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# Challenges in Compressing Hydrogen-Blended Gas for Gas Turbine Power Plants

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**Abstract:** The increasing shift towards sustainable and net-zero targets has heightened interest in substituting hydrogen for natural gas in gas turbines and combined cycle power plants. This study investigates the compressibility of hydrogen within gas compressors, situated upstream of gas turbines, particularly when blended with various gases. Emphasis was placed on the inherent properties of hydrogen, including its behavior under compression, susceptibility to material embrittlement, and the influence of its gas characteristics on compressor performance. An extensive examination of prevalent compression methods, notably centrifugal compressors, was conducted to evaluate their efficacy in managing hydrogen at varying blend ratios. Issues related to material compatibility and safety were highlighted, alongside the formulation of reliable compression processes crucial for hydrogen-rich gas mixtures. Operational challenges posed by different hydrogen fuel proportions were identified, with proposed solutions including the implementation of precision control systems or the introduction of innovative materials. The study culminates in a discussion on prospective research directions and necessary technologies for effective hydrogen-rich gasification compression technology. The findings offer critical insights for ongoing initiatives aimed at enhancing and promoting hydrogen compression technology, facilitating the integration of hydrogen into existing infrastructures and supporting the sustainable development of the energy sector.

**Keywords:** Hydrogen-blended gas; Gas compression; DWSIM process simulator; Gas turbine power plants; Centrifugal compressor

## 1 Introduction

The exploration of hydrogen as a renewable and versatile source of energy has been accelerated by the growing pressure to shift to sustainable energy. Hydrogen can be strategically added to gas turbine power plants, which is essential to the world's energy infrastructure and can lower carbon emissions. However, when combined with conventional natural gas in gas turbine power plants, hydrogen's special qualities such as its high compressibility and reactivity bring a new set of difficulties. Compressors designed for hydrocarbon-based fuels have historically been used in gas turbine and combined cycle power plants, therefore, adding hydrogen to the fuel blend requires a thorough grasp of the difficulties involved. The unique properties of hydrogen affect the efficiency, dependability, and safety of gas compression systems, which in turn affects the overall efficiency of power generation [1].

The urgent necessity to resolve these issues and clear the path for the effective integration of hydrogen-blended gas compression in gas turbine power plants is what drives this research. This study has considerable advantages, such as improved flexibility in power generation, fewer greenhouse gas emissions, and increased energy efficiency. But to fully utilize these benefits, it is necessary to thoroughly examine and resolve the challenges presented by hydrogen's special qualities in the context of gas compression [2].

This study aims to fill a significant knowledge gap by thoroughly investigating the difficulties related to compressing hydrogen-blended gas in gas turbine power facilities, thereby supporting the creation of customized solutions, best practices for operations, and developments in compressor technology. The overarching objective is to enable the smooth integration of hydrogen, thereby promoting a cleaner and more resilient energy landscape and easing the shift to sustainable energy systems [3].

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The necessity of shifting to low-carbon, sustainable energy sources has sparked increased interest in using hydrogen as a fundamental component of the power generation system. Of all the uses for hydrogen, adding it to gas turbine power plants has the most potential to improve energy efficiency overall and lower carbon emissions. As the globe struggles with the pressing need to combat climate change, it is crucial to examine the difficulties involved in compressing hydrogen-blended gas in gas turbine power plants. In the context of gas turbine power plants, this study focuses on the intricate processes and challenges inherent in the compression of hydrogen-blended gases. Recognized for its clean energy attributes, hydrogen brings a distinct set of challenges when being used with conventional natural gas or other hydrocarbons. These complexities include possible problems of material compatibility and safety considerations, as well as its extreme compressibility and reactivity [4]. The successful integration of hydrogen into the current gas turbine infrastructure requires an understanding of and commitment to addressing these obstacles.

This study investigates the difficulties in operation brought about by the different compositions of hydrogen blends, which involve compression power increases and efficiency variations. With the world population promising to decarbonize the energy sector, this study attempts to provide important new understandings of the challenges posed by compressed hydrogen mixed gas. By recognizing and comprehending obstacles, this study can help create new compression technologies, best practices for operations, and improved safety measures. To promote a sustainable and resilient energy future, the goal is to make it easier for hydrogen to be seamlessly integrated into gas turbine power plants as a clean energy carrier [5].

## 2 Methodology

### 2.1 Literature Review

As concern over greenhouse gas emissions and the global demand for sustainable clean energy rapidly grows, hydrogen has become popular as a promising clean energy. This literature review aims to explore the utilization of hydrogen as a clean energy source. Recent studies have brought attention to the use of hydrogen in electricity generation as a clean energy carrier, while some experts have highlighted the important role hydrogen can play in decarbonizing several industries including transportation, and power generation. The literature mainly focuses on the incorporation of hydrogen into power generation, especially in gas turbines and fuel cells. Apart from the improvement of grid stability and combustion efficiency as well as pollutant reduction caused by hydrogen-rich fuels, researchers have investigated the technological and financial viability of converting current power plants to hydrogen-powered systems [6].

The interest in blended fuel combustion in gas turbine power plants has been increasing and it represents a turning point in searching for a versatile energy source. The viability and benefits of blending hydrogen with natural gas in gas turbines and combined cycle power plants have been a popular topic among recent researchers. The principal aim is to improve combustion efficiency while addressing environmental issues through the reduction of carbon emissions [7].

The complex dynamics of adding hydrogen to the fuel mix of gas turbine power plants have been studied by researchers. The technical details of the integration process were explored in the feasibility studies, which focus on flame stability, combustion characteristics, and overall system performance. The goal of these studies is to find the ideal ratios for blending hydrogen with conventional fuels to minimize emissions while maintaining energy efficiency [8]. Hydrogen compression technology is a critical aspect of hydrogen utilization, essential for the advancement of hydrogen as a clean energy carrier. Recent research in this field focuses on improving efficiency, reducing costs, and enhancing the durability and reliability of hydrogen compressors. Researchers have explored high-strength materials such as advanced alloys and composite materials to withstand higher pressures and reduce wear and tear. For instance, materials like titanium alloys and carbon fiber composites were investigated for their potential to enhance compressor longevity and efficiency [2, 6]. The use of nanomaterials was explored to reduce friction and wear in compressor components, potentially increasing efficiency and reducing maintenance requirements. In addition, improved sealing technologies were developed to minimize hydrogen leakage, which is crucial for both safety and efficiency. Innovations in sealing materials and designs help maintain the integrity of high-pressure systems [3].

The literature mainly focuses on the substantial benefits that hydrogen integration may bring to gas turbines. Hydrogen's intrinsic properties, like its high density of energy and undetectable combustion profile, provide chances to boost overall productivity and support environmental sustainability. Additionally, researchers have highlighted the modifications of gas turbines to accommodate different hydrogen concentrations, offering flexibility in the shift to a hydrogen-centric energy future. In this setting, gas turbines play a role that goes beyond their typical use. Scholars have underscored their potential as crucial resources in expediting the shift towards a more sustainable energy paradigm. Gas turbines can generate large amounts of electricity and blending with hydrogen can play a critical role in energy systems that are robust and enable them to adapt to the needed changes for a sustainable future. It is challenging to use hydrogen for compression equipment, due to its specific characteristics, including low molecular weight, high compressibility, and potential to embrittle materials. Researchers have investigated the impact of hydrogen on the materials used in compressors and some problems including embrittlement and stress corrosion cracking caused by hydrogen. It is essential to comprehend these difficulties to guarantee the durability and integrity of compression systems [9]. Some studies highlight the operational difficulties of compressing hydrogen-blended gases, including variations in efficiency and the tendency for compressor surge. Researchers have investigated safety factors, including combustion risks and the possibility of hydrogen leaks, and the demand for effective monitoring and control systems to guarantee the safe functioning of gas turbine power plants [10].

The processes of steam methane reformation, electrolysis, and various other innovative approaches are some methodologies that could be utilized to produce hydrogen. The cost of hydrogen generation is heavily reliant on the specific technique employed for its synthesis. The cost profiles of various forms of hydrogen differ significantly, specifically green hydrogen produced through renewable-powered electrolysis, blue hydrogen generated from natural gas with carbon capture and storage, and grey hydrogen obtained from natural gas with carbon capture. Because of the costs associated with electrolysis technology and the production of renewable energy, green hydrogen is generally more expensive compared to other methods. Historically, natural gas has proven to be more economical than hydrogen, especially when utilizing traditional production techniques such as the steam methane reformation process. However, the growing emphasis on decarbonization and the expanding utilization of renewable energy sources have stirred a surge of interest in green hydrogen [11]. As technology advances, economies of scale have been accomplished, and more renewable energy sources have been incorporated into the hydrogen generation process. Therefore, it is anticipated that hydrogen can become more cost-competitive. It's important to remember that the dynamics of the energy market are subject to change, and shifts can influence the relative costs of natural gas and hydrogen in global energy trends, government regulations, and technological advancements. In addition, ongoing endeavors to decrease the expense of hydrogen production, especially for environmentally friendly hydrogen, are anticipated to have a substantial influence on the future pricing of these two energy sources [12]. The Japanese government has been taking active actions to reduce the cost of hydrogen-based electricity generation to 17 yen per kWh by 2030, with the ultimate objective of achieving even lower costs of 12 yen per kWh. This is noteworthy as the current unit cost of liquefied natural gas (LNG) power generation stands at 12 yen/kWh, based on a natural gas import price of $0.2/Kg, which is then converted based on the calorie content of hydrogen. Accordingly, these cost reductions will make hydrogen-based electricity generation more competitive compared to LNG power generation. Conversely, the ongoing global energy crisis and the diminishing supply of fossil fuels contribute to the escalating costs associated with LNG procurement [3].

### 2.2 Methodology and Modelling

In many processes or power plant industries, including petrochemicals, and transportation sectors, gas compression is essential. Hydrogen-blended compression has some challenges that users and engineers must address to ensure reliable and efficient operation [13]. DWSIM, a free, open-source chemical process simulation program, is used to analyze the effects of the gas compression process and compressor sizing. The results adhere to comparable paid software. The compressor's optimal operation is referred to as isentropic, or constant entropy, and is determined by the compressor's efficiency in addition to the thermodynamic path (adiabatic or polytropic) [2].

The polytropic or isentropic (adiabatic) power is calculated using the following equations [14]:

$$P = \frac{H_{2s} - H_1}{\eta} W \tag{1}$$

$$P = (H_{2s} - H_1) \times W \times \eta \tag{2}$$

where, $H_{2s}$ is the outlet enthalpy for the isentropic process, and $H_1$ is the inlet enthalpy.

The adiabatic and polytropic heads are calculated using the equation provided by DWSIM (2023).

$$H = P/(W \times g) \tag{3}$$

where, $H$ is the adiabatic or polytropic head $(\mathrm{m})$, $P$ is the adiabatic or polytropic power $(\mathrm{kW})$, and $g$ is the gravitational constant $\left(9.8\ \mathrm{m/s^2}\right)$.

The following Peng-Robinson equation is used for thermodynamic properties [14]:

$$P = \frac{RT}{(V-b)} - \frac{a(T)}{V(V+b)+b(V-b)} \tag{4}$$

where, $P$ is the pressure (bar), $R$ is the ideal gas universal constant $(8.314\ \mathrm{J/K \cdot mol})$, $V$ is the molar volume $\left(\mathrm{m}^3\right)$, $b$ is the parameter related to hard sphere volume, and $a$ is the parameter related to intermolecular forces.

The efficiency of a gas compressor is calculated based on actual work done divided by isentropic work done as per the following equation [9]:

$$\eta c = \frac{\text{Actual work done}}{\text{Isentropic work done}} \tag{5}$$

The comparison and characteristics of natural gas and hydrogen are briefly tabulated in Table 1.

**Table 1.** Physical properties of hydrogen and natural gas [8, 11]

| **Formula** | **Hydrogen**<br>$H_2$ | **Natural Gas**<br>$CH_4$ |
|---|---|---|
| Byproducts upon combustion | Water, nitrogen oxide | Carbon dioxide, nitrogen oxide |
| Molecular weight (gram/mol) | 2 | 16 |
| LHV (per volume) $\mathrm{MJ/Nm^3}$ | 11 | 36 |
| LHV (per mass) MJ/kg | 120 | 50 |
| Flammability limit (LL %/HL %) | $4/75$ | $7/20$ |

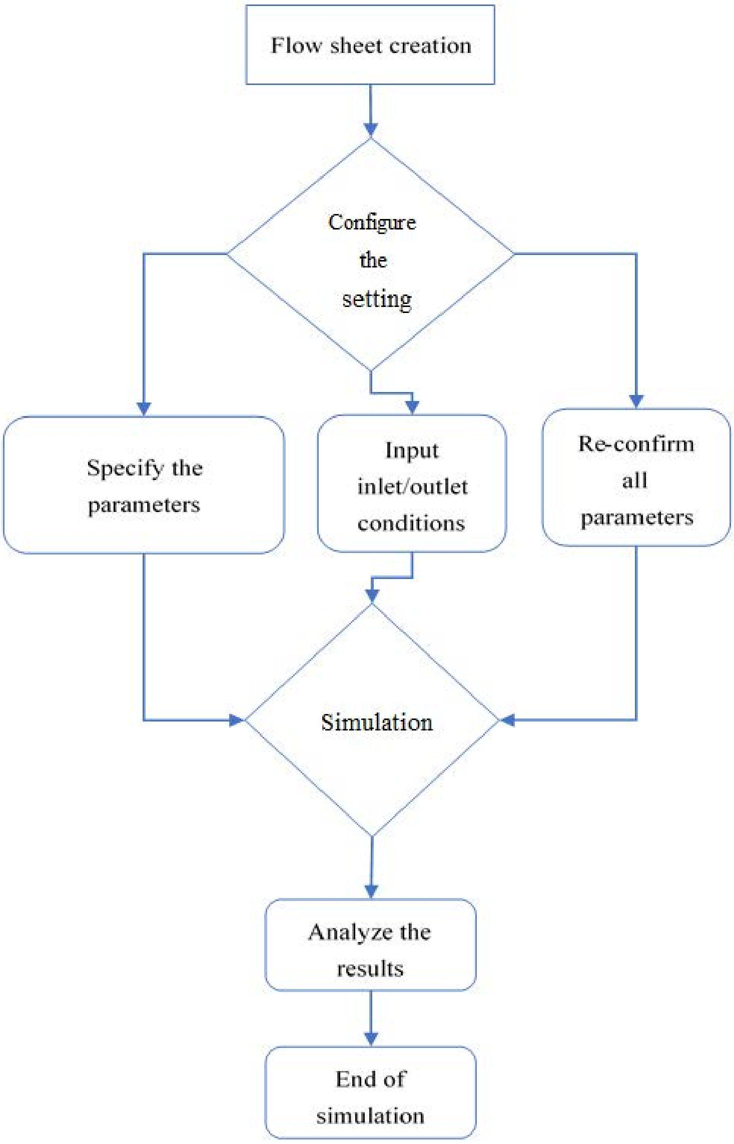

**Figure 1.** Process simulation flowchart

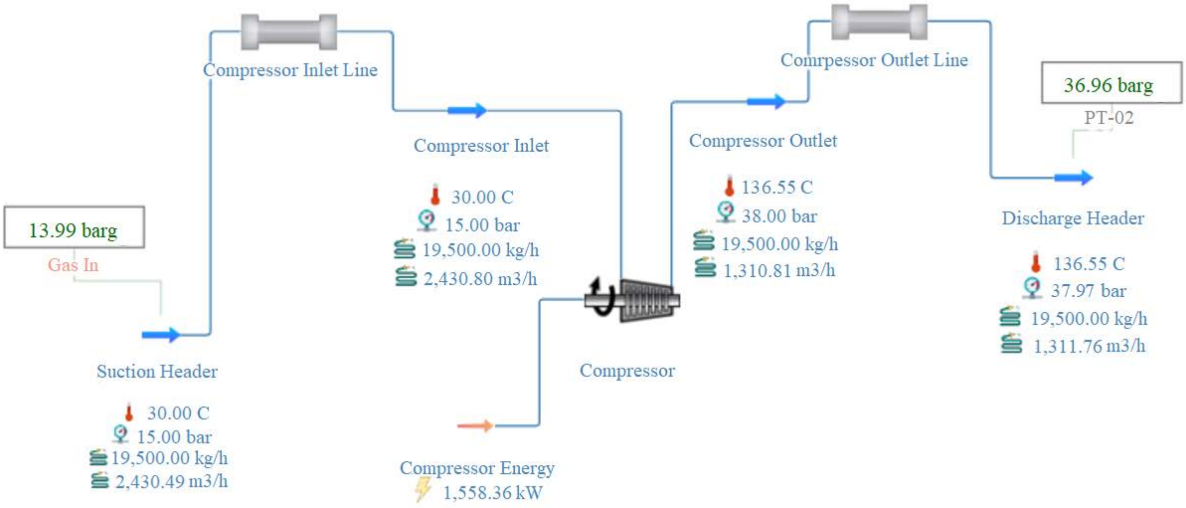

**Figure 2.** Simulation for blended fuel compression (10% hydrogen and 90% natural gas) [15]

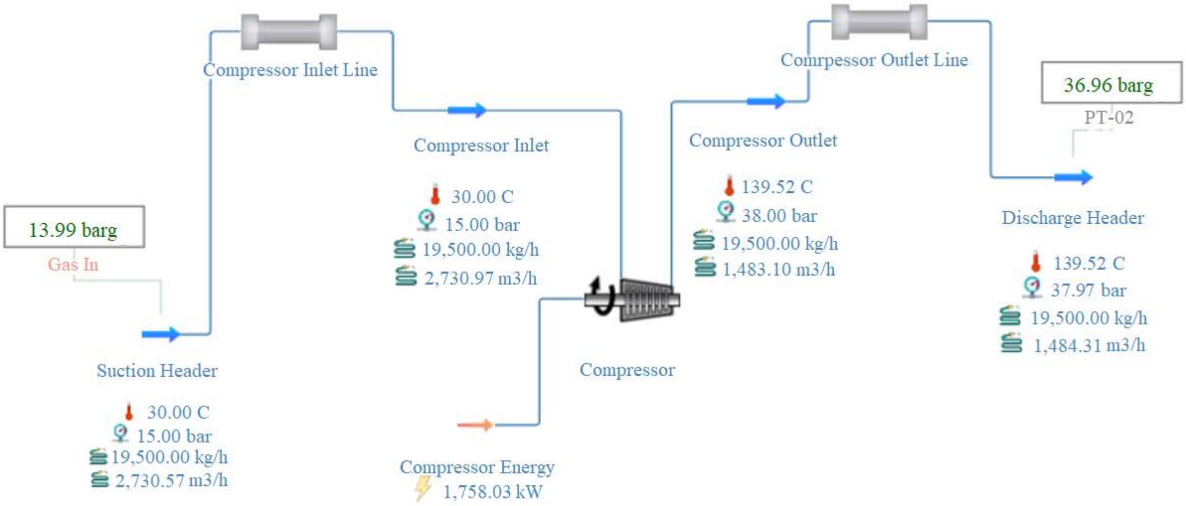

**Figure 3.** Simulation for blended fuel compression (20% hydrogen and 80% natural gas) [15]

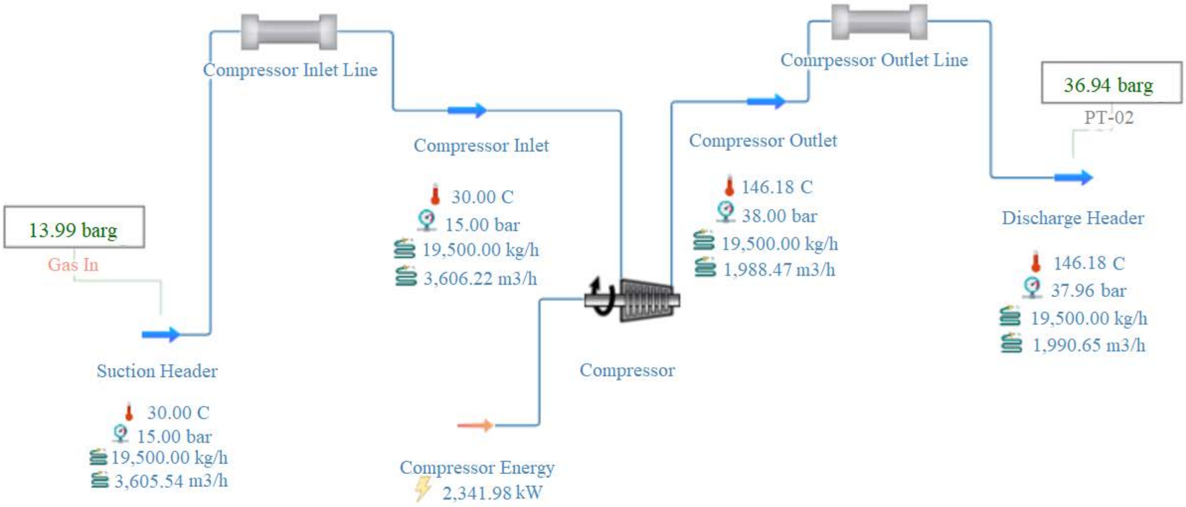

**Figure 4.** Simulation for blended fuel compression (30% hydrogen and 70% natural gas) [15]

Figure 1 shows the DWSIM simulation procedure adopted. It is assumed in the simulation that the 243 MW output capacity of the GE Gas Turbine Model 7F.05 operates at full load with a fuel flow rate of 19,500 kg/hour mass flow [8]. When calculating the compressor's inlet temperature and pressure, it is assumed that the fuel supply is upstream from the gas supply source at 15 barg. At the discharge header, the necessary discharge pressure of 38 barg is considered. When choosing a compressor, it is important to analyze the change in the gas composition and its impact on the compression power under different gas conditions. Figure 2 depicts 10% hydrogen with 90% natural gas compression; Figure 3 represents 20% hydrogen with 80% natural gas compression; Figure 4 represents 30% hydrogen with 70% natural gas compression; and Figure 5 represents 50% hydrogen with 50% natural gas compression. The simulations using the DWSIM software were run using various ratios of hydrogen blending.

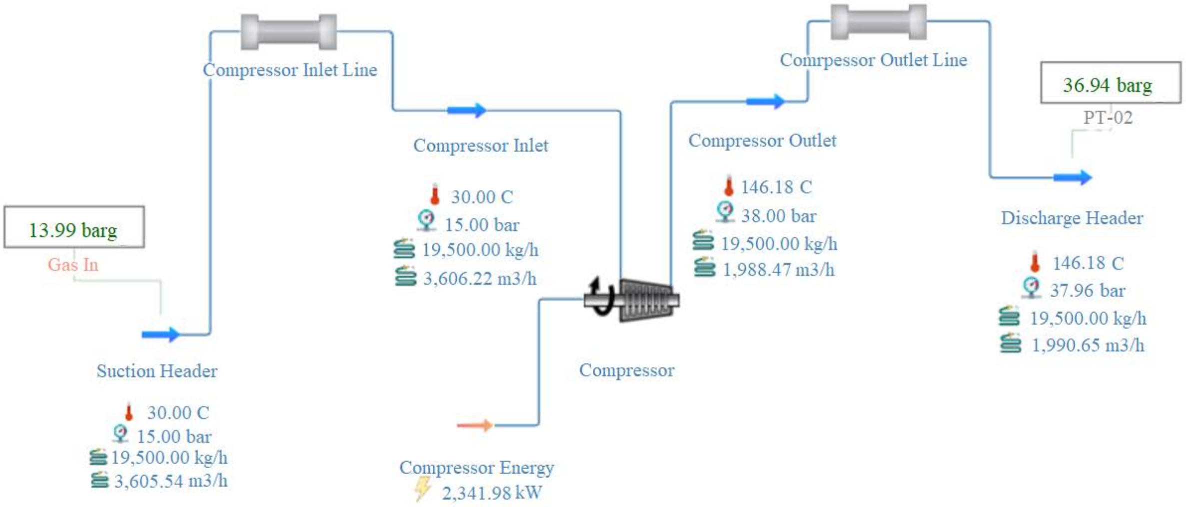

**Figure 5.** Simulation for blended fuel compression (50% hydrogen and 50% natural gas) [15]

## 3 Results and Discussion

Based on the simulation results, as shown in Figure 6, the adiabatic efficiency decreases when the hydrogen blending ratio increases. A higher adiabatic efficiency indicates a more effective compression process with minimal losses.

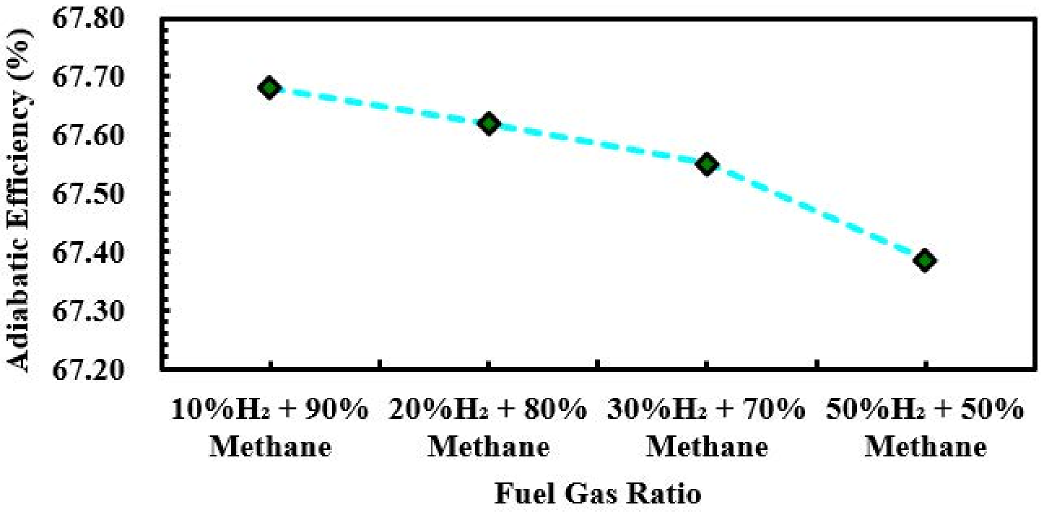

**Figure 6.** The efficiency against fuel-gas blended ratio

The discharge or compressor outlet temperature rises as the hydrogen blending ratio rises, as seen in Figure 7. A compressor's discharge temperature is a crucial factor that affects the compressor's and the system's overall performance and dependability. It speaks about the compressed gas's temperature right after it leaves the compressor. To guarantee safe and effective operation, this temperature is continuously monitored and controlled in a variety of applications, governed by several parameters [2]. In this case, changes in gas characteristics and an increase in the compression ratio cause the discharge pressure to rise. The compression ratio, which is the ratio of the suction to discharge pressure, has a major impact on the discharge temperature. Discharge temperatures are often higher with higher compression ratios. The discharge temperature is also influenced by the kind of gas being compressed and its specific heat ratio, sometimes known as the adiabatic index [16]. The temperature increases during compression vary depending on the gas properties.

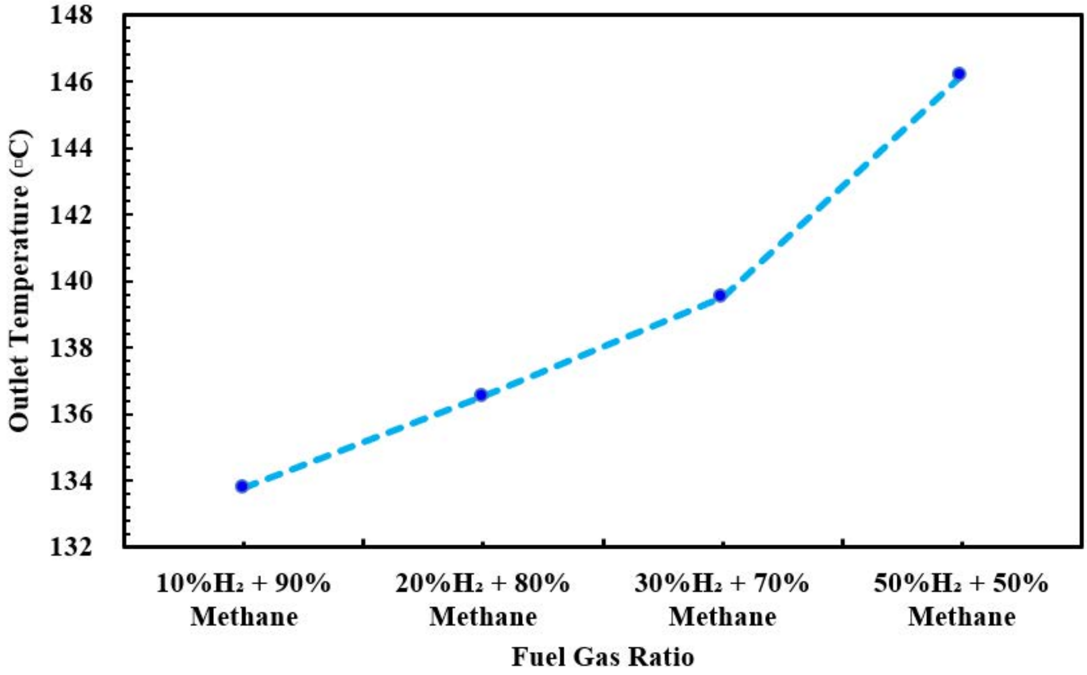

**Figure 7.** Compressor outlet temperature against fuel gas blended ratio

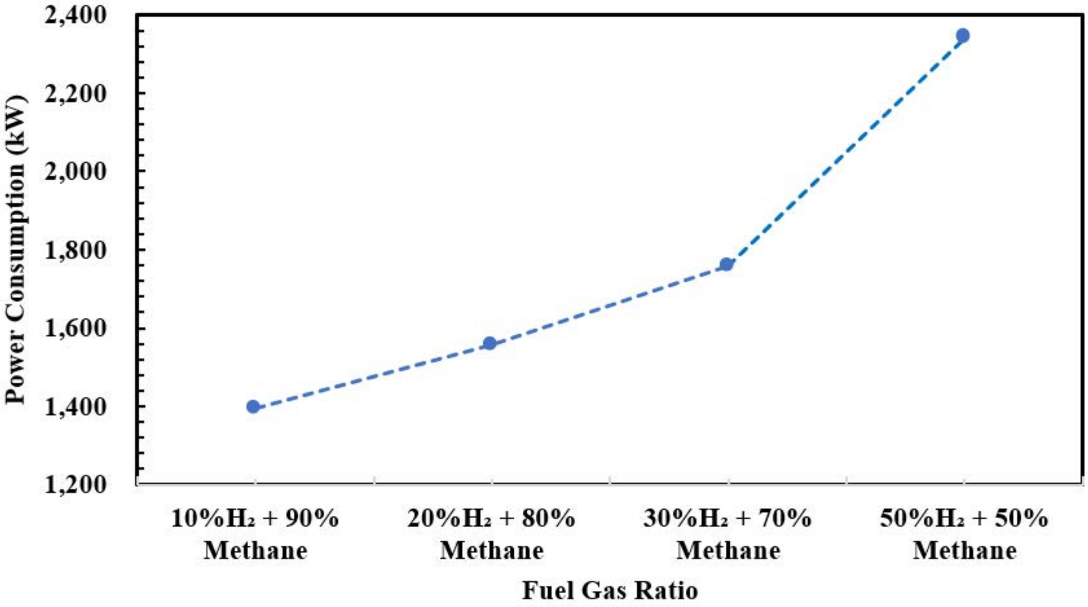

**Figure 8.** Power consumption against fuel gas blended ratio

As shown in Figure 8, power consumption increases when the hydrogen blending ratio increases. The power consumption of a compressor is influenced by various factors, and changes in gas properties can significantly impact its energy requirements. Compressors are widely used in various industries for compressing gases. Understanding how alterations in gas properties affect power consumption is essential for optimizing efficiency. Alterations in gas properties have a direct impact on the power consumption of compressors. It is crucial to understand these relationships to design efficient compression systems and implement strategies to minimize energy consumption while meeting the desired compression requirements [17].

As shown in Figure 9, adiabatic and polytropic heads rise as the hydrogen blending ratio increases. The work done on the gas to raise its pressure results in a rise in the adiabatic and polytropic heads during gas compression. When analyzing gas compression, both adiabatic and polytropic processes are frequently seen. The energy provided to the gas to overcome compression resistance and accomplish the intended pressure rise is represented by the increase in the head. This energy is reflected in the temperature increase of the gas, which is a result of the work done on the gas molecules as they are compressed. The specific processes (adiabatic or polytropic) are chosen based on the nature of the compression and the conditions under which it occurs, with adiabatic being a more idealized scenario, and polytropic allowing for a more realistic representation of heat exchange effects [2].

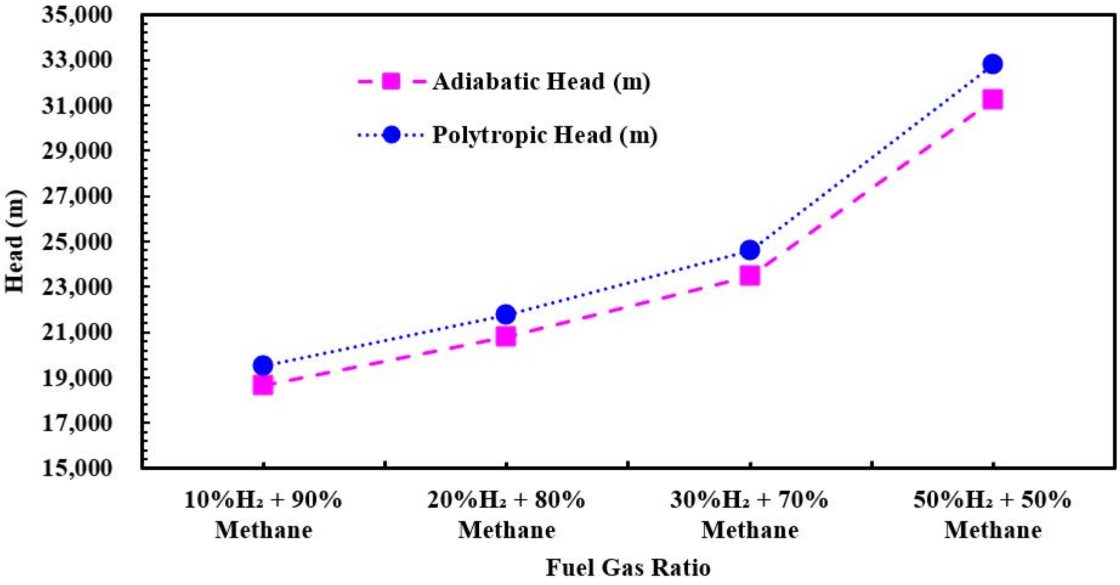

**Figure 9.** Adiabatic/polytropic head against fuel gas ratio

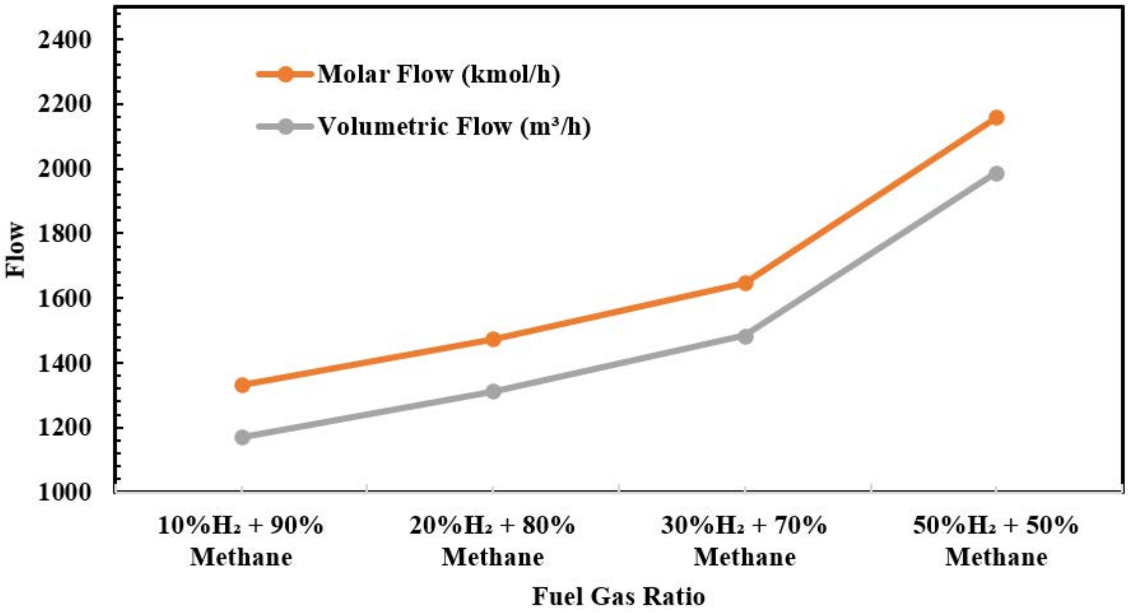

**Figure 10.** Molar/volumetric flow against fuel gas blending ratio

Figure 10 shows that when the hydrogen blending ratio increases, both molar flow and volumetric flow increase. As a result of the compression process itself, including decreasing the gas's volume and then raising its pressure, there is a rise in both molar and volumetric flow during gas compression. This phenomenon is caused by Boyle's Law, the conservation of energy and mass, and the rise in molar and volumetric flow during gas compression. As gas is compressed to higher pressures, variations in molar and volumetric flow can be explained by these basic laws, which also control the behavior of gases during compression.

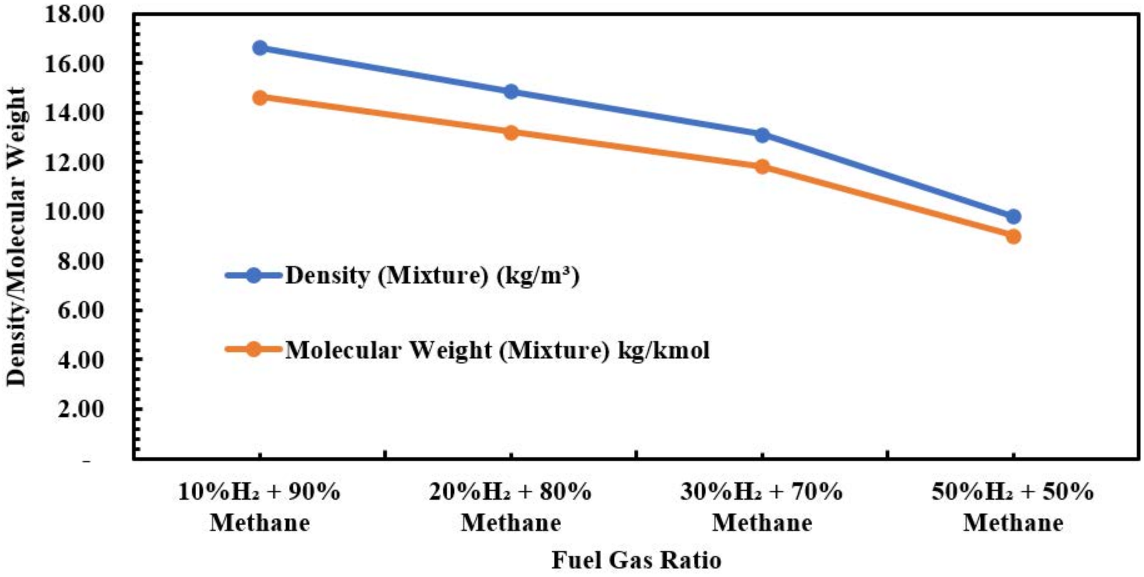

**Figure 11.** Density/molecular weight against fuel gas blended ratio

According to the data presented in Figure 11, it can be observed that the density and molecular weight of gas blending exhibit a diminishing trend as the hydrogen blending ratio increases. This occurrence can be elucidated by investigating the intricate connection between pressure, volume, temperature, and the fundamental principle of the ideal gas law. Multiple factors contribute to the reduction in density and molecular weight during the compression of gas. In conclusion, the decrease in sparsity and weightiness during gas shrinkage cannot be assigned to the basic principles that govern gas behavior, such as the fake gas law, violation of mass, Boyle's Law, and violation of energy [2]. The specific alterations experienced are contingent upon variables such as temperature, pressure, and the inherent characteristics of the gas undergoing compression [16, 18].

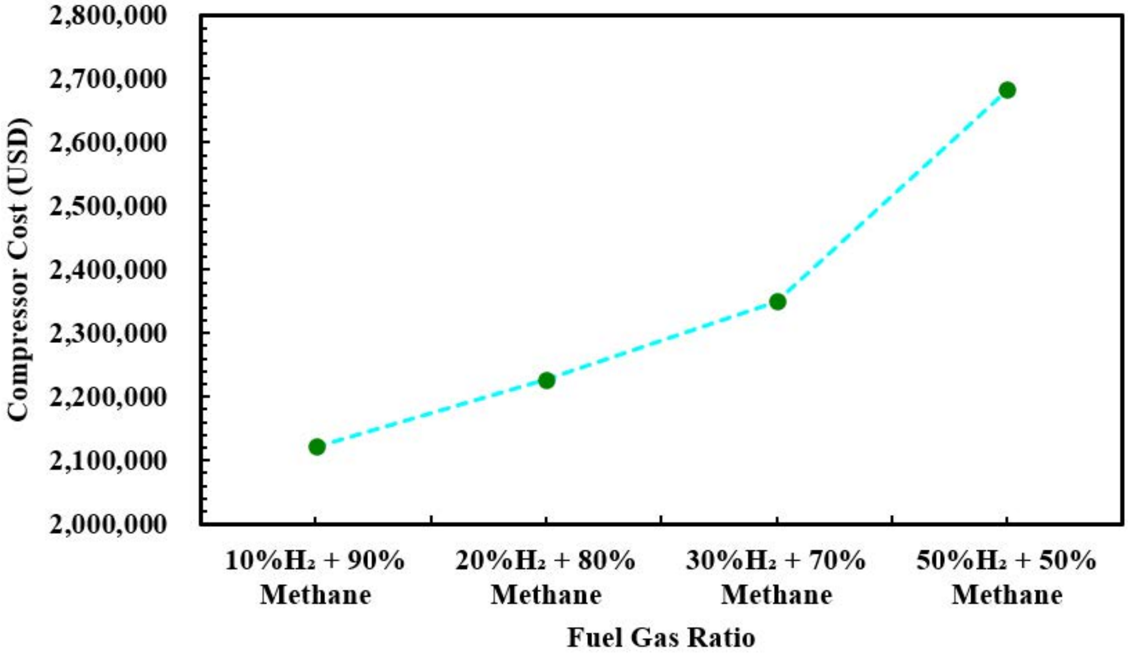

**Figure 12.** Compressor capital cost against fuel gas blended ratio

The capital expenditure for the compressor increases with the increase in compression power, as shown in Figure 12. Enlarged compressors, accompanied by corresponding components such as motors, valves, and piping, typically necessitate a greater quantity of materials and manufacturing effort, thereby contributing to escalated capital expenditures [19–21]. The capital cost of a gas compressor increases with the compression power due to the necessity for larger and more robust machinery, specialized materials, precise manufacturing, advanced technologies, and adherence to safety and regulatory standards. The overall intricacy and magnitude of the compressor system contribute to the heightened initial investment required for compressors with higher compression power [22–24].

## 4 Conclusions

The main findings of this study are as follows:

(a) When hydrogen is combined at a ratio of 30% with 70% natural gas, there is no discernible increase in compression capacity or energy consumption.

(b) The adiabatic efficacy does not significantly increase when hydrogen is mixed at a proportion of 30% with 70% natural gas.

(c) When hydrogen is blended at a ratio of 30% with 70% natural gas, the discharge temperature does not significantly rise.

(d) When 30% hydrogen and 70% natural gas are combined, there is no discernible effect on capital costs.

In summary, the transition of gas turbine power plants from traditional fossil fuels to hydrogen-based fuels necessitates careful hydrogen compression. Effective hydrogen compression is essential, but there are certain obstacles to overcome, including increased energy requirements, the need for materials that are compatible with high-pressure hydrogen, and safety concerns throughout the compression process. To position hydrogen as a viable energy source, it is imperative to improve the efficiency of compression technologies, reduce energy usage, develop advanced materials, and improve safety protocols. Partnerships between scientists, engineers, and business partners can stimulate creativity, and progress in compressing hydrogen can hasten its smooth assimilation into the international energy system.

## Author Contributions

Conceptualization, D.F.; methodology, D.F.; data analysis, D.F.; software simulation, D.F.; writing an original research paper, D.F.; supervision and review, T.M.

## Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

## Conflicts of Interest

The authors declare no conflict of interest.

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**Nomenclature**

| | |
|---|---|
| $LL$ | Lower limit |
| $HL$ | Higher limit |
| $SMR$ | Steam methane reform |
| $W$ | Mass flow |
| $\eta$ | Adiabatic or polytropic efficiency (%) |