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Research article

Techno-economic analysis on the balance of plant (BOP) equipment due to switching fuel from natural gas to hydrogen in gas turbine power plants

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Abstract: The concerns over greenhouse gas emissions, environmental impacts, climate change, and sustainability continue to grow. As a result of countermeasures, many modern gas turbine power plants and combined cycle power plants are considering to use hydrogen as a clean fuel alternative to fossil fuels in the power plant industry. We assessed the implications of such transition from natural gas to hydrogen as fuel in a gas turbine power plant's balance of plant (BOP) equipment. Using the DWSIM process simulation software and the methodology of compression power changes against different gas compositions, the impact of blending hydrogen with natural gas on temperature differentials, energy consumption, adiabatic efficiency, compression power, and economic implications in gas turbine power plants were examined in this paper. We discovered, through analysis, that there was not a noticeable boost in compression power or energy consumption when 50% hydrogen and 50% natural gas were blended. Similarly, there was no discernible difference in temperature differentials or adiabatic efficiency when 30% hydrogen and 70% natural gas were blended. Moreover, mixing 50% hydrogen and 50% natural gas did not result in a noticeable cost climb. In addition, the techno-economic analysis presented in this paper offered valuable insights for power plant engineers, power generation companies, investors in energy sectors, and policymakers, highlighting the nature of the fuel shift and its implications on the economy and technology.

Keywords: techno-economic analysis; hydrogen compression; balance of plant equipment; compressor sizing; simulation in DWSIM

1. Introduction

Hydrogen is a promising energy source that can help to reduce greenhouse gas emissions. In recent decades, the awareness of the negative effects of climate change has been increasing and people are trying to mitigate it. This phenomenon is caused by the accumulation of harmful gases, also known as greenhouse gases, in the atmosphere. These gases lead to global warming and have severe consequences for both the environment and society. To face these global challenges and ensure a sustainable future, the most important issue to address is the reduction of greenhouse gases worldwide. The main reason for this reduction is to mitigate the impact of climate change. Higher temperatures result in extreme weather conditions, rising sea levels, ecosystem disruptions, and negative effects on human health, including the agricultural economy [1]. By limiting greenhouse gas emissions, biodiversity is protected since many species are at risk of climate-related disruptions and ecosystem changes [2]. Additionally, moving away from fossil fuels and reducing greenhouse gas emissions ensures energy security by decreasing reliance on finite and geopolitically sensitive resources and reducing air pollution. When hydrogen is burned, it only emits water and heat, making it a clean and eco-friendly option. This energy source can be used in various sectors such as transportation, industry, and power generation as a replacement for fossil fuels [3]. Sebastian Verhelst and Thomas Wallner investigated the use of hydrogen in internal combustion engines [4]. Additionally, hydrogen can store excess renewable energy, guaranteeing a stable and continuous energy supply. However, supportive policies, research and development, and international cooperation are necessary to realize hydrogen's potential fully [2]. While there is a lot of research and literature available on hydrogen in the transport sector, hydrogen storage, and hydrogen safety, there is a lack of research on the use of hydrogen in the power generation industry. We focus on how switching from fossil fuels to hydrogen in gas turbine power plants can reduce greenhouse gas emissions and pollutants like carbon dioxide, sulfur dioxide, and nitrogen oxide [3]. Gas turbine power plants can be deployed at various scales, making them suitable for distributed generation, where smaller plants can be located closer to the points of electricity consumption, reducing transmission losses. However, natural gas supply can be unpredictable due to price fluctuations and geopolitical factors, and burning it releases carbon dioxide. Despite these limitations, gas turbine power plants are important components in the global energy mix, providing efficient and flexible electricity generation. Gas turbines that run on natural gas are known to produce lower emissions and exhibit better environmental performance compared to other fossil fuel-based power plants. As such, they are increasingly being considered as a crucial step towards a more sustainable energy future [5]. The primary objective is to conduct a comprehensive analysis of the balance of plant equipment in a gas turbine power plant while transitioning from natural gas to hydrogen as fuel.

This endeavor will involve a detailed assessment of the feasibility of replacing natural gas with hydrogen, identifying any necessary modifications required to accommodate this new fuel, and evaluating the compatibility of existing equipment with hydrogen [3]. We will also consider potential challenges and safety concerns that may arise during the transition phase. Additionally, this analysis will provide an economic comparison of the costs associated with switching to hydrogen as fuel.

The objective of the work is to analyze the implications on the balance of plant (BOP) equipment especially fuel gas compressor which is major BOP equipment in gas turbine power plants due to the fuel switch. This research aims to advance the understanding of hydrogen's role in decarbonizing the energy sector and help accelerate the transition towards a cleaner, more sustainable energy future. By exploring the feasibility of hydrogen as a fuel source in gas turbine power plants, it hopes to contribute to the ongoing global efforts towards achieving a carbon-neutral energy system [6].

2. Materials and methods

2.1. Literature review

Hydrogen is gaining attention as an alternative fuel for power generation and its potential to contribute to a low-carbon energy future. Power-to-gas, which involves using excess renewable electricity to produce hydrogen through electrolysis, has been explored for energy storage. It has been suggested that P2G has the potential to balance intermittent renewable energy and provide grid flexibility [7]. Additionally, some literature examines the potential of co-firing hydrogen with fossil fuels in existing power plants. By co-firing hydrogen with natural gas, emissions can be reduced, and it can act as a transitional solution to gradually integrate hydrogen into the energy mix. Some studies conduct life cycle assessments to compare the environmental impacts of hydrogen-based power generation with conventional fossil fuel-based power plants [7]. Economic analyses evaluate the costs and benefits of hydrogen adoption, including the effects of scale, policy incentives, and hydrogen infrastructure development. While some studies have shown that supportive policies, incentives, and regulations are crucial in transitioning to hydrogen-based power generation [8]. Policymakers analyze and assess the impact of government interventions on the market penetration and deployment of hydrogen technologies. Some works of literature investigate the challenges and opportunities of integrating hydrogen-based power generation into existing energy systems, including grid integration, system stability, and its role in a low-carbon energy future. Despite challenges, hydrogen offers great potential as a clean and versatile energy carrier that can help decarbonize power generation and support sustainable energy transition. Ongoing research and technological advancements continue to contribute to the growing body of knowledge on hydrogen's role in a low-carbon energy future [9].

Fuel switching in gas turbine power plants is also a subject of interest in several studies and projects, with a focus on investigating the effects of transitioning from one fuel to another, such as natural gas to hydrogen or ammonia. These studies assess technical feasibility, performance changes, emissions reductions, and economic implications. A comprehensive techno-economic review evaluates using hydrogen as a fuel in gas turbine power plants, exploring technical challenges associated with hydrogen combustion, necessary turbine modifications, potential efficiency gains, and economic considerations. It also evaluates the impact of hydrogen integration on power plant performance, emissions, and cost-effectiveness [7]. The researchers investigate the feasibility of co-firing hydrogen with natural gas in gas turbine power plants and assess the effects of different hydrogen blending ratios on turbine performance, emissions, and combustion dynamics. We aim to determine the potential benefits and challenges of incorporating hydrogen into the existing natural gas infrastructure [3].

Two studies have evaluated the concept of power-to-gas and its potential use in grid-balancing services. The first study, conducted by the International Energy Agency in 2019, focuses on using excess renewable energy to produce hydrogen through electrolysis. The hydrogen is later re-electrified using gas turbines during high-demand periods. This approach is assessed for its technical and economic viability in enhancing grid stability and energy storage [10]. The second study, conducted by the European Commission in 2021, explores the role of hydrogen in decarbonizing various sectors, including power generation. The European Commission investigates different hydrogen pathways, including their use in gas turbines and fuel cells, and analyzes the potential impact on greenhouse gas emissions. They also examine the impact of hydrogen blending on the combustion process, emissions, and overall performance of gas turbines. Moreover, they provides recommendations for optimizing hydrogen blending in gas turbine power plants and addresses technical challenges [2]. Such research is vital for informing policymakers, industry stakeholders, and investors about the opportunities and implications of adopting hydrogen and other alternative fuels in power generation as the transition to cleaner energy sources gains momentum. In the context of power plants, it is essential to consider the Balance of Plant (BOP) equipment to ensure that the operation is both reliable and efficient. This crucial aspect of power plant management has been the subject of extensive research, covering a wide range of topics, including but not limited to design, operation, and cost-effectiveness. The objective of BOP equipment research is to optimize the design and layout of the auxiliary systems to maximize energy efficiency and minimize operational costs while complying with environmental regulations [9].

Moreover, studies in this area also focus on the integration of renewable energy sources to enhance sustainability. Some researchers explore various equipment choices such as reliability and maintenance costs, considering the associated costs. Cost estimation models help evaluate the financial viability of different BOP configurations and inform investment decisions. Furthermore, life cycle assessment techniques are employed to evaluate the environmental impact of BOP equipment. This approach provides a holistic view of the environmental performance of the auxiliary systems, supporting the transition to a more sustainable and cost-effective energy future [11].

In summary, this study aims to analyze the implication of cost increase due to higher compression power when blending a higher percentage of hydrogen, technical challenges, and careful selection of proper gas compression equipment. The findings from this research can significantly contribute to the awareness of techno-economic implications, and enhance the productivity of the power plant industry, as they help support the transition to a more sustainable and cost-effective energy future.

2.2. Methodology and modelling

The main challenge of fuel switching in gas turbine power is fuel compression and fuel blending to feed the flow and pressure demand required by gas turbines. There are several parameters to be considered in the selection and sizing of hydrogen compressors, which include the suction pressure, temperature, volumetric flow rate, impeller sizes, and discharge pressure [12]. The discharge pressure and feed flow rates are usually based on the full load demand pressure and fuel flow requirement from the gas turbine. Operating speed is especially relevant because the polytropic head and pressure ratio that a compressor or stage produces is proportional to the square of the speed. Due to low molecular weight and high sonic velocity, it will have a comparatively lower pressure rise per stage of the compressor relative to heavier gases [13]. This means that in applications with high discharge pressures, the impeller operating speed must be increased, or additional compressor stages must be added. In some instances, the maximum permissible shaft length may not provide sufficient space to incorporate the required number of stages. In such cases, the only option is to increase the impeller's operating speed. However, it requires consideration of material strength limits [11]. The impact of the gas compression process and compressor sizing is analyzed using DWSIM which is open-source chemical process simulation software, and the results are reliable and comparable to other available commercial software [14]. Kwanchanok T et al. investigated the accuracy of simulation results from DWSIM open-source gas compression model simulation is comparable to Aspen Plus which is a popular commercial software in the process engineering industry and no noticeable difference was observed [15]. The ideal process in the compressor is isentropic, which is also known as (constant entropy) and it is considered based on the thermodynamic path (adiabatic or polytropic), and the efficiency of the compressor.

Isentropic (Adiabatic) or Polytropic power is calculated from the following equations (Eqs 1 and 2) below.

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

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

H_{2s} Outlet Enthalpy for Isentropic Process
H_1 Inlet Enthalpy
W Mass Flow
η Adiabatic or Polytropic Efficiency

Adiabatic and Polytropic Heads are calculated from Eq 3 below.

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

where
H Adiabatic or Polytropic Head
P Adiabatic or Polytropic Power
W Mass Flow
η Adiabatic or Polytropic Efficiency
g Gravitational Constant (9.8 m/s²)

In thermodynamic properties, the Peng-Robinson Equation (Eq 4) is used which is stated below.

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

where
P Pressure
R Ideal gas universal constant
V Molar Volume
b parameter related to hard sphere volume
a parameter related to intermolecular forces

Thermodynamic power calculation for single-stage compressors is generally idealized using an isentropic process that is both adiabatic and reversible [7]. Physical properties comparison of hydrogen and natural gas are summarized in Table 1.

Table 1. Physical properties of hydrogen and natural gas [7,8].

	Hydrogen	Natural gas
Composition	100% Hydrogen	90% Methane, Ethane, Propane, Butane
Byproducts upon combustion	water, nitrogen oxide	carbon dioxide, nitrogen oxide
Molecular weight (gram/mol)	2.00	16.00
Lower heating value (per volume) MJ/Nm³	10.80	35.80
Lower heating value (per mass) MJ/kg	120.00	50.00
Flame speed (m/s)	2.01168 ~ 2.98704	0.3048 ~ 0.39624
Flammability limit (lower limit %/higher limit %)	4/75	7/20

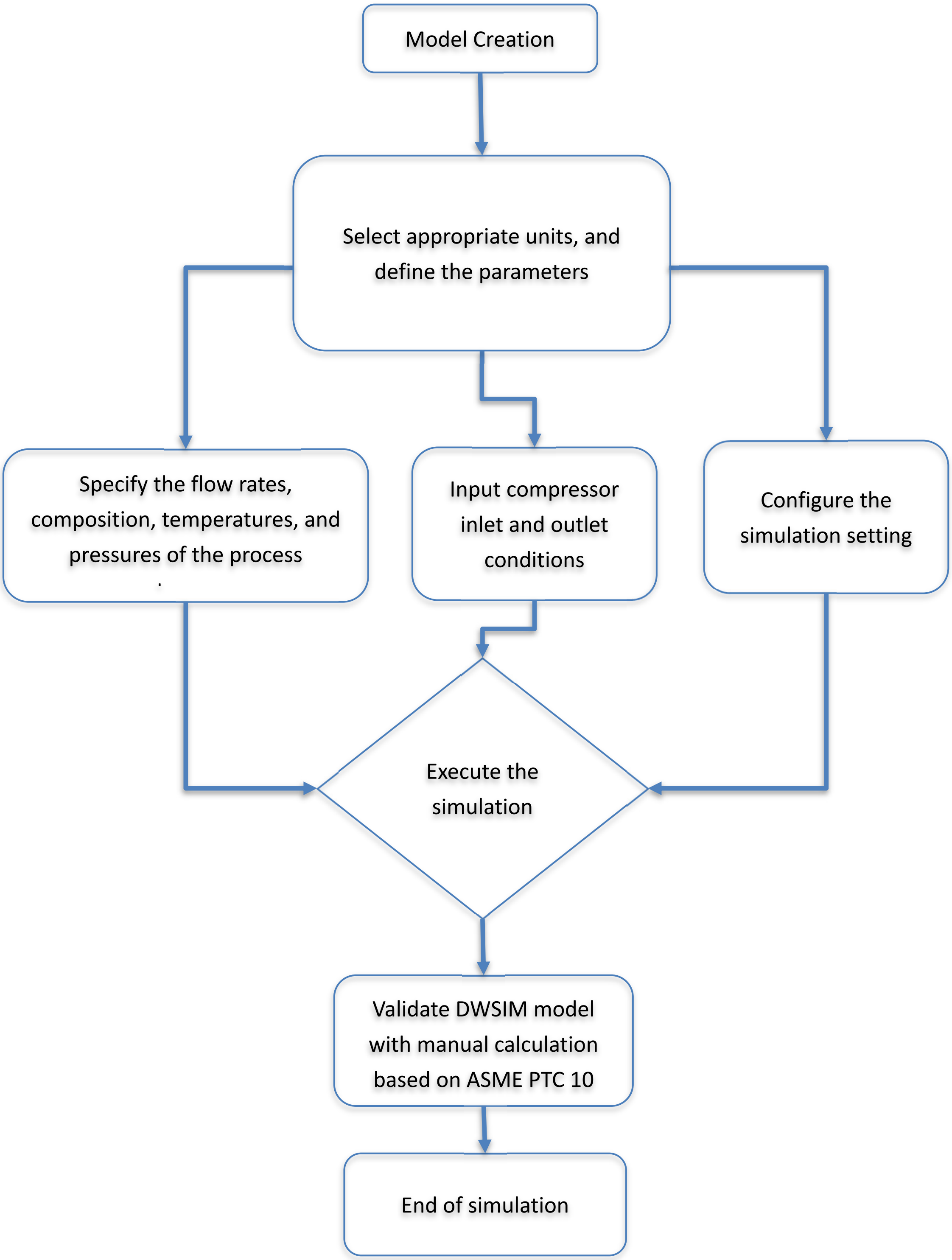
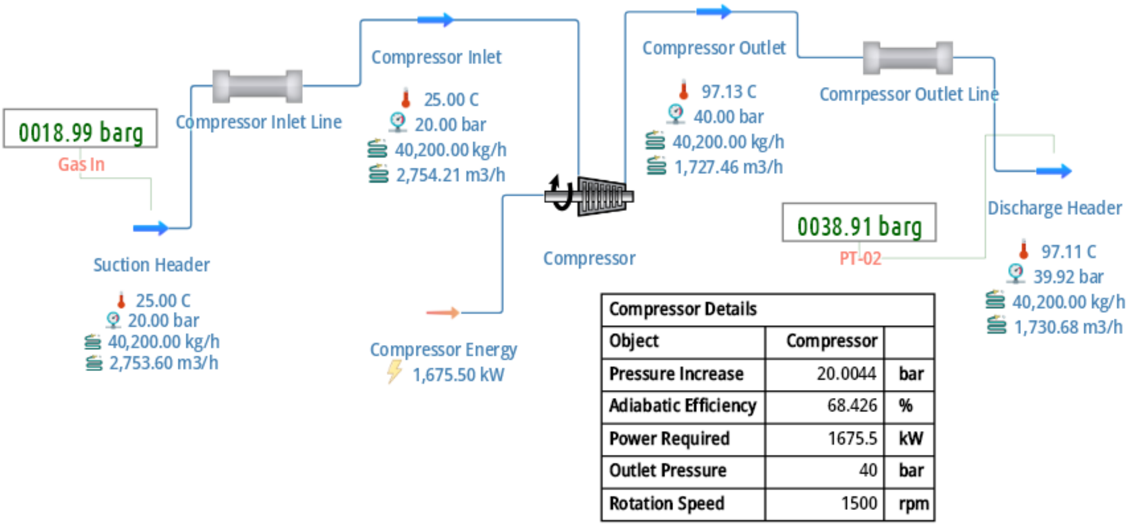


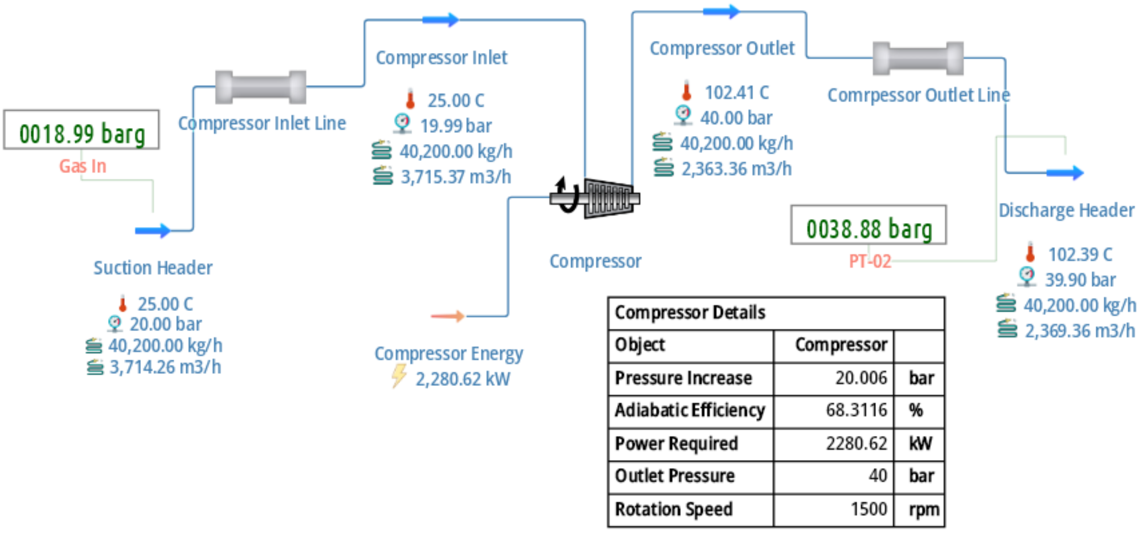
Figure 1. Flowchart of DWSIM simulation for fuel gas compression [16].

Figure 1 is the flow chart idea before the simulation with the DWSIM process simulator. In the DWSIM simulation, the required fuel flow rate (40,200 kg/hour Mass Flow) is considered for full load operation of 557 MW output capacity of GE Gas Turbine Model 9HA.02 [8]. Compressor inlet pressure 20 Bar at 25 °C is considered by assuming upstream pressure of fuel supply from metering or supply station. The required discharge pressure of 40 bar at the discharge header is considered. The composition of natural gas (Methane 90%, Ethane 5%, and Nitrogen 5%) is considered. The change in gas composition will affect the compression power depending on gas conditions should be considered when determining the compressor selection [11]. The simulations in DWSIM software were carried out using different ratios of hydrogen, where Figure 2 represents 100% natural gas compression, Figure 3 represents 30% H_2 + 70% natural gas compression, Figure 4 represents 50% H_2 + 50% natural gas compression, and Figure 5 represents 100% H_2 compression.



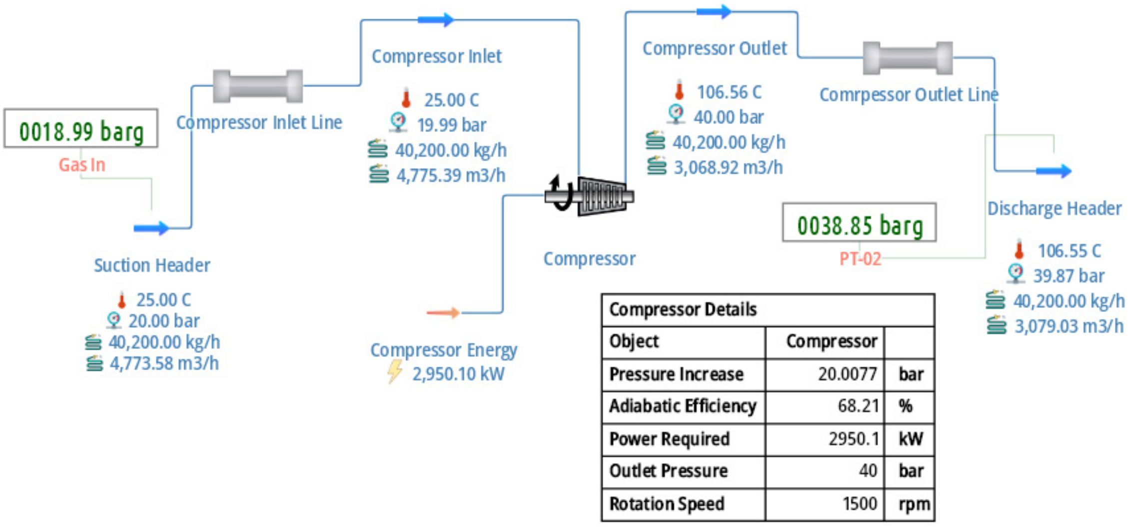
Compressor Details		
Object	Compressor	
Pressure Increase	20.0044	bar
Adiabatic Efficiency	68.426	%
Power Required	1675.5	kW
Outlet Pressure	40	bar
Rotation Speed	1500	rpm

Figure 2. Simulation flow sheet for 100% natural gas compression [16].



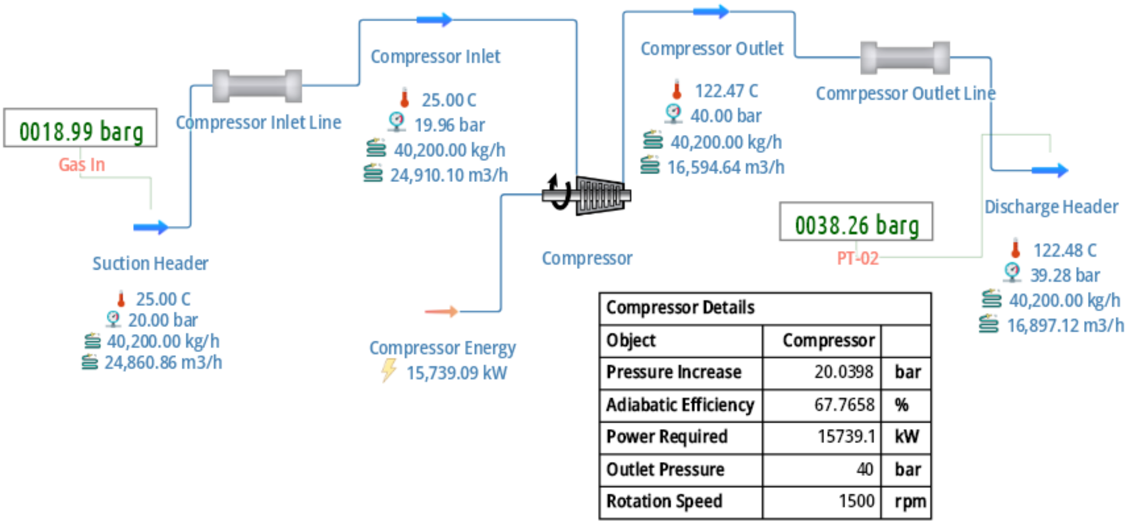
Compressor Details		
Object	Compressor	
Pressure Increase	20.006	bar
Adiabatic Efficiency	68.3116	%
Power Required	2280.62	kW
Outlet Pressure	40	bar
Rotation Speed	1500	rpm

Figure 3. Simulation flow sheet for 30% H_2 + 70% natural gas compression [16].



Compressor Details		
Object	Compressor	
Pressure Increase	20.0077	bar
Adiabatic Efficiency	68.21	%
Power Required	2950.1	kW
Outlet Pressure	40	bar
Rotation Speed	1500	rpm

Figure 4. Simulation flow sheet for 50% H_2 + 50% natural gas compression [16].



Compressor Details		
Object	Compressor	
Pressure Increase	20.0398	bar
Adiabatic Efficiency	67.7658	%
Power Required	15739.1	kW
Outlet Pressure	40	bar
Rotation Speed	1500	rpm

Figure 5. Simulation flow sheet for 100% H_2 compression [16].

2.3. Techno-economic analysis

The gas compressor is the key balance of plant (BOP) equipment in gas turbine power plants. At the bidding and conceptual design stage, it is essential to estimate the capital cost of compressors reasonably accurately [17]. The capital cost of gas compressors highly depends on the power (kW) required to drive the compressor and the number of stages required to compress. The simulation from DWSIM shows that the required power and the number of stages highly depend on the gas compositions to be compressed. Both academic literature and industries use empirical cost correlations or rules of thumb to determine how much a compressor will cost based on its size. The cost of the compressor is calculated using these correlations and is based on the required compressor motor [11].

The calculation of capital costs associated with compressors using the correlations provided in the HDSAM model [18].

The Chemical Engineering Design Book written by Gavin Towler and Ray Sinnott gives the method of estimating centrifugal gas compressor capital costs as shown in Eq 5 [19].

$$C_e = a + bS^n \tag{5}$$

where

C_e Purchased equipment cost in USD
a, b Cost constants given in Chemical Engineering Design Book
S Size parameter, units given in Chemical Engineering Design Book
n Exponent for that type of equipment

Douglas provides the estimated compressor cost as shown in Eq 6 [17].

$$Compressor\ Cost = 5{,}840(kW)^{0.82} \tag{6}$$

The textbook "Analysis, Synthesis and Design of Chemical Processes" gives separate cost curves for the compressor and the driver [19]. Turton predicts a carbon-steel compressor cost of $280 per kW at 1000 kW and an electric drive cost of $120 per kW [17].

The detailed cost assumptions for the total installed cost of hydrogen compressors estimated by the HDSAM model is as per Eq 7 [18].

$$Compressor\ Cost = 2274\ (kW)^{0.8335} \tag{7}$$

Chemical Process Equipment Selection and Design gives the capital cost of Centrifugal compressors without drivers and for the driver, an additional 1.3 to be added as shown in Eq 8 [19].

$$Compressor\ Cost = 7.9\ x\ 1000(HP)^{0.62} x\ 1.3 \tag{8}$$

Table 2. Comparison of centrifugal gas compressor costs (USD) [17–19].

	0% H_2 + 100% Natural gas	30% H_2 + 70% Natural gas	50% H_2 + 50% Natural gas	100% H_2
Power required (kW)	1,675	2,280	2,950	15,739
Cost of compressor (Che. Eng Book) [17]	2,299,950	2,649,480	2,995,080	7,175,050
Cost of compressor (Douglas) [17]	2,571,650	3,311,435	4,089,580	16,141,220
Cost of compressor (analysis, synthesis and design) [19]	1,228,995	1,487,899	1,745,340	4,928,430
Cost of compressor (HDSAM) [18]	1,106,920	1,431,290	1,773,780	7,160,990

The capital cost of centrifugal gas compressors was evaluated based on different sources as summarized in Table 2. Among the above-mentioned sources, the estimate per HDSAM model [18] appears to be more realistic comparing to current market price.

3. Results and discussion

The simulation was carried out based on the different ratios of natural gas and hydrogen blending. The results show that the adiabatic efficiency decreases when the hydrogen ratio increases as shown in Figure 6. DWSIM model for Figure 6 (adiabatic efficiency) verified with manual calculation method (Type 2 Test for the centrifugal compressor) specified in ASME PTC 10 Performance Test Code on Compressors and Exhausters. The results show that there is no noticeable discrepancy between DWSIM model, and the calculation carried out as per PTC 10 [20]. The higher adiabatic efficiency defines the more effectiveness in the compression process [12]. Figure 7 shows that polytropic efficiency is the same regardless of fuel-gas ratio change. That is because polytropic efficiency is a measure of energy conservation in gas compression process and the polytropic efficiency of compressing hydrogen should be the same as compressing other gases under similar conditions [11].

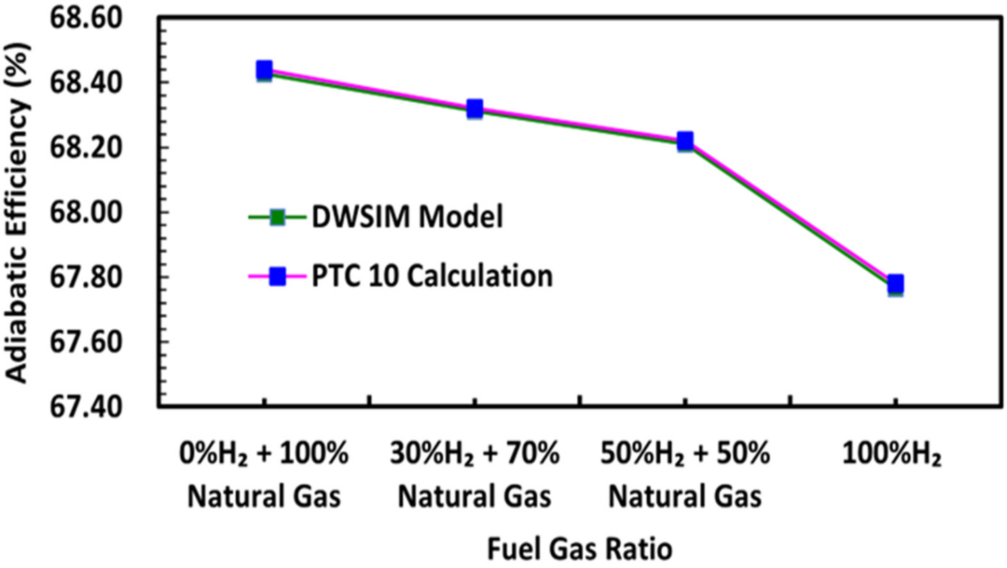


Figure 6. Adiabatic efficiency against fuel gas ratio [16,20].

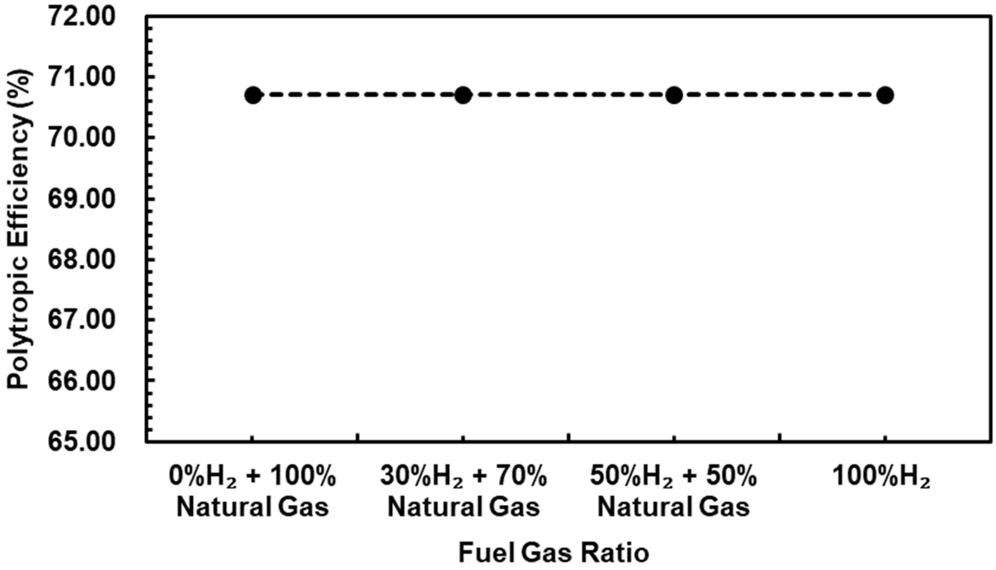


Figure 7. Polytropic efficiency against fuel ratio [16].

Similarly, the temperature difference (ΔT) increases when increasing the hydrogen ratio as shown in Figure 8. The S.M Walas investigated that the discharge pressure in single stage should limit not greater than 200 ℃ [21]. The increases in discharge temperature requires the bigger size of cooler to cool down the discharge side of fuel gas.

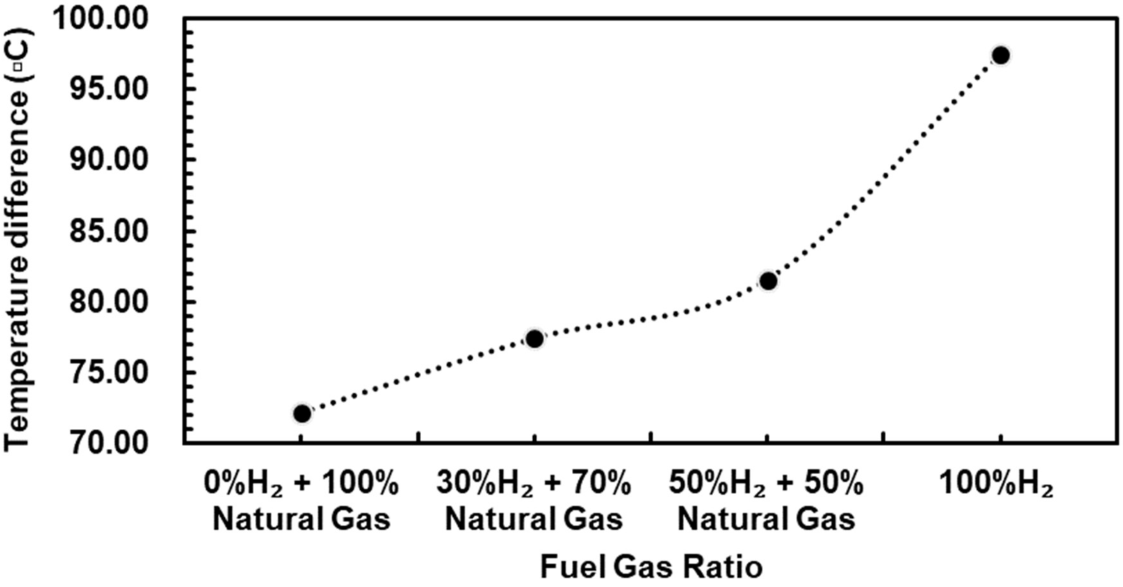


Figure 8. Temperature difference (ΔT) against fuel ratio [16].

The density and molecular weight of hydrogen are extremely low compared to methane as shown in Figure 9 which means that, to store the same amount of energy, a larger volume of hydrogen to be compressed as compared to natural gas.

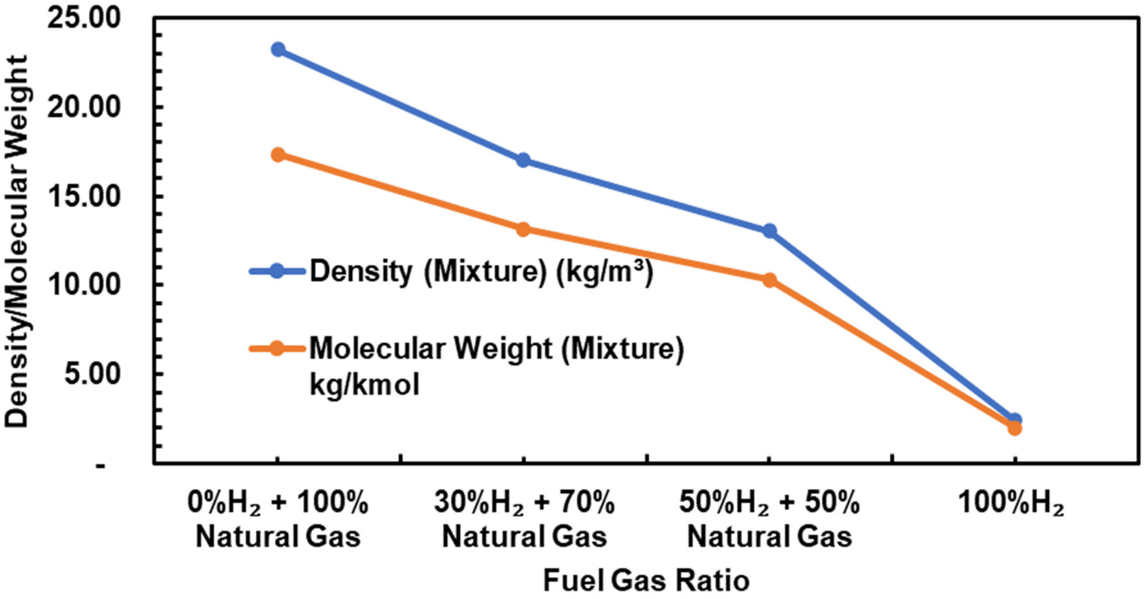


Figure 9. Density/Molecular weight against fuel ratio [16].

Due to the low density of molar energy, the compression power is much higher as compared to 100% natural gas. As discussed in the techno-economic section, the cost of the gas compressor is highly dependent on the compression power in which the power required for the compression of 100% H_2 is 9.4 times higher than the compression of 100% natural gas. Also, a 15,739 kW electricity load will collapse the grid system and it is required to divide 3 × 35% compressors if 100% H_2 compression will be selected. Based on this study, it is observed that there is no significant power increase up to 50% H_2 blending as shown in Figure 10 below. DWSIM model for Figure 10 (power consumption) verified with manual calculation method specified in ASME PTC 10 Performance Test Code on Compressors and Exhausters. The results show that there is no noticeable discrepancy between the DWSIM model and the calculation as per PTC 10 [20].

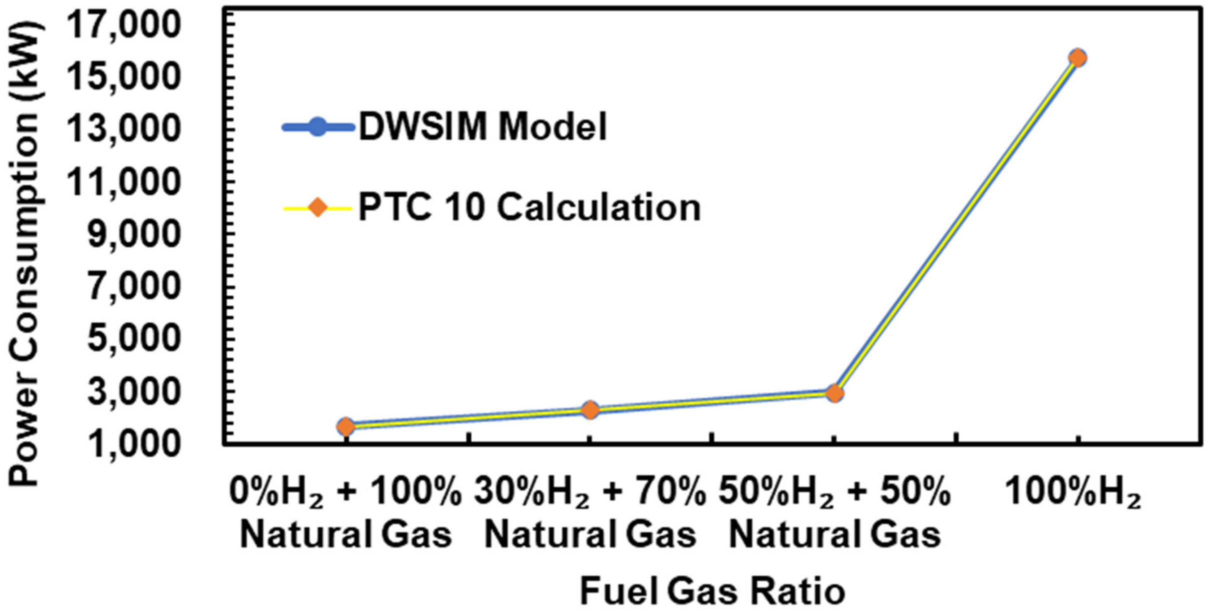


Figure 10. Power consumption against fuel ratio [16,20].

The adiabatic head & polytropic head significantly increased when the ratio of hydrogen is higher as can be seen in Figure 11. The increase in adiabatic and polytropic head during gas compression is a consequence of the work done on the gas to raise its pressure. Both adiabatic and polytropic processes are common in the analysis of gas compression. The increase in head represents the energy added to the gas [11].

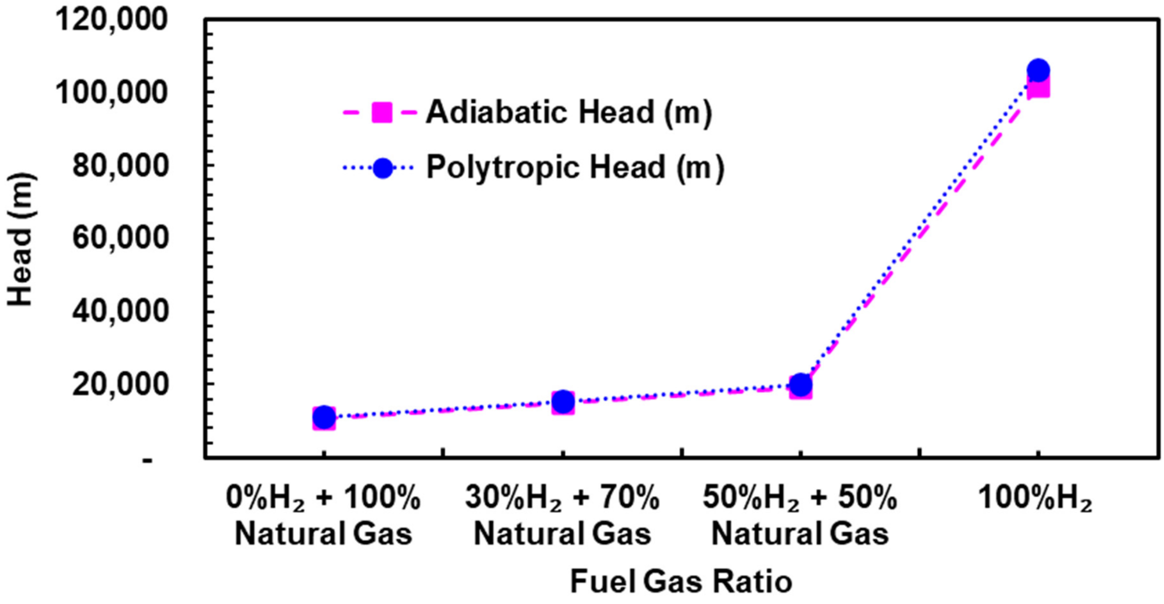


Figure 11. Adiabatic/Polytropic head against fuel ratio [16].

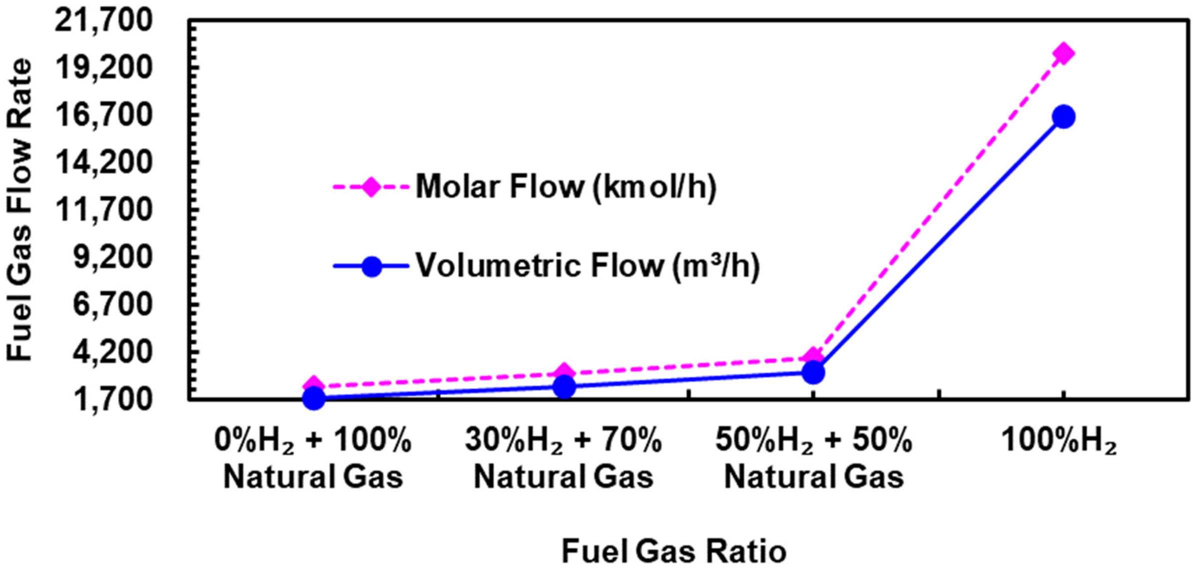


Figure 12. The results of molar flow, and volumetric flow against fuel ratio [16].

As shown in Figure 12, no significant increase in the molar flow and volumetric flow up to 50% fuel blending. The results identified that drastic increase from 50% above fuel blending. The increase in molar flow and volumetric flow during gas compression is a direct consequence of the compression process. The higher volumetric flow and the higher molar flow required a higher-pressure ratio and more compression power [11].

4. Conclusions

Based on this study, the major findings are as follows.

1. No significant increase in compression power or energy consumption when the hydrogen blends 50% with 50% natural gas. Therefore, hydrogen blending can be considered up to 50% with natural gas.
2. No significant increase in adiabatic efficiency when the hydrogen blends 30% with 70% natural gas.
3. No significant temperature difference (ΔT) increases when hydrogen blends 30% with 70% natural gas.
4. No significant cost impact when the hydrogen blends 50% with 50% natural gas.

In conclusion, the transition from fossil fuels to hydrogen-based fuels in gas turbine power plants necessitates precise compression of hydrogen. While effective hydrogen compression is critical, it poses challenges such as high energy consumption, maintaining compatibility with high-pressure hydrogen, and ensuring safety during the compression process. To establish hydrogen as a practical energy source, further improvements, research, and developments are essential to enhance the efficiency of compression technologies, decrease energy consumption, develop advanced materials, and improve safety measures. Cooperation between researchers, engineers, and industry stakeholders will foster innovation, and progress in hydrogen compression will facilitate its smooth integration into our worldwide energy framework.

Use of AI tools declaration

The authors declare that they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

The authors declare that there are no conflicts of interest in this research article.

Author contributions

Daido Fujita: Conceptualization, methodology, data analysis, software simulation, writing an original research paper. Takahiko Miyazaki: Supervision and review.

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