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A Layered Taxonomy and Classification of Hydrogen Gas Turbine Combustion for Power Generation Process

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Abstract: Hydrogen gas turbines are emerging as a pivotal technology in the quest for cleaner and more sustainable power generation. The efficient utilization of hydrogen fuel in gas turbines necessitates a comprehensive understanding of combustion processes and their optimization. This paper presents a layered taxonomy and classification framework for hydrogen gas turbine combustion, aimed at improving clarity and facilitating advancements in power generation. The proposed taxonomy categorizes combustion technologies and strategies into distinct layers based on fuel type, combustion dynamics, and performance metrics. It encompasses fundamental principles of hydrogen combustion, including flame characteristics, stability issues, and optimization techniques. By examining the different levels of combustion processes and their interactions, this framework provides a structured approach to analyzing and improving hydrogen gas turbine performance. The review highlights recent developments, challenges, and future directions in hydrogen gas turbine technology, offering valuable insights for researchers, engineers, and policymakers seeking to enhance the efficiency and sustainability of power generation systems.

Keywords: Combustion technologies, flame characteristics, fuel type, hydrogen combustion, hydrogen gas turbines, power generation.

I. INTRODUCTION

As the global energy landscape increasingly shifts towards more sustainable and eco-friendly solutions, hydrogen gas turbines have emerged as a pivotal technology for clean power generation [1]. This shift is driven by the urgent need to mitigate the environmental impact of conventional energy sources, which are major contributors to climate change and air pollution. Hydrogen, as a fuel, holds immense promise due to its potential to significantly reduce greenhouse gas emissions compared to traditional fossil fuels like coal, oil, and natural gas. Unlike these fossil fuels, which release substantial amounts of carbon dioxide (CO_2), sulfur oxides (SOx), and nitrogen oxides (NOx) into the atmosphere, hydrogen combustion primarily produces water vapor and heat, resulting in very low levels of these harmful pollutants [2]. In addition to its environmental benefits, hydrogen can enhance overall cycle efficiency in gas turbines, leading to improved energy conversion rates and reduced fuel consumption. The potential to develop new types of power cycles further underscores hydrogen's role in advancing energy technology [3]. By utilizing hydrogen as shown in Figure 1, in gas turbines, we can not only achieve cleaner energy production but also explore innovative approaches to power generation that align with global sustainability goals.

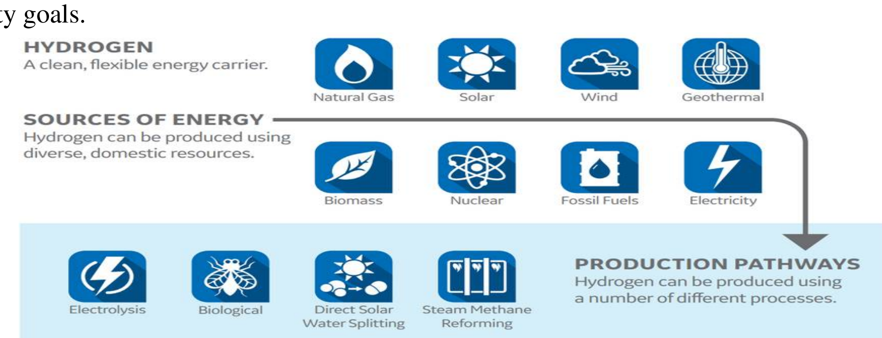

Figure 1.

Despite the significant environmental advantages of hydrogen, its integration into gas turbine systems presents a range of unique and complex challenges that necessitate a thorough and systematic understanding of hydrogen combustion processes [4]. One of the primary challenges is hydrogen's low volumetric energy density, which means that it occupies more space compared to conventional fuels to provide the same amount of energy. This characteristic affects the design and operation of gas turbines, as it requires modifications to accommodate larger volumes of hydrogen and optimize its use. Additionally, hydrogen burns at higher temperatures than most conventional fuels, which can lead to increased thermal stresses and potential damage to turbine components if not managed properly [5]. Addressing these challenges involves tackling issues such as hydrogen's high reactivity, which can lead to rapid combustion and increased risk of flame instability. Ensuring stable and efficient combustion is crucial for maintaining turbine performance and longevity.

Furthermore, optimizing the efficiency of hydrogen combustion involves developing advanced combustion technologies and control systems that can handle the unique properties of hydrogen, such as its wide flammability range and high diffusivity [6]. Successfully overcoming these engineering complexities is essential for realizing the full potential of hydrogen as a clean fuel source and achieving reliable and efficient gas turbine operation. To address these issues effectively, a comprehensive and organized approach to hydrogen gas turbine combustion is necessary. This paper introduces a layered taxonomy and classification framework designed to systematically categorize and analyze the various aspects of hydrogen combustion in gas turbines. The proposed framework is structured as a hierarchical taxonomy, starting with the core combustion processes and branching out to detail the associated phenomena and technologies.

II. FUNDAMENTALS OF GAS TURBINE OPERATION

Gas turbines are essential in both power generation and aerospace applications due to their ability to efficiently convert fuel into mechanical work through a continuous thermodynamic cycle. The fundamental principles governing gas turbine combustion are crucial for optimizing turbine performance and ensuring efficient and stable operation [7]. They are basically four types of gas turbines based on structure and function as detailed in Figure 2. This section provides a detailed examination of these principles and their implications for using alternative fuels like hydrogen.

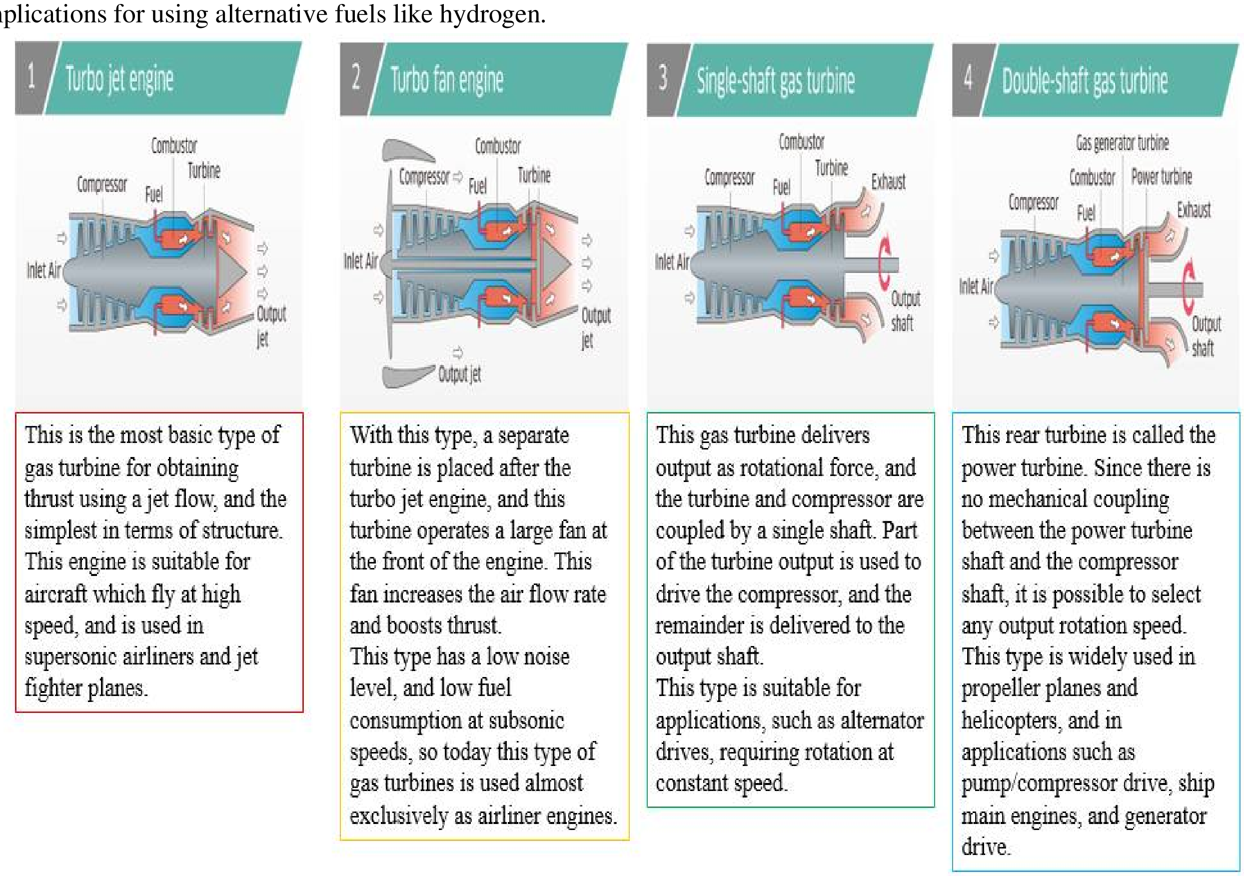

Fig. 2 Four types of gas turbines based on structure and function.

A. Principles of Gas Turbine Operation

Just like a diesel or gasoline engine, a gas turbine is a type of internal combustion engine and operates using the cycle of intake, compression, combustion (expansion) and exhaust [8]. One major difference, however, is the basic movement. A gas turbine is rotary movement, in contrast to the back-and-forth movement of a reciprocating engine [9]. The basic principle of a gas turbine is as shown in Figure 3. First, air is compressed by a compressor, and this compressed air is guided into the combustor. Here, fuel is continuously combusted to produce gas at high temperature and pressure. What a gas turbine for industry does is the gas produced in the combustor is expanded in the turbine (a vaned rotor made by attaching multiple blades to a round disk), and as the result, the rotational energy, which operates the compressor at the previous stage, is produced. The remaining energy is delivered with an output shaft.

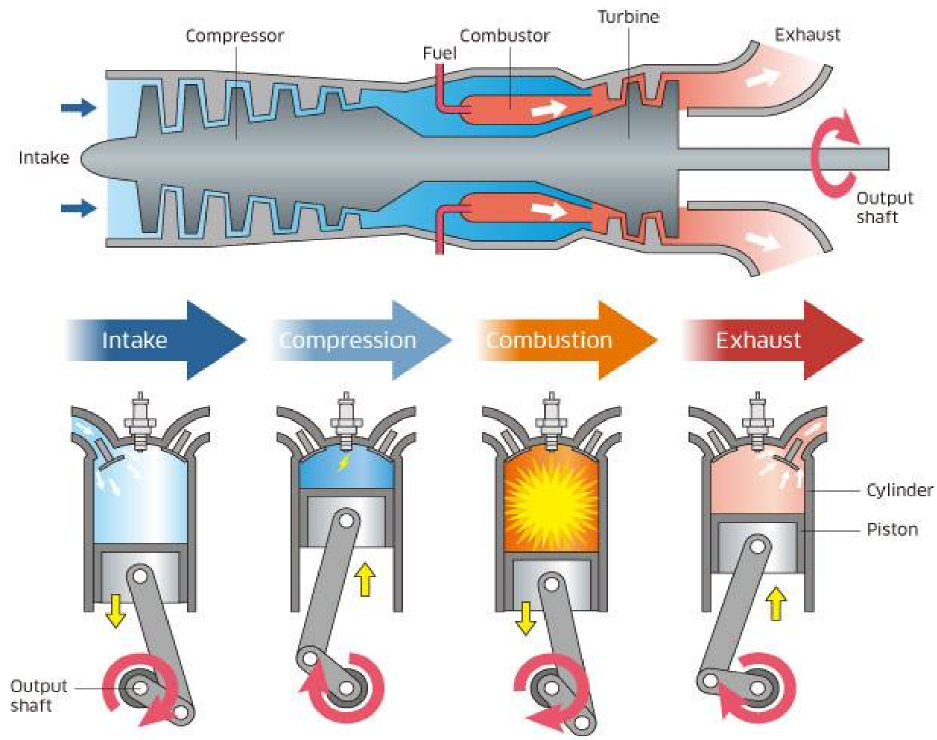

Figure 3 Basic principle of a gas turbine.

Gas turbines operate based on the thermodynamic process consisting of four main stages:

1) *Compression:* Ambient air is drawn into the compressor, where it is compressed to a higher pressure. This process increases the air's density, which is crucial for efficient combustion. The compressor typically consists of multiple stages of rotating and stationary blades that incrementally increase the pressure of the air.
2) *Combustion:* In the combustion chamber, the high-pressure air is mixed with fuel and ignited. This stage is critical as it converts the chemical energy of the fuel into thermal energy. The mixture of fuel and compressed air must be precisely controlled to ensure efficient combustion and to prevent incomplete combustion, which can lead to higher emissions.
3) *Expansion:* The high-temperature, high-pressure gases produced in the combustion chamber then expand through the turbine section. This expansion drives the turbine blades, which are connected to a shaft that generates mechanical work. The expansion process converts thermal energy into mechanical energy, which can be used to drive generators or propellers.
4) *Exhaust:* Finally, the exhaust gases exit the turbine and are expelled through the exhaust system. The efficiency of this stage is affected by how well the turbine has converted the energy from the combustion process into work. Minimizing energy losses and optimizing exhaust flow are essential for improving overall turbine efficiency.

The performance of a gas turbine is influenced by several factors, including the pressure ratio (the ratio of the compressor discharge pressure to the ambient pressure), turbine inlet temperature (which impacts the energy conversion efficiency), and the efficiency of both the compressor and turbine [10].

B. Combustion Chamber Design

The combustion chamber design plays a pivotal role in determining the efficiency and stability of the combustion process. Key design considerations include:

1) *Geometry:* The combustion chamber's shape and size affect how well the air and fuel mix, how the flame behaves, and how heat is transferred to the surrounding components. Common designs include annular, can-annular, and silo-type chambers. Each design has its own advantages and is selected based on the specific requirements of the turbine application.
2) *Fuel Injection:* Effective fuel injection systems are crucial for achieving optimal combustion. The fuel must be atomized (broken into fine droplets) to ensure thorough mixing with the air. Various techniques such as pre-mixing (mixing air and fuel before entering the combustion chamber) and staged injection (introducing fuel in stages) are employed to improve combustion efficiency and reduce emissions.
3) *Cooling:* Combustion chambers operate at extremely high temperatures, which necessitates effective cooling methods to protect chamber materials and maintain structural integrity. Common cooling techniques include air cooling (using compressed air to cool the chamber walls), film cooling (creating a thin film of cool air along the chamber walls), and transpiration cooling (using porous materials to allow cool air to seep through and cool the chamber).

C. Fuel-Air Mixing and Ignition

Proper fuel-air mixing and ignition are essential for stable and efficient combustion:

1) *Fuel-Air Mixing:* Efficient mixing ensures that the fuel is evenly distributed throughout the air, leading to uniform combustion. Poor mixing can result in localized rich or lean zones, which can affect flame stability and lead to incomplete combustion. Methods to improve mixing include using swirlers or turbulence generators to enhance the mixing process.
2) *Ignition Systems:* Ignition systems are responsible for initiating the combustion process. In gas turbines, this is typically achieved using spark plugs or igniter devices. The ignition system must ensure reliable and consistent ignition under various operating conditions. Factors such as ignition timing, fuel composition, and air-fuel ratio play a role in the effectiveness of the ignition system.

D. Flame Stability and Control

Maintaining flame stability is crucial to prevent issues such as blow-off (flame detachment), flashback (flame traveling back into the burner), or instability (flame fluctuations). Techniques for ensuring flame stability include:

1) *Flame Stabilizers:* Devices like flame holders or swirlers create specific flow patterns that help stabilize the flame. Flame holders create recirculation zones where the flame can anchor itself, while swirlers generate rotational flow to improve mixing and stability.
2) *Control Systems:* Advanced control systems monitor various parameters such as air-fuel ratio, combustion temperature, and pressure to maintain stable combustion. These systems adjust the fuel and air supply in real-time to respond to changes in operating conditions and ensure optimal performance.

E. Emissions and Environmental Impact

The environmental impact of gas turbine combustion is a significant concern, particularly with respect to emissions:

1) *Lean Combustion:* Operating with a lean air-fuel ratio (more air relative to fuel) can reduce nitrogen oxides (NOx) emissions but may impact flame stability and efficiency. Balancing the air-fuel ratio is essential to achieve low emissions while maintaining stable combustion.
2) *Low-NOx Burners:* Specialized burners designed to minimize NOx formation through advanced combustion techniques are used to reduce emissions. These burners incorporate technologies such as staged combustion or lean-premixed combustion to lower NOx emissions.
3) *Emission Control Systems:* Technologies such as selective catalytic reduction (SCR) and exhaust gas recirculation (EGR) are employed to further reduce emissions. SCR uses a catalyst to convert NOx into nitrogen and water, while EGR recirculates a portion of the exhaust gases back into the combustion chamber to lower NOx formation.

F. Advanced Combustion Technologies

Recent advancements aim to improve efficiency, reduce emissions, and enable the use of alternative fuels:

1) *Dry Low-NOx Burners:* These burners operate at low NOx levels without the need for additional water or steam injection. They achieve this by optimizing the combustion process to minimize NOx formation.
2) *Lean Premixed Combustion:* This technique involves mixing fuel and air before combustion to achieve lower emissions and higher efficiency. By maintaining a lean mixture, the formation of NOx is reduced, although challenges related to flame stability must be addressed.
3) *Hybrid Combustion Systems:* Hybrid systems combine different fuel types or combustion technologies to optimize performance and emissions. For example, hydrogen may be blended with natural gas to leverage its low emissions while maintaining stable combustion.

III. FUEL CHARACTERISTICS

The fuel characteristics used play a crucial role in determining the efficiency, performance, and environmental impact of power generation systems [11]. Each fuel type exhibits unique properties that influence its suitability for gas turbines. Table 1 provides a detailed evaluation of each fuel based on its characteristics, advantages, and applications. Hydrogen is notable for its high energy content, zero CO2 emissions, and potential role in clean energy systems [12]. Natural gas is recognized for its lower greenhouse gas emissions compared to coal, cost-effectiveness, and versatility in power generation [13]. Coal, despite its high energy content and widespread availability, is reliable but poses significant environmental challenges [14]. Diesel is valued for its high energy density and reliability under various conditions, making it particularly useful for backup power and mobile applications [15]. Biomass is highlighted as a renewable option that can help reduce waste and net CO2 emissions [16]. While these fuels share applications in power generation and industrial processes, each has distinct strengths. For example, hydrogen is promising for research and development and as a transitional fuel, whereas biomass is particularly suited for agriculture and biofuel production. This comparison underscores the diverse energy landscape, balancing environmental impact, efficiency, reliability, and existing infrastructure across different fuel types.

TABLE 1. A detailed evaluation of each fuel based on its characteristics, advantages, and applications.

Fuel Type	Characteristics	Advantages	Applications
Hydrogen	- High specific energy content - High flame speed - Low air/oxygen requirement - No nitrogen oxides - Wide flame stability range - Low radiation levels - No harmful emissions - Produced from renewable sources	- Zero CO2 emissions - Reduced pollutants (SOx, NOx) - Increased efficiency - Lightweight turbine designs - Improved durability and performance	- Power generation - Industrial applications - Research and development - Transition fuel for cleaner energy systems
Natural Gas	- High energy density - Well-established infrastructure - Lower CO2 emissions compared to coal - Reliable and efficient	- Lower greenhouse gas emissions than coal - Cost-effective - Mature technology - Flexibility in power generation	- Power generation - Heating - Industrial processes - Backup power
Coal	- High energy content - Abundant and widely available - Established infrastructure	- Reliable and consistent energy supply - Low initial cost - Infrastructure is well-developed	- Power generation - Industrial processes - Heating
Diesel	- High energy density	- Reliable for standby and	- Backup power

	- Reliable and flexible - Existing infrastructure	backup power - Good performance in various conditions - Established technology	- Mobile power generation - Marine engines - Industrial machinery
Biomass	- Renewable - Can reduce waste - Lower net CO2 emissions (carbon-neutral)	- Sustainable - Reduces reliance on fossil fuels - Can use waste materials	- Power generation - Heating - Biofuel production - Agriculture

Table 2 outlines key justifications for using hydrogen as a fuel source, particularly in turbine systems. Hydrogen offers significant environmental benefits, producing only water vapor during combustion, which results in zero CO2 emissions and reduced air pollutants [2]. Its high specific energy content (120,000 kJ/kg) and rapid flame speed (100-200 m/s) contribute to efficient power generation and enhanced combustion processes. Hydrogen requires less air or oxygen for combustion, allowing for more compact turbine designs. It maintains good flame stability across various conditions, produces lower radiation levels during combustion, and doesn't emit harmful organic compounds or sulfur dioxide. These properties reduce thermal stress on turbine components, improving durability and performance. Importantly, hydrogen combustion doesn't contribute to global warming or climate change. It can be produced sustainably through electrolysis powered by renewable energy sources, making it a clean and sustainable fuel option. Finally, hydrogen can be integrated into existing gas turbine infrastructure with modifications, facilitating a transition to cleaner energy sources while utilizing current systems.

TABLE 2. Justifications for using hydrogen as a fuel source

Justification Aspect	Details
Environmental impact	Hydrogen combustion produces only water vapor, resulting in zero CO2 emissions and significantly reduced pollutants such as SOx and NOx. This helps mitigate global warning and air pollution.
High Specific Energy	Hydrogen has a high specific energy content (about $120{,}000\ \mathrm{kJ/kg}$), providing a high energy yield per unit mass, which can lead to efficient power generation.
Flame Speed	Hydrogen has a very high flame speed ($100-200\ \mathrm{m/s}$), which can enhance the combustion process and reduce exposure times to turbine components, potentially increasing efficiency and longevity.
Reduced Air/Oxygen Requirement	Hydrogen requires less air or oxygen for combustion compared to fossil fuels. Allowing for smaller, lighter turbine designs and reducing overall equipment size and
Flame Stability	Hydrogen maintains a wide range of flame stability, which can improve operational flexibility and reliability under various operating conditions.
Lower Radiation Levels	The combustion of hydrogen produces lower radiation levels, which helps to reduce thermal stresses on turbine components and improves their durability and performance.
Absence of Harmful Emissions	Hydrogen combustion does not produce harmful organic compounds or sulfur dioxide, leading to cleaner emissions and contributing to better air quality.
No Contribution to Global Warming	Since hydrogen combustion does not produce greenhouse gases, it does not contribute to global warming or climate change.
Compatibility with Existing Infrastructure	Hydrogen can be integrated into existing gas turbine systems with modifications, allowing for the use of existing infrastructure while transitioning to cleaner energy sources.
Clean and Sustainable Production	Hydrogen can be produced via electrolysis using renewable energy sources, making it a clean and sustainable energy source with a low environmental impact.

IV. HYDROGEN GAS TURBINES COMBUSTION

Hydrogen gas is abundant, energy-rich, and clean-burning [17]. Because of its clean-burning characteristic, hydrogen is considered a good candidate to be utilized as fuel for gas turbines in the power generation sector.

The combustion process that takes place in the combustor of a gas turbine is very important for the efficiency of the gas turbine, as well as for the pollutant emission levels of the gas turbine. Hydrogen, being one of the simplest hydrocarbon fuels and due to the lack of carbon content in its chemical structure, the combustion process of hydrogen is not as complex as for hydrocarbon fuels. This becomes a strong motivation to study the physical and chemical aspects of hydrogen combustion inside the gas turbine combustor. This section deals with the interaction of hydrogen combustion with supersonic and continuous detonation regimes.

The development of air-breathing supersonic combustion ramjet (scramjet) engines rests on the efficient burning of hydrogen in the supersonic (non-premixed) mode of gas turbine-type combustion, and a significant amount of research has been devoted to this topic. During supersonic or detonation modes, a continuous detonation can be sustained inside the combustor, creating supersonic combustion mode. The potential of a direct introduction of the continuous detonation combustion mode is high due to its fast reaction time [18]. The fast reaction time, due to the fast-moving combustion front of the detonation wave, provides significant un-bypassed energy release inside the combustor volume. This has the potential to reduce the size of the combustion section of the engine dramatically. However, a continuous detonation regime with larger geometry, such as a continuous detonation wave in a cylindrical tube, does not allow for effective energy release. Therefore, in order to create the desired combustion conditions in a continuous mode, it is important to create the necessary conditions for Transverse Cumulative Depth Vortex Structures. The kinetics of the combustion must anyway support the physically realized possibility to create any mode of combustion inside the Gas Turbine Combustor.

A. *Combustion Process Overview*

Clean, efficient combustion of hydrogen fuel offers several benefits for power generation processes. The hydrogen gas turbine combustion process can meet many of these efficiency, emission, and technology requirements. This paper presents the full transparency of one attempt to discipline the analysis of hydrogen gas turbine combustion more rigorously, through the underlying methodology of classification of hydrogen gas turbine combustion and full presentation to enable a proposed understanding to be verified. The work establishes a hierarchical structure for the categorization of overlapping themes and covers in detail all the likely attributes that need to be addressed to improve both scientific understanding and the principles applied to solve practical problems. This involves significantly expanding the detail and disciplines of other works and reports. This provides a basis for future developments to effectively involve a range of parameters to be combined and optimization pursued.

Environmental pressures on our energy instill a need to convert as much feedstock fuel as possible into work output, to reduce the greenhouse gases that are created and to use the least renewable or finite energy resources. There is a likely demand for increasing electricity supplies. Gas turbine generation is ideal to meet the plants of future low emission and high renewal addition [19]. Hydrogen gas turbine plants promise to realize much of the desired performance and environmental performance in the medium term, prior to other polymetric and system-level promoted advanced technology being achieved. Efficient combustion of hydrogen fuel can power such benefits. The hydrogen gas turbine combustion does not use or need high support technology. Hydrogen constituents from normal chemical engineering and the high combustion temperatures allow the conversion of hydrogen into work to be supported. A zero emission from hydrogen gas turbine plants can be achieved. The gas and steam mixtures being the synthetic gas air turbine combustion as a genuine source as they offer advanced opportunity for full system carbon removal, high energy output from the heat exchange processes (more process air is heated and supports production of the greenhouse gases i.e. N2/CO2 and/or H2O), and development of flexible low emission gas turbine combined heat and power systems.

B. *Key Considerations for Hydrogen Combustion*

Hydrogen's most significant advantage is related to greenhouse gas (GHG) emissions. When burned, hydrogen can be used without producing CO2 emissions. Combustion of the hydrogen fuel also normally does not produce CO and SOx in appreciable quantities. Use of hydrogen in the generation of electrical power can significantly reduce GHG emissions and result in higher percentage renewable energy, shorter payback periods, and significantly reduce soot, CO2, CO, and NOx emissions. This technology makes an increased depth of vacation of the Earth's carbon reserves possible. Additionally, sulfur compounds can be removed or minimized at the production level and do not need to be removed at the plant.

However, hydrogen's diffusion in solids, high flame temperature, low ignition energy, high autoignition temperature, and low local minimum ignition energy limit implementations of typical flame temperature requirements for gas turbines burning natural gas and can pose significant challenges to reliable operation in existing combustion systems. In such settings, hydrogen's unique combustion qualities present significant challenges.

How these hydrogen combustion challenges are managed can determine hydrogen's role in future energy system economies. These factors vary with the time-scale of interest.

For the more immediate commercial time-sale, hydrogen's fuel efficiency, capital and operating costs, capital improvements, permitting, and environmental impacts are design drivers. Several considerations should rightly be paramount in the design, installation, and operation of hydrogen-combustion systems: (1) reaction temperature control; (2) flame stabilization; (3) flammability, including ultra-lean flame speed, quench, and autoignition; and (4) flameholding over external flows. However, the potential commercial value of hydrogen produces demand for recognition and tested understanding of critical aspects of hydrogen combustion, science, and technological challenges. Several key considerations in developing hydrogen-fueled combustion for gas turbine electrical power generation are recounted in this section. From indicated research needs, it is hoped that a sufficient foundation is laid for successful commercial electrical power generation development, verification, technology maturation, introduction, and public acceptance.

V. APPLICATIONS OF HYDROGEN GAS TURBINE COMBUSTION

A coherent classification and description of hydrogen gas turbine combustion as the last stage of the power generation process are given in the paper. Hydrogen gas turbine combustion - the characteristics of flow processes realized according to an alternative scenario and the formed equivalent-as-economic characteristics are considered. In view of the completed research and the obtained angles, possibilities of implementation and development of the hydrogen gas turbine statement of the problem are included. Although the description is general, examples explaining its practical realization are given. The hydrogasification/steam-oxygen/hydrogen gas turbine structure is demonstrated as the conversion-to-enduse technique of the future. Its simplicity is characterized. Its real/abstract scenario and characteristics of flow process are determined. The suggested hierarchy of the processes is used for other ends as well.

In view of the performed basic research, the initiated experiments, and the obtained results in the last years, a costing, conception of production, and implementation of hydrogen as a power generation agent in advanced combined cycle and regenerative structures on classical and alternative energy technologies for centralized and low-size power generation outside populated areas is proposed. The structure, whose efficiency is equal to 70%, does not pose an increased level of danger to people and the environment. The advantages of obtaining and energy transformation are considered. The composition of the included stages of energy transformation is justified. Power generation parts of the developed simulation are given. Safe transport is possible.

A. Power Generation Industry

The power generation industry can provide power for the community, and the power can be generated through various methods. Around 70% of the power is produced by fossil fuels. However, the negative impacts on the environment and corresponding rules and regulations control are under consideration. The U.S. Energy Information Administration (EIA) reports that the gross output of U.S. generators in 2017 was less than 12 thousand terawatt-hours. The most significant power generation energy sources, coal-fired power generation, have more stringent rules and regulations. Renewable sources are continually growing with 19% of the U.S. gross output in 2017. The share of renewable types of equipment has increased year by year since 2006. The combined output of fossil fuels has decreased from 68% in 2007 to 62% in 2017. The new generation power generation energy sources used in the U.S. also contribute to the renewable gain in the U.S. and to relieve environmental impacts. Since power generation consumes a significant percentage of gas turbines, the development of effective hydrogen combustion is attracting increasing attention.

B. Aerospace and Defense Applications

Aerospace and defense applications. In addition to operational cost savings and performance benefits, security of supply and reduced carbon emissions, hydrogen has important national and strategic defense and security benefits for aerospace and defense turbine propulsion engines. These national interests are not inconsistent with the commercial market interest in becoming more competitive and fulfilling national and global emissions and climate goals. The defense application may have similar and substantial effect in driving hydrogen power turbine growth to the space market. Both the D and the A may therefore operate on different rules of engagement in terms of combustion system design features specified from the aerospace system integrator.

The secure supply of hydrocarbon fuels - the lifeblood for aerospace operations - is a key defense priority that requires regular military and political vigilance. With the exception of the UK's designation of defense importance for North Sea oil and gas pipeline physical security and access, military and national aerospace interest in black gold supply have been underspecified. Always strategically important and far too fragile; always fragile but sometimes strategically important - these former oil and gas dispatchable tools will become hydrogen dispatchable very rapidly.

This section has described the reason any aerospace application would be sponsored by work funded from a nation's defense department that would have exclusive development - not for commercial applications (and vice versa). This combination could drive rapid hydrogen to methane replacement for turbine propulsion applications. Turbine propulsion would still not be, and nor would APU even if they were a stationary aero derivative form, the largest call on delivered CO2 emissions to the Earth's total air breathing engine contribution.

VI. ENVIRONMENTAL AND ECONOMIC IMPLICATIONS

Generally, effluent flows from hydrogen-combustion power generators are water vapor and nitrogen oxide. Water vapor has a heat capacity that interacts with global heat transfer, but emissions do not contain sufficient heat to delay serious global heat exchange. Nitrogen oxide is composed of a chemical reaction between nitrogen in the air and oxygen radicals generated in combustion at high temperatures. Emitted nitrogen oxides from the exhaust gas flow outside and form photochemical air pollutants with sunlight. The major components are hydrocarbons and nitrogen oxides, and it is more effective as a photochemical oxidant compared to carbon monoxide and sulfur oxide. It becomes harmful PM components when combined with water vapor. Also, due to the particularity of the time and concentration distribution of generation, it is more sensitive to local pollution problems.

In order to minimize these effluent emissions from low-NOx gas turbine combustion technology, it is used effectively in a lean premixed combustion system, which has high mixing uniformity, stretched and divided flame. This is achieved by reducing the average temperature in the combustion chamber and creating temperature uniformity to reduce nitrogen oxide emissions. The thermodynamic cycle performance management system is operated externally with intermittent combustion, avoiding high-temperature operation, which can effectively suppress nitrogen oxide generation in the combustion process. The intermittent combustion of a hydrogen gas turbine was investigated with a thermal efficiency of 72%, and with weekly operation at 12% active load, with peak loads for 30 minutes on weekends. It has the characteristics of high-efficiency cycle performance and response flexibility. SMR hydrogen gas-turbine engine systems have been considered to be in use together with intermittent wind power to consider energy supply stability as a flexibility resource. It is expected to be implemented while substantially reducing annual CO2 emissions. The infrastructure that stores and supplies hydrogen for this is unstable in large quantities, and operation management and safety protection must be achieved.

A. Emissions Reduction Potential

The combustion of hydrogen in a gas turbine produces a number of direct emissions, namely local emissions (NOx, CO, HC) resulting from the combustion process itself, and also global emissions (CO2, H2O) [20]. Looking at pollution and increased interest in gas turbine combustion are the reasons supporting the proposition for the ultra-low emissions gas turbine. The ultra-low emissions gas turbine must keep low CO, HC, and NOx emissions, important to decrease the surface ozone concentration and photochemical smog formation, as well as diverse organic compounds' impacts on human health [21].

In the perspective of CO2 reduction, hydrogen co-firing is the most important solution [22]. Using hydrogen in gas turbines is also a very promising technology because the power generation efficiency is not significantly reduced when the gas turbine runs with hydrogen. The composition of typical gas turbine combustion for power generation produces a number of direct emissions, namely local emissions (NOx, CO, HC) resulting from the combustion process itself, and also global emissions (CO2, H2O). Recent and increased interest in gas turbine combustion is motivated by two fundamentally different reasons. The first reason is the general agreement on the need to reduce air pollution from gas turbine operation. Recent and increased interest in gas turbine combustion is motivated by two fundamentally different reasons. The first reason is the general agreement on the need to reduce air pollution from gas turbine operation. The progressive global championing of LNG through CO2 emissions is also reflected in the image [23]. As a matter of fact, emissions of nitrogen oxides are characteristically cut by 50 percent, but the release to the atmosphere of nearly 100 million tons of CO2 per year is substantial.

B. Cost Analysis and Economic Viability

In this section, the cost of several hydrogen gas turbine combustion routes was assessed, namely the use of natural gas, the use of natural gas with micro-CO2 capture, the reforming of natural gas with direct CO2 capture, and the use of SH micro-CO2 capture natural gas. Furthermore, it was assessed the use of an integrated methane oxy-combustor (MOC), and the use of a standalone and integrated Solid Oxide Fuel Cell reactor with and without an additional methane MOC for carbon capture part load operation.

For these comparisons, past studies have considered the architecture of the plant, i.e., a first study concerned with a High-Efficiency Hybrid CO2 Cyclic Hydro.SuSyStor power plant configuration, another study with an advanced post-combustion CO2 capture concept for natural gas-fired gas turbine power cycles, another study with a combination of natural gas combined cycle power plant equipped with carbon capture utilization and storage system, and another study with a gas turbine based advanced supercritical CO2 power cycle.

It was considered a 130 MW H-class having a design gas turbine inlet temperature of 1500 °C with a net electrical efficiency of 58.2% for baseload operation (10,000 h/year) and an electrical efficiency of 53%. To obtain the latter, changes in compressor mode and part-load operation as well as an increase in pressure loss and reheat instead of chemical recuperation were assumed. Furthermore, not only the excessive air compressor power demand of 2.5 points but also the CO2 purity reduction to 95% pure outlet for enhanced oil recovery were considered. First of all, control parameters are to be selected. As 50% part-load electrical power refers to about 65%-part load to compressor requirements (assuming equal proportions), the minimum efficient operational fraction for the gas turbine is set to 65%, and all base-load-operational requirements are set to 65% of the respective values.

VII. CONCLUSION

In this comprehensive review of hydrogen gas turbine combustion, the layered taxonomy and classification framework provided offers valuable insights into the multifaceted aspects of hydrogen fuel application in power generation. The proposed taxonomy effectively categorizes the diverse dimensions of hydrogen combustion, encompassing fuel characteristics, and combustion dynamics. By structuring the classification into distinct layers, from fundamental properties of hydrogen to advanced technological innovations, this framework facilitates a deeper understanding of the complexities and challenges associated with hydrogen gas turbines. The detailed analysis of fuel characteristics reveals how hydrogen's unique properties, such as its high flame speed and low ignition energy, and impact combustion stability.

Furthermore, the examination of combustion dynamics highlights the need for sophisticated control strategies to manage flame behavior and optimize efficiency. Furthermore, this layered taxonomy provides a structured and systematic approach to understanding and optimizing hydrogen gas turbine combustion processes. It serves as a valuable resource for researchers, engineers, and policymakers, guiding future research and development efforts aimed at leveraging hydrogen's potential for sustainable and efficient power generation. Through this framework, the path towards more effective and environmentally friendly hydrogen gas turbines is clearer, supporting the broader transition to cleaner energy solutions.

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