynamics, and NOx emissions, highlighting the necessity for better combustion technologies. The document analyzes hydrogen production techniques, including steam methane reforming (SMR) and electrolysis, emphasizing their scalability and ecological consequences. Innovations from industry giants such as GE and Mitsubishi are emphasized, including creating specialized combustor designs, hydrogen co-firing systems, and ammonia-cracking technology. These improvements highlight hydrogen's promise as a zero-carbon fuel, which can bolster grid stability, improve renewable energy integration, and meet global decarbonization objectives by 2050. A thorough examination of performance data and operating experiences yields significant insights into the problems and opportunities related to hydrogen integration in gas turbines.

1. INTRODUCTION

The increasing reliance on renewable energy sources like solar and wind has led to a shift in power generation, posing challenges to grid stability. Gas turbines, which can operate on hydrogen, offer a solution to this issue by operating on a zero-carbon fuel. This paper examines the role of gas turbines in a reduced-carbon energy ecosystem, their ability to operate on hydrogen, the modifications needed for existing turbines, and the advancements needed for future technologies. Hydrogen production methods, such as steam methane reforming (SMR) and water electrolysis, are analyzed for their viability in meeting large-scale power generation needs. This paper discusses hydrogen's role in enabling a carbon-free energy ecosystem and the need for large-scale hydrogen production through SMR and electrolysis.

Hydrogen synthesis by electrolysis necessitates substantial energy and water resources. The 9HA.02 turbine requires around 19.5 GWh of electricity and 361 m^3 of water per hour, emphasizing the integration of renewable energy to facilitate green hydrogen generation. This table illustrates the environmental consequences of hydrogen production by steam methane reforming (SMR). The hydrogen requirements and corresponding CO_2 emissions of each turbine underscore the necessity for carbon capture and sequestration (CCS) to attain carbon-neutral operations. Hydrogen's cost forecasts are substantial but expected to decrease over time due to advancements in production technologies and economies of scale. By 2050, the cost of hydrogen is expected to be $14.6-19.6 per MMBTU, making it competitive with natural gas in some areas. The reduction of CO_2 emissions with hydrogen/methane blends is nonlinear, with minor augmentations in hydrogen content producing early incremental decreases. Governments worldwide are investing in hydrogen plans to reduce emissions and integrate renewable energy. Japan's Ministry of Economy, Trade, and Industry plans to establish a hydrogen supply chain by 2030. Understanding these issues is crucial for progressing hydrogen-based systems while maintaining efficiency and sustainability [2].

Table 1. SMR Requirements for Hydrogen Operation [1].

Gas Turbine Model	Output (MW)	Heat Input (GJ/hour)	Heat Input (MMBTU/hour)	100% H_2 Flow Rate (kg/hour)	CO_2 Generated (kg/hour)	CO_2 Generated (Metric tonnes/year)
GE-10	11.2	129	122	1,140	6,250	50,000
TM2500	34.3	350	332	3,120	16,950	135,600
6B.03	44	473	448	4,170	22,900	183,000
6F.03	87	857	813	7,550	41,500	332,000
7F.05	243	2,197	2,083	19,500	106,500	852,000
9F.04	288	2,677	2,537	23,600	130,000	1,040,900
9HA.02	557	4,560	4,322	40,200	221,000	1,800,000

2. CHALLENGES IN THE UTILIZATION OF HYDROGEN IN GAS TURBINES FROM AN ACADEMIC PERSPECTIVE

Incorporating hydrogen as a fuel in gas turbine combustion systems presents complex issues in flame stabilization, flashback prevention, thermoacoustic behavior, and NOx emissions control. In traditional natural gas combustors, flame stability is achieved using swirl-induced stabilization and recirculation zones, facilitating effective fuel and air mixing while ensuring the flame remains safe from the fuel injection point. These approaches depend on a balance of turbulent fluxes and regulated mixing to maintain a stable flame structure. The elevated flame speed of hydrogen markedly heightens the possibility of flashback, a phenomenon in which the flame advances upstream into cooler areas around the injection point, potentially inflicting substantial damage to system components. This risk requires sophisticated adjustments to injection techniques, such as dividing hydrogen into several parallel streams, implementing crossflow injection, and exercising meticulous control over fuel and air velocities. These methodologies seek to regulate flame attachment and mitigate flashback by facilitating sufficient mixing and preventing the flame from securing in undesired areas.

The stabilizing mechanism for hydrogen combustors is intricate, necessitating the consideration of the interplay between swirling airflows and the distinct burning characteristics of hydrogen. Swirl-induced stabilization, commonly employed in natural gas systems, encounters constraints when utilized for hydrogen due to its elevated reactivity and extensive flammability range. Innovative concepts like the Micromax idea, using several small flames stabilized by limited recirculation zones, are being created to overcome these restrictions. Dispersing the hydrogen flow through numerous small nozzles diminishes the magnitude of individual flame contacts, enhances flashback resistance, and optimizes mixing efficiency. Nonetheless, the essential physics of stabilizing hydrogen flames, especially in stratified or partially premixed environments, continues to be a subject of ongoing investigation. Critical elements such as flame-vortex interactions, flame liftoff dynamics, and the interplay between turbulence and chemical reactions necessitate additional investigation to guarantee dependable functioning.

Thermoacoustic phenomena pose considerable difficulty in hydrogen combustion systems. Lean-burn hydrogen flames, preferred for their capacity to reduce NOx emissions, are susceptible to combustion instabilities caused by oscillatory interactions between unsteady heat release and acoustic pressure waves. These instabilities, marked by significant oscillations, can inflict considerable damage on combustor hardware and interfere with operation. The heightened sensitivity of hydrogen flames to fluctuations in equivalency ratio intensifies this problem, as slight alterations in fuel-air mixing can result in considerable variances in heat release. Advanced modeling and experimental investigations indicate that the dynamic stability of hydrogen combustors is affected by variables like inlet gas temperature, flame stabilization techniques, and injection system design. For instance, elevated inlet temperatures can enhance the inherent stability of hydrogen flames, whilst novel injection configurations can alleviate the effects of flame-vortex interactions and diminish vulnerability to self-excited oscillations [3-5].

NOx emissions constitute a significant concern in hydrogen combustion owing to the elevated adiabatic flame temperature of hydrogen. In contrast to hydrocarbon fuels, hydrogen does not generate NOx via rapid or fuel-based pathways, making thermal NOx the primary creation method. Mitigating NOx emissions necessitates reducing flame temperatures by lean operation or steam injection, minimizing residence periods in elevated temperature regions, and enhancing the mixing process to prevent stoichiometric situations.[6, 7]. The intricacy of these methods is exacerbated by the necessity of maintaining high efficiency and dependable performance in gas turbines. Mixing is crucial in NOx management since inadequate or uneven mixing can generate areas conducive to NOx generation. Advanced models, such as the Incompletely Stirred Reactor (ISR) framework, tackle this issue by including mixture fraction changes in prediction calculations. These models provide precise evaluations of the impact of mixing dynamics on NOx emissions, offering essential insights for the design of hydrogen combustion systems [8].

Moreover, the interrelation among mixing processes, flame dynamics, and turbine cycle conditions highlights the complex issues associated with hydrogen combustion. The placement and speed of hydrogen injection about swirling airflows can significantly influence the mixture's distribution, the flame's structure, and the emissions' characteristics. Experimental and computational investigations have highlighted the significance of turbulence-chemistry interactions, residence time distributions, and injector plate cooling in regulating flame stability and emissions. These characteristics are especially crucial in high-pressure settings, such as aviation or industrial gas turbines, where minor alterations in operating conditions can result in significant fluctuations in performance and emissions [9-11].

The effective incorporation of hydrogen into gas turbine combustion systems necessitates a comprehensive strategy that integrates sophisticated technical solutions, thorough experimental validation, and precise computer modeling. Advancements in combustor design, injection methodologies, and mixing technologies are crucial to tackle the challenges of hydrogen's distinct combustion characteristics. As research and development improve, these innovations will facilitate hydrogen's pivotal role in attaining sustainable, low-emission power generation, bolstering global decarbonization initiatives and the shift towards a carbon-neutral energy future [12, 13].

3. GE GAS TURBINE COMBUSTION TECHNOLOGY

3.1 Hydrogen-Optimized Gas Turbine Combustion Systems

Gas turbines' capacity to function successfully on high-hydrogen fuels requires the implementation of sophisticated combustion systems tailored to the distinct characteristics of hydrogen.

Traditional dry low NOx (DLN) combustion systems may accommodate modest hydrogen concentrations; however, their efficacy diminishes with moderate to high hydrogen levels due to the intrinsic differences in combustion properties between hydrogen and methane. Specialized combustion systems that can accommodate elevated hydrogen concentrations are necessary to tackle this difficulty. General Electric (GE) has engineered a variety of combustion systems, compatible with both Aeroderivative and Heavy-Duty gas turbines, capable of functioning with hydrogen concentrations from a minimum of 5% (by volume) to 100%.[2]

3.2 Obstacles in Hydrogen Combustion

Gas turbine combustion systems are generally tuned for fuels with flame speed ranges. Nonetheless, hydrogen exhibits a markedly greater flame speed than methane, rendering traditional systems engineered for methane inadequate for high-hydrogen fuels. Combustion systems designed for high-hydrogen operation necessitate a redesign to accommodate hydrogen's distinct combustion characteristics [14, 15].

3.3 Safety Considerations

The utilization of hydrogen presents numerous safety problems. Low Luminosity: Hydrogen flames are challenging to perceive visually, requiring sophisticated flame detection equipment. Diffusion Risks: Hydrogen molecules can infiltrate seals deemed impenetrable to other gases, necessitating substitution with welded connections or alternative advanced sealing technology. Elevated Flammability: Hydrogen has a lower flammability threshold (4% in air) than methane (5%), augmenting the possible safety hazards linked to leaks. Therefore, enhanced plant safety standards must be enforced to reduce risks, encompassing adjustments to exclusion zones and operational processes[16, 17].

3.4 Hydrogen-Adapted Combustion Systems by GE

GE's aero-derivative gas turbines employ a Single Annular Combustor (SAC) designed to function with various fuels, including hydrogen-enriched mixtures. This system has been implemented in over 2,600 turbines, together accumulating over 100 million operational hours. SAC combustors may accommodate hydrogen concentrations between 30% and 85% by volume, contingent upon the turbine model.GE's Heavy-Duty gas turbines have two distinct combustion designs for high-hydrogen fuels:

- Single Nozzle Combustor (SN): This technology functions efficiently in B and E-class turbines with hydrogen concentrations reaching around 90-100% by volume.
- The Multi-Nozzle Quiet Combustor (MNQC) is utilized in E and F-class turbines, having been installed in more than 1,700 turbines and achieving 3.5 million operational hours on low calorific value fuels, including syngas and refinery gases. During the 1990s, GE assessed the MNQC for high-hydrogen fuels, successfully accomplishing combustion with hydrogen concentrations ranging from 43.5% to 89%.
- Dry Low Emission (DLE) and Dry Low Nitrogen Oxides (DLN) Combustors: GE's DLE and DLN combustors are engineered for restricted hydrogen concentrations. The DLE system, utilized in Aeroderivative turbines, is restricted to 5% hydrogen by volume.
- The DLN1 combustor, utilized in 6B, 7E, and 9E turbines, can support hydrogen concentrations of up to 33% when mixed with natural gas.
- The DLN 2.6+ system permits hydrogen concentrations of approximately 15%, while its corresponding fuel systems generally necessitate enhancements to manage elevated hydrogen levels safely.
- GE has developed a low-NOx hydrogen combustion system in collaboration with the U.S. Department of Energy's Advanced IGCC/Hydrogen Gas Turbine Program. This system uses small-scale jet-in-crossflow mixing and rapid fuel-air premixing to ensure stable combustion for highly reactive gaseous fuels like ethane, propane, and hydrogen. The system, which can operate with hydrogen concentrations of up to 50% by volume, is now available on GE's 9HA gas turbines, addressing the growing demand for low-carbon energy options. GE's innovations in combustion technology highlight the importance of customized solutions for high-hydrogen applications, utilizing advancements in premixed combustion,

improved safety protocols, and confirmed operational efficacy. These solutions are crucial in achieving sustainability objectives while ensuring operational reliability and safety.

3.5 PLANT EXPERIENCE WITH HYDROGEN IN GAS TURBINES

Hydrogen is an advantageous fuel for energy production, with gas turbines demonstrating versatility and efficacy across multiple industrial sectors, including steel mills, refineries, and petrochemical facilities. General Electric (GE) possesses substantial operational expertise, with over 70 gas turbines functioning on hydrogen-enriched fuels, amassing more than 4 million operational hours and exceeding 300 terawatts of power generation. Twenty-five gas turbines have effectively functioned on fuels comprising at least 50% hydrogen by volume, amassing over one million operating hours.

Hydrogen fuel mixing is an effective strategy when the hydrogen volume is inadequate for complete gas turbine loading. Conventional Dry Low NOx (DLN) combustion systems are capable of accommodating blended fuels. The Dow Plaquemine Plant in the USA combined hydrogen with natural gas to produce a mixture consisting of 5% hydrogen and 95% natural gas. The CEPSA Gibraltar-San Roque Refinery in Spain operates a GE 6B.03 gas turbine utilizing refinery fuel gas (RFG) with a hydrogen component that fluctuates up to around 32% by volume.

GE's heavy-duty gas turbines have been effectively utilized in numerous steel mill operations, utilizing low calorific value fuels such as blast furnace gas (BFG) and coke oven gas (COG), which frequently contain substantial quantities of hydrogen. GE's heavy-duty and aeroderivative gas turbines have surpassed 1 million operational hours utilizing steel mill gases worldwide. Synthesis gas (syngas) is a low-calorific value fuel, with hydrogen content often between 20% and 50% by volume. GE has installed its gas turbines in various Integrated Gasification Combined Cycle (IGCC) plants globally, cumulatively reaching over 1.5 million operational hours.

Converting to high-hydrogen fuels is feasible with gas turbines, which provide considerable versatility. Current gas turbine installations can be adapted to utilize fuels with differing hydrogen concentrations, contingent upon the hydrogen content and particular fuel properties. Instances of high-hydrogen gas turbine initiatives encompass the Daesan Refinery in South Korea, where a GE 6B.03 gas turbine has functioned for over 20 years utilizing fuel comprising over 70% hydrogen by volume.

Gas turbines are adaptable devices capable of functioning on a range of fuels, encompassing low, moderate, and high hydrogen concentrations. As hydrogen emerges as a pivotal component of future energy systems, gas turbines are anticipated to be important in facilitating the transition to a sustainable, low-carbon energy future.

Fig. 1. Possible effects of hydrogen fuel conversion on gas turbine systems [2].

4. MITSUBISHI EFFORTS AND OBJECTIVES FOR HYDROGEN CO-FIRING AND COMPLETE HYDROGEN COMBUSTION [13, 18, 19]

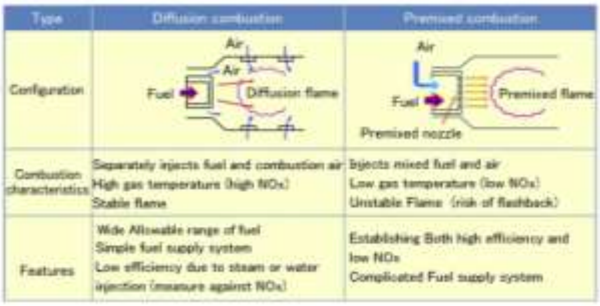
Mitsubishi Power Ltd. has proven that the JAC gas turbine can co-fire with natural gas using up to 30% hydrogen by volume, with intentions to attain 100% hydrogen operation in the future. This capability is essential for the shift from natural gas-dominated systems to hydrogen-exclusive systems as hydrogen production, transportation, and storage technologies advance. Hydrogen co-firing has the subsequent advantages [20]:

- Decreased CO_2 Emissions: At a 30% hydrogen co-firing ratio, CO_2 emissions are markedly diminished compared to solely natural gas systems.

- Operational Stability: Hydrogen is a dependable secondary energy source that enhances renewable energy and alleviates power fluctuations.
- Flexibility for Future Hydrogen Supply Chains: The JAC turbine's architecture facilitates seamless incorporation into hydrogen-based energy systems without significant infrastructural alterations.
- Hydrogen and Advanced Component Technologies in the JAC Turbine. The JAC turbine integrates advanced technologies to facilitate hydrogen combustion and high-temperature performance.
- Enhanced Air-Cooled Combustor: The JAC turbine's air-cooled mechanism supersedes conventional steam cooling, augmenting operability and efficiency.
- The device guarantees stable combustion at 1650°C, an essential criterion for hydrogen-rich fuels. The technology enhances performance in both flexible and steady-state operations by regulating turbine clearance during load variations.
- The turbine incorporates sophisticated Thermal Barrier Coating (TBC) materials created as part of the national "1700°C Class Ultrahigh-Temperature Gas Turbine Component Technology Development" initiative.
- The increased thickness of the TBC improves durability and dependability, enabling it to withstand elevated combustion temperatures linked to hydrogen-rich fuels.
- High-Pressure Ratio Compressor: The compressor is engineered to accommodate the elevated flow demands of hydrogen-rich combustion while preserving aerodynamic stability and efficiency.
- The 1650°C Class JAC gas turbine has been validated by the T-point 2 facility, confirming its reliability, performance, and emissions characteristics. The turbine's enhanced air-cooled system and combustor design enable stable operation under varying loads, with hydrogen co-firing showing no adverse effects on combustion stability.
- Mitsubishi Heavy Industries (MHI) has established itself as a pioneer in this transition by innovatively developing hydrogen-fired gas turbines and associated technology. The company's combustor designs address the combined concerns of NOx reduction and flashback prevention. MHI’s Dry Low NOx (DLN) Multi-Nozzle Combustor employs premixing to achieve constant flame temperatures, hence obviating the necessity for steam or water injection to mitigate NOx emissions. This design incorporates air injection at the vortex core to avert flashback and maintain stable operation with hydrogen concentrations reaching 30%, as confirmed by engine pressure testing. MHI’s Multi-Cluster Combustor facilitates swift air-hydrogen mixing at elevated hydrogen concentrations, eliminating whirling flows, hence improving flashback resistance and sustaining low NOx emissions. Moreover, Diffusion Combustors offer versatility, accommodating hydrogen concentrations of up to 90% with steam or water injection for NOx mitigation, as evidenced by the WE-NET program [19].
- MHI is innovating ammonia cracking systems for gas turbine combined cycle (GTCC) plants, extending its expertise beyond combustor design. Ammonia possesses a hydrogen density 1.5 times greater than that of liquefied hydrogen, utilizing current LPG infrastructure for transportation and storage. In these systems, ammonia undergoes thermal cracking to generate hydrogen for turbine combustion, maintaining net efficiency by chemical recuperation. The research aims to diminish leftover ammonia to reduce NOx emissions and to optimize the catalyst for extensive uses. MHI is globally engaged in innovative hydrogen initiatives, such as the transformation of the Nuon Magnum GTCC facility in the Netherlands to operate entirely on hydrogen. This program illustrates the technical viability of upgrading current infrastructure to support hydrogen, thereby substantially decreasing CO_2 emissions.
- MHI's initiatives underscore its crucial position in the worldwide shift towards a hydrogen economy. MHI is fostering innovation towards a CO_2-free world through the integration of modern hydrogen-fired turbine technology, ammonia cracking systems, and active involvement in international hydrogen initiatives. These developments facilitate the incorporation of renewable energy into the grid while also offering transitional solutions utilizing fossil fuel-derived hydrogen in conjunction with

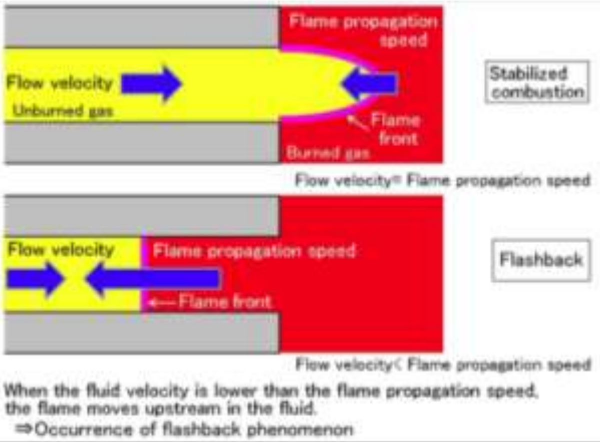
carbon capture and storage (CCS). As hydrogen-fueled GTCC systems advance, they are set to be pivotal in attaining global CO_2 reduction objectives by 2050, guaranteeing dependable and efficient power generation for the future.

- In response to the increased risk of flashback due to hydrogen's rapid flame propagation speed, MHI implemented air injection at the combustor's vortex core to enhance flow velocity and mitigate low-velocity areas susceptible to flashback. This innovative method was confirmed using non-combustion airflow testing, exhibiting a 2.5-fold enhancement in flow velocity relative to traditional designs.
- MHI conducted comprehensive combustion studies under actual engine pressure settings at its Takasago Plant, validating the feasibility of co-firing up to 30% hydrogen by volume. Although there was a slight increase in NOx emissions attributed to hydrogen's rapid burning characteristics, the emissions stayed under permissible regulatory thresholds, and combustion instability pressures showed minimal fluctuations, guaranteeing operational reliability. MHI created a multi-cluster combustor featuring distributed nozzles to facilitate quick fuel-air mixing at hydrogen concentrations over 30%, thereby reducing flashback concerns and sustaining low NOx emissions without swirling flows. Moreover, diffusion combustors were utilized for applications demanding greater flexibility, capable of accommodating hydrogen concentrations up to 90%; nevertheless, these systems require steam or water injection for NOx mitigation.
- MHI's innovations encompass more than combustion technology, focusing significantly on hydrogen infrastructure compatibility, including creating ammonia cracking devices for hydrogen production and storage. These devices thermally degrade ammonia into hydrogen while preserving efficiency via chemical recuperation. MHI is engaged in innovative projects globally, including converting the 1.32 GW Nuon Magnum GTCC plant in the Netherlands to operate entirely on hydrogen, showcasing the feasibility of adapting existing gas turbine systems for decarbonized power generation.
- MHI is establishing a standard for sustainable power production by tackling significant hurdles in hydrogen combustion technology and incorporating novel solutions in combustor designs, safety systems, and fuel flexibility. Their strategy emphasizes the feasibility of hydrogen co-firing. It establishes hydrogen as a crucial component in worldwide initiatives to attain a low-carbon energy future, with comprehensive hydrogen integration aimed for 2025 and after that.
- The 1650°C Class JAC gas turbine significantly advances gas turbine combined cycle (GTCC) power generation technology. Hydrogen integration in GTCC systems aligns with global efforts to reduce CO_2 emissions and enhance renewable energy reliability. The M501JAC gas turbine, operating at an unprecedented 1650°C inlet temperature, incorporates advanced technologies to improve efficiency, reduce emissions, and allow for hydrogen co-firing. Hydrogen combustion generates zero direct CO_2 emissions, making it an ideal complement to natural gas for GTCC systems. The turbine's ability to operate with up to 30% hydrogen co-firing reduces greenhouse gas emissions, paving the way for future hydrogen-dominant power generation systems.



Type	Diffusion combustion	Premixed combustion
Configuration	Air Air Fuel Diffusion flame	Air Fuel Premixed flame Premixed nozzle
Combustion characteristics	Separately injects fuel and combustion air High gas temperature (high NOx) Stable flame	Injects mixed fuel and air Low gas temperature (low NOx) Unstable Flame (risk of flashback)
Features	Wide Allowable range of fuel Simple fuel supply system Low efficiency due to steam or water injection (measure against NOx)	Establishing Both high efficiency and low NOx Complicated Fuel supply system

Fig. 2. Comparison of Combustor Types [19].



When the fluid velocity is lower than the flame propagation speed, the flame moves upstream in the fluid.
⇒Occurrence of flashback phenomenon

Fig. 3. Flash Back in Gas Turbines [19].

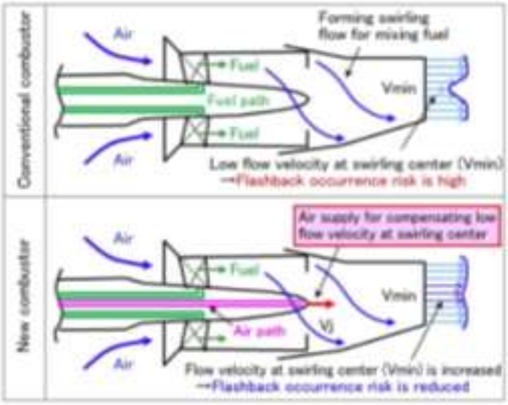
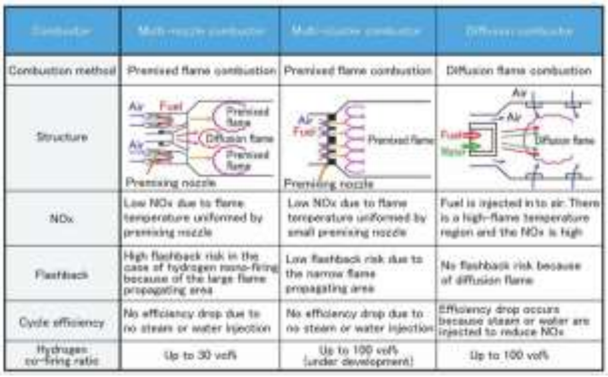


Fig. 4. Mitsubishi New Combustor Design [19].



Combustor	Multi-nozzle combustor	Multi-cluster combustor	Diffusion combustor
Combustion method	Premixed flame combustion	Premixed flame combustion	Diffusion flame combustion
Structure	Air Fuel Premixed flame Diffusion flame Premixed flame Premixing nozzle	Air Fuel Premixed flame Premixing nozzle	Air Air Fuel Water Diffusion flame
NOx	Low NOx due to flame temperature uniformed by premixing nozzle	Low NOx due to flame temperature uniformed by small premixing nozzle	Fuel is injected in to air. There is a high-flame temperature region and the NOx is high
Flashback	High flashback risk in the case of hydrogen mono-firing because of the large flame propagating area	Low flashback risk due to the narrow flame propagating area	No flashback risk because of diffusion flame
Cycle efficiency	No efficiency drop due to no steam or water injection	No efficiency drop due to no steam or water injection	Efficiency drop occurs because steam or water are injected to reduce NOx
Hydrogen co-firing ratio	Up to 30 vol%	Up to 100 vol% (under development)	Up to 100 vol%

Fig. 5. Mitsubishi New Combustor Design [13].

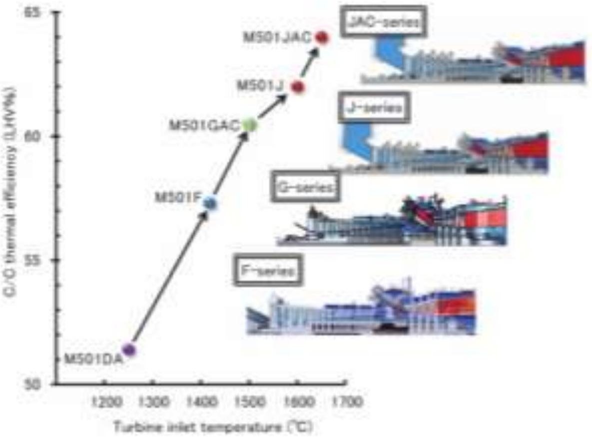


Fig. 6. Mitsubishi Gas Turbines (KAZUKI MORIMOTO YOSHIKAZU MATSUMURA, 2021).

Table 2. Performance comparison (KAZUKI MORIMOTO YOSHIKAZU MATSUMURA, 2021).

Parameter	M501J	M501JAC
Frequency (Hz)	60	60
Pressure Ratio	23	25
Gas Turbine Output (MW)	330	435
Gas Turbine Efficiency (%-LHV)	42	44
Combined Cycle Output (MW)	484	630
Combined Cycle Efficiency (%LHV)	62	>64

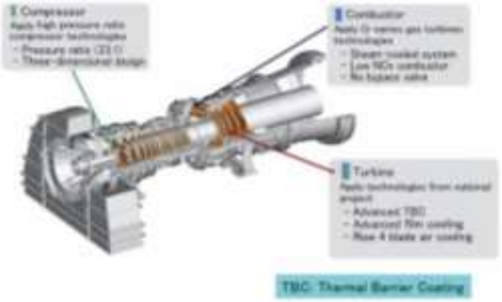


Fig. 7. Technological attributes of M501J series gas turbine components (KAZUKI MORIMOTO YOSHIKAZU MATSUMURA, 2021).

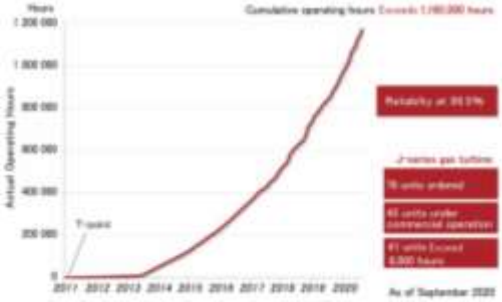


Fig. 8. Operating results of M501J series gas turbine (including 50 Hz units) (KAZUKI MORIMOTO YOSHIKAZU MATSUMURA, 2021).

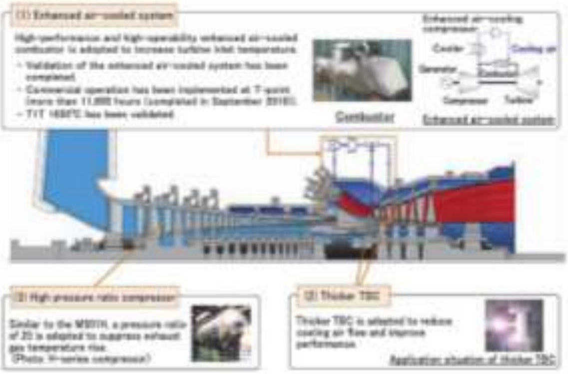


Fig. 9. Development idea of the 1650°C class JAC series gas turbine (KAZUKI MORIMOTOYOSHIKAZU MATSUMURA, 2021).

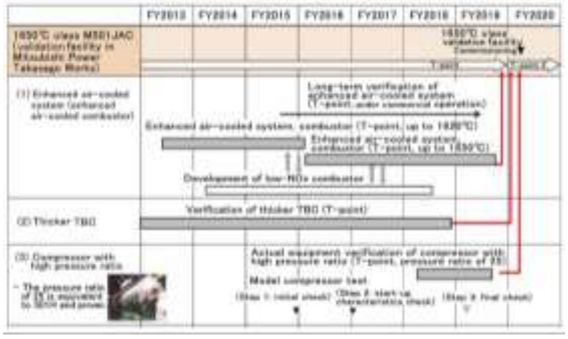


Fig. 10. The Modifications 1650°C class JAC series gas turbine (KAZUKI MORIMOTO YOSHIKAZU MATSUMURA, 2021).

5. CONCLUSION

The incorporation of hydrogen into gas turbine systems signifies transformative progress in sustainable energy, tackling essential issues arising from the worldwide transition to a carbon-neutral future. Gas turbines' capacity to co-fire and ultimately function entirely on hydrogen offers a means to diminish greenhouse gas emissions while ensuring grid stability. This study has examined the technological and operational obstacles, breakthroughs, and prospects related to hydrogen-fueled gas turbines.

Significant issues in hydrogen combustion encompass flame stabilization, flashback prevention, NOx emissions, and thermoacoustic behavior, necessitating creative technological solutions. The strong reactivity and flame velocity of hydrogen elevate the risk of flashback and combustion instability, requiring sophisticated combustor designs. Mitsubishi's multi-cluster combustor and GE’s low-NOx combustion systems have effectively addressed these difficulties through innovative fuel-air mixing methods, dispersed injection schemes, and resilient flame stability mechanisms.

The environmental and economic viability of hydrogen as a principal fuel source depends on scalable production techniques such as steam methane reforming (SMR) with carbon capture and water electrolysis powered by renewable energy. SMR is a viable short-term solution but necessitates effective carbon capture and storage (CCS) technologies to attain genuine carbon neutrality. Electrolysis provides a wholly sustainable hydrogen solution but requires substantial energy and water resources, highlighting the necessity of using renewable energy sources. The operational requirements of the 9HA.02 turbine underscore the substantial energy and water inputs necessary for hydrogen production, highlighting the imperative for further improvements in electrolysis efficiency and renewable energy capacity.

The advancements by industry heavyweights like General Electric and Mitsubishi Heavy Industries highlight the feasibility of hydrogen integration in current and prospective gas turbines. GE's combustion systems, comprising the Single Nozzle Combustor and Multi-Nozzle Quiet Combustor, exhibit adaptability to diverse hydrogen concentrations, while Mitsubishi's JAC turbines attain exceptional efficiency and emission reductions at turbine inlet temperatures of 1650°C. The advancement of ammonia cracking systems broadens the potential of hydrogen as a fuel by tackling storage and transportation issues, utilizing existing LPG infrastructure, and enabling chemical recovery to sustain efficiency.

Operational experiences with hydrogen co-firing and high-hydrogen fuel mixtures in several industrial sectors have yielded significant insights into performance and emissions attributes. Initiatives like Mitsubishi’s Nuon Magnum GTCC facility in the Netherlands and GE’s widespread implementation in steel mills and refineries exemplify the versatility of gas turbines with various fuel compositions and their contribution to the decarbonization of industrial processes. These examples underscore the importance of safety measures, including sophisticated sealing technologies and improved flame detection systems, to mitigate hydrogen's distinctive physical characteristics, such as low brightness and strong diffusivity.

The shift to hydrogen-centric power generation has several obstacles. The intricacies of mixing dynamics, turbulence-chemistry interactions, and high-pressure working conditions necessitate ongoing research and development. Computational models, including the Incompletely Stirred Reactor (ISR) framework, provide essential instruments for enhancing mixing, flame stabilization, and NOx reduction. These models and experimental validation furnish the basic knowledge required to improve combustor designs and operational methods.

Hydrogen-fueled gas turbines are set to be essential in meeting global decarbonization objectives by 2050. Hydrogen's capacity to enhance renewable energy sources through grid stability and progress in production, storage, and combustion technologies establishes it as a fundamental element of the energy transition. Nonetheless, actualizing this promise necessitates collaborative endeavors among policymakers, industry participants, and researchers to surmount technological and economic obstacles. Hydrogen-fired gas turbines can facilitate the transition to a sustainable energy ecosystem by tackling these difficulties, guaranteeing reliable, efficient, and environmentally responsible power generation for future generations.

REFERENCES

[1] L. Ge, Y. Fan, J. Lai, Y. Sun, and Y. Zhang, "Artificial Intelligence Enabled Microgrid Optimization Technology for Low Carbon Economy," Gaodianya Jishu/High Voltage Engineering, vol. 49, no. 6, 2023, doi: 10.13336/j.1003-6520.hve.20230414.

[2] J. Goldmeer, "Power to Gas: Hydrogen For Power Generation Fuel Flexible Gas Turbines as Enablers for a Low or Reduced Carbon Energy Ecosystem," 2019.

[3] R. A. Bakar et al., "Experimental analysis on the performance, combustion/emission characteristics of a DI diesel engine using hydrogen in dual fuel mode," International Journal of Hydrogen Energy, vol. 52, pp. 843–860, 2024, doi: 10.1016/j.ijhydene.2022.04.129.

[4] V. M. Domínguez, J. J. Hernández, Á. Ramos, M. Reyes, and J. Rodríguez-Fernández, "Hydrogen or hydrogen-derived methanol for dual-fuel compression-ignition combustion: An engine perspective," Fuel, vol. 333, p. 126301, 2023, doi: 10.1016/j.fuel.2022.126301.

[5] M. Ikegami, K. Miwa, M. Shioji, And M. Esaki, "A Study on Hydrogen-fueled Diesel Combustion," Bulletin of JSME, vol. 23, no. 181, pp. 1187–1193, 1980, doi: 10.1299/jsme1958.23.1187.

[6] C. Li, Y. Wang, B. Jia, Z. Zhang, and A. Roskilly, "Numerical Investigation on NOx Emission of a Hydrogen-Fuelled Dual-Cylinder Free-Piston Engine," Applied Sciences, vol. 13, no. 3, p. 1410, 2023, doi: 10.3390/app13031410.

[7] V. Chintala and K. A. Subramanian, "Hydrogen energy share improvement along with NOx (oxides of nitrogen) emission reduction in a hydrogen dual-fuel compression ignition engine using water injection," Energy Conversion and Management, vol. 83, pp. 249–259, 2014, doi: 10.1016/j.enconman.2014.03.075.

[8] A. Abbass, "Hydrogen as a Clean Fuel: Review of Production, Storage, Fuel Cells, and Engine Technologies for Decarbonization," International Journal of Progressive Research in Engineering Management and Science, vol. 4, no. 11, 2024.

[9] Y. Karagöz, İ. Güler, T. Sandalcı, L. Yüksek, and A. S. Dalkılıç, "Effect of hydrogen enrichment on combustion characteristics, emissions and performance of a diesel engine," International Journal of Hydrogen Energy, vol. 41, no. 1, pp. 656–665, 2016, doi: 10.1016/j.ijhydene.2015.09.064.

[10] S. Nag, P. Sharma, A. Gupta, and A. Dhar, "Experimental study of engine performance and emissions for hydrogen diesel dual fuel engine with exhaust gas recirculation," International Journal of Hydrogen Energy, vol. 44, no. 23, pp. 12163–12175, 2019, doi: 10.1016/j.ijhydene.2019.03.120.

[11] B. Annamalai and P. Murugesan, "The combined effect of hydrogen enrichment and exhaust gas recirculation on the combustion stability, performance and emissions of CI engine energized by algae biodiesel," International Journal of Hydrogen Energy, vol. 50, pp. 524–546, 2024, doi: 10.1016/j.ijhydene.2023.09.278.

[12] E. A. Tingas, Hydrogen for Future Thermal Engines. 2023.

[13] [13] M. Nose, T. Kawakami, H. Araki, N. Senba, and S. Tanimura, "Hydrogen-fired gas turbine targeting realization of CO2-free Society," Mitsubishi Heavi Industries Technical Review, vol. 55, no. 4, 2018.

[14] University of Idaho., "ME529 Combustion and Air Pollution," 2012.

[15] M. Ilhan Ilhak, S. Tangoz, S. Orhan Akansu, and N. Kahraman, "Alternative Fuels for Internal Combustion Engines," The Future of Internal Combustion Engines, 2019, doi: 10.5772/intechopen.85446.

[16] L. Yip et al., "A Review of Hydrogen Direct Injection for Internal Combustion Engines: Towards Carbon-Free Combustion," Applied Sciences, vol. 9, no. 22, 4842, 2019, doi: 10.3390/app9224842.

[17] University of Idaho, "ME433 Internal Combustion Engine Systems," 2024.

[18] K. Morimoto and Y. Matsumura, "Validation Results of 1650°C Class JAC Gas Turbine at T-point 2 Demonstration Plant," Mitsubishi Heavy Industries Technical Review, Vol. 58 No. 1, 2021.

[19] K. Inoue, K. Miyamoto, S. Domen, I. Tamura, T. Kawakami, and S. Tanimura, "Development of Hydrogen and Natural Gas Co-firing Gas Turbine," Mitsubishi Heavy Industries Technical Review, vol. 55, no. 2, 2018.

[20] J. Ghojel, "Fundamentals of Heat Engines," 2020, doi: 10.1002/9781119548829.