Satina Anastasia Olegovna,
Senior teacher
L-3 department “English for Mechanical Engineering”
Federal State Autonomous Educational Institution of Higher Education
Bauman Moscow State Technical University
Moscow
Сатина Анастасия Олеговна
Старший преподаватель кафедры Л-3 «Английский язык для машиностроительных специальностей»
ФГАОУ ВО Московский государственный технический университет им. Н.Э. Баумана
г. Москва
Сон Елизавета Дмитриевна,
Студент 1 курса
ФГАОУ ВО Московский государственный технический университет им. Н.Э. Баумана
г. Москва

Son Elizaveta Dmitrievna,
1st year student
Federal State Autonomous Educational Institution of Higher Education
Bauman Moscow State Technical University
Moscow

HYDROGEN TECHNOLOGIES IN MODERN MECHANICAL ENGINEERING

Аннотация: В статье рассматриваются особенности применения водорода в газотурбинных установках [3]. Показаны ключевые отличия водородного топлива от традиционных углеводородов. Особое внимание уделяется инженерным проблемам, возникающим при использовании водорода, таким как водородная хрупкость материалов и особенности процесса горения [4]. В работе анализируются современные технические решения, направленные на повышение эффективности и безопасности турбин. Рассматриваются области применения водородных турбин в машиностроении. В заключение оцениваются перспективы развития данной технологии.

Annotation

The article examines the features of hydrogen application in gas turbine systems [3]. The key differences between hydrogen fuel and traditional hydrocarbons are presented. Particular attention is given to engineering challenges arising from the use of hydrogen, such as hydrogen embrittlement of materials and the specifics of the combustion process [4]. The paper analyzes modern technical solutions aimed at improving the efficiency and safety of turbines. The areas of application of hydrogen turbines in mechanical engineering are considered. In conclusion, the prospects for the development of this technology are evaluated.

Ключевые слова: водород, технологии, машиностроение, газотурбинные установки, устойчивость горения, водородная инфраструктура, оксиды азота, машиностроение, сгорание водорода, охрупчивание, хранение водорода.

Key words: hydrogen, technologies, mechanical engineering, gas turbine systems, combustion stability, hydrogen infrastructure, nitrogen oxides, mechanical engineering, hydrogen combustion, embrittlement, hydrogen storage.

Hydrogen is considered one of the most promising energy carriers [2], finding applications in both the transportation sector and the energy industry. In particular, it is used in internal combustion engines as well as in gas turbine systems. The growing interest in hydrogen is largely driven by the global need to reduce greenhouse gas emissions and transition to sustainable energy sources. In modern conditions, hydrogen technologies are becoming an important direction of scientific and technological development.

One of the key advantages of hydrogen is the variety of available production methods [2]. Currently, hydrogen can be obtained through steam methane reforming, coal gasification, water electrolysis, pyrolysis, partial oxidation, and biotechnological processes. This diversity allows flexibility in its large-scale implementation across different industries and regions. Furthermore, the development of renewable energy sources contributes to the increasing production of "green hydrogen," which is obtained with minimal environmental impact.

In addition, hydrogen has the highest specific energy among all chemical fuels, reaching approximately 120.2 MJ/kg [2], which significantly exceeds that of conventional fuels. This property makes it particularly attractive for high-efficiency energy systems. However, it is important to consider not only gravimetric energy density but also volumetric energy density, which is relatively low for hydrogen and creates additional challenges.

However, despite its advantages, hydrogen presents significant challenges related to storage and transportation [1]. Various storage methods exist, including its absorption in metals in the form of metal hydrides. Although this approach offers increased safety, it is limited in efficiency, especially for transportation applications. In addition, storing hydrogen in compressed or liquefied form requires substantial energy input and complex technical solutions.

One of the key advantages of hydrogen is its environmental friendliness.

The use of hydrogen as a fuel, including in aviation and gas turbine systems, offers significant environmental advantages compared to conventional hydrocarbon fuels [1]. During hydrogen combustion, emissions of carbon monoxide (CO), carbon dioxide (CO_2), sulfur oxides (SOx), unburned hydrocarbons, and soot are virtually eliminated. This makes hydrogen an important component of global decarbonization strategies.

The main products of hydrogen combustion are water vapor and nitrogen oxides (NOx), with overall emission levels being considerably lower than those of modern fossil-fuel-based engines. Although NOx emissions still have an environmental impact, various technological solutions can be applied to reduce their formation.

However, despite its significant environmental benefits, the use of hydrogen in gas turbine systems introduces a number of technical challenges related to the combustion process.
Hydrogen combustion in gas turbine systems differs significantly from that of conventional hydrocarbon fuels [3]. One of the main features of hydrogen is its high flame speed, which increases the risk of flame flashback into the combustion chamber. In addition, hydrogen has a low ignition energy, making it highly reactive and difficult to control during operation.

Another important characteristic is the high combustion temperature, which can lead to increased formation of nitrogen oxides (NOx) (fig. 1) [3].

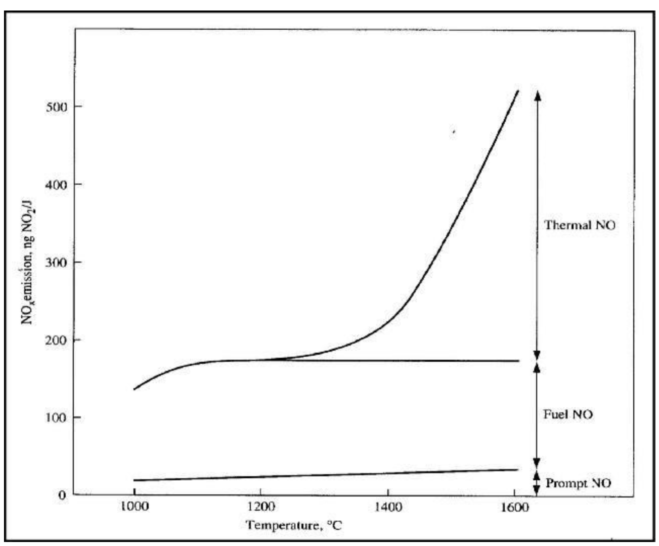

Figure 1 - NOx emissions vs combustion temperature

Furthermore, hydrogen has a wide flammability range, which complicates the stabilization of the combustion process. These factors require significant modifications in the design of gas turbine combustion systems.
As a result, the use of hydrogen in gas turbine systems is associated with several significant engineering challenges.

The use of hydrogen in gas turbine systems is associated with several significant engineering challenges that must be addressed to ensure safe and efficient operation. One of the most critical issues is hydrogen embrittlement, which leads to the degradation of metallic materials and reduces their mechanical strength [4]. Hydrogen atoms can penetrate the crystal lattice of metals, causing the formation of microcracks and increasing the risk of structural failure during operation.

Another important challenge is hydrogen leakage. Due to its extremely small molecular size, hydrogen can easily escape through seals and microscopic defects in materials. This creates serious safety concerns.
In addition, hydrogen has a very low volumetric energy density compared to conventional fuels. Although it has a high specific energy per unit mass, its low density requires either high-pressure storage or liquefaction.

Hydrogen storage itself presents significant difficulties. It can be stored either in compressed gaseous form or as a cryogenic liquid at extremely low temperatures (around −253 °C) [2]. However, cryogenic storage introduces additional challenges, as materials become more brittle at low temperatures, increasing the likelihood of structural damage [4].

Another major issue is the high combustion temperature of hydrogen, which results in increased formation of nitrogen oxides (NOx). This imposes additional thermal loads on turbine components.
Furthermore, hydrogen combustion is often associated with flame instability and

combustion oscillations. These phenomena can negatively affect the performance and reliability of gas turbine systems.

Safety considerations also play a crucial role in hydrogen applications. Hydrogen has a wide flammability range and a nearly invisible flame, making leaks difficult to detect.

Finally, the lack of developed infrastructure for hydrogen production, storage, and transportation remains a significant barrier to its widespread implementation [5]. In addition, protective coatings and surface treatments are often applied to further improve material performance.

One of the key factors in the design of hydrogen storage and transportation systems is the proper selection of materials. In particular, the use of high-quality stainless steels with specially tailored chemical compositions is essential to ensure resistance to hydrogen exposure [4].

Another effective approach to overcoming the challenges associated with hydrogen use is the application of hydrogen–natural gas fuel blends [1]. This method allows the gradual integration of hydrogen into existing gas turbine systems without the need for significant modifications.

The addition of hydrogen to natural gas improves combustion characteristics and reduces carbon dioxide emissions, while maintaining stable operation of the turbine. Moreover, the use of blended fuels enables a smoother transition to hydrogen-based energy systems.

In addition, the proportion of hydrogen in the mixture can be adjusted depending on the technical capabilities of the turbine and safety requirements.

The development of hydrogen energy has been accelerating in recent years due to significant investments and strong governmental support [2]. Countries and regions such as the European Union, Japan, and the United States are actively implementing large-scale projects aimed at developing hydrogen infrastructure.

Hydrogen is considered one of the key solutions for achieving clean and sustainable energy systems.

However, as demonstrated in this study, the application of hydrogen is associated with a number of engineering challenges. Modern technological solutions allow these challenges to be gradually addressed.

At the same time, further progress in this field requires substantial financial investment in research, infrastructure development, and technological innovation. Therefore, hydrogen has strong potential and can become a key component of future energy systems and modern mechanical engineering.

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