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*Research paper*

# *Combined CFD and Field Study of Hydrogen-Supplemented Natural Gas Combustion in Gas Turbines*

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## ABSTRACT

The transition toward low-carbon energy systems has accelerated research on alternative fuels that can be integrated into existing power generation technologies. Hydrogen has emerged as a promising energy carrier due to its high energy density and carbon-free combustion characteristics. Gas turbines, widely used in large-scale electricity production, offer significant potential for partial substitution of natural gas with hydrogen. In this context, the present study investigates the combustion behavior and emission characteristics of hydrogen-enriched natural gas in an annular gas turbine combustion chamber using computational fluid dynamics (CFD). A three-dimensional combustor model was developed using SolidWorks and imported into ANSYS Fluent for numerical simulations. The analysis was performed under non-premixed combustion conditions using real operational data obtained from industrial gas turbine units to define the boundary conditions. In the simulation, natural gas was supplied through the premix line while hydrogen was introduced through the pilot line. The fuel mixture consisted of 92% methane and 8% hydrogen by mass. Key combustion parameters, including temperature distribution, flow velocity, pressure characteristics, turbulence intensity, and pollutant emissions, were evaluated to assess the effects of hydrogen enrichment. The simulation results indicate that the addition of hydrogen significantly influences the combustion process by increasing flame temperature and enhancing combustion efficiency. The maximum combustion temperature in the chamber increased compared with conventional natural gas operation. More importantly, pollutant emissions were considerably reduced. The predicted nitrogen oxide (NOx) and carbon monoxide (CO) concentrations were substantially lower than those typically observed in natural gas–only combustion systems. Overall, the findings demonstrate that moderate hydrogen blending in natural gas-fired gas turbines can improve environmental performance while maintaining stable combustion characteristics. The results highlight the potential of hydrogen-enriched combustion as a practical approach for reducing emissions in existing gas turbine power plants without requiring extensive modifications to the combustion system.

**Keywords:** *Hydrogen Co-Firing, Combined Cycle Power Stations, Gas Turbines, Emission Reduction, Annular Combustor.*

## I. INTRODUCTION

Global climate change has become one of the most critical global challenges, requiring significant efforts to reduce pollutant and greenhouse gas emissions. In December 2015, the Paris Climate Agreement (COP21) was signed by 195 countries with the aim of limiting global temperature rise and

mitigating climate change impacts (Szulejko et al., 2017; Scott et al., 2016; Rose et al., 2017). The agreement established a global commitment to keep the increase in average global temperature well below 2 °C above pre-industrial levels by significantly reducing greenhouse gas emissions (Van Beek et al., 2022). Among the world's most populous and industrialized countries, the United States and China account for a substantial share of global energy consumption and carbon dioxide ($CO_2$) emissions. This situation is largely attributed not only to population growth but also to extensive industrial activities and the widespread use of fossil fuels in transportation, electricity generation, and other sectors. Consequently, considerable research efforts have recently focused on the development of alternative and sustainable energy systems to mitigate the environmental impacts of conventional energy technologies (Siksnelyte-Butkiene et al., 2020; Hoang et al., 2021). Among the proposed alternatives, hydrogen has emerged as a promising energy carrier due to its high energy density and environmentally friendly combustion characteristics (Atilhan et al., 2021; Felseghi et al., 2019; Akal et al., 2020).

Fluctuations in petroleum prices with increasing environmental concerns have accelerated the search for alternative fuels. The evaluation of such fuels typically involves considerations of technical feasibility, economic viability, and environmental sustainability. As the global population and energy demand continue to grow, reliance on fossil fuels is expected to increase if alternative solutions are not implemented. This trend may lead to further increases in $CO_2$ emissions and exacerbate climate change challenges (Al-Maamary et al., 2017; Sallee et al., 2016; Stančin et al., 2020).

The evolution of global $CO_2$ emissions between 1990 and 2020 indicates a significant increase of approximately 68%. This trend highlights the urgent need for all energy-intensive sectors to reassess their fuel consumption patterns and adopt cleaner technologies. During this period, emissions associated with international transportation, industrial fossil fuel consumption, electricity generation, and local transportation increased by approximately 64% and 90%, respectively, compared with their 1990 levels (Yuan et al., 2014). Therefore, the rapid implementation of improved and emerging energy technologies is essential to effectively reduce $CO_2$ emissions.

In this context, the present study investigates the feasibility of using hydrogen in combination with natural gas in heavy-duty, large-scale gas turbines (GTs) employed for electricity generation. Gas turbines are capable of producing large amounts of power within relatively compact systems and can be integrated with other power generation cycles such as Rankine, simple, and Brayton cycles (Buonomano et al., 2015; Ahmadi et al., 2018; Poullikkas, 2005). However, most modern gas turbine systems are primarily operated within Brayton cycle configurations. A typical Brayton cycle consists of four main components: an inlet section, a compressor, a combustion chamber, and a turbine section. The overall performance and efficiency of these systems are strongly influenced by the characteristics of the combustion process occurring within the combustor. Since most gas turbines currently operate using fossil fuels, the combustion process results in the emission of various greenhouse gases (Sleiti and Al-Ammari, 2021; Scaccabarozzi et al., 2016). One of the major drawbacks of fossil fuel utilization is therefore its contribution to environmental pollution and global warming (Polat, 2022). To address these issues, alternative fuels such as hydrogen and biofuels have been proposed as cleaner energy sources for future gas turbine applications. Hydrogen production is a complex process that can be achieved through various feedstocks and technological pathways. Conventional resources such as coal and natural gas, as well as renewable energy sources and biomass, can be utilized for hydrogen generation (Bartels et al., 2010; Taipabu et al., 2022). Several production technologies have been developed for this purpose, including thermochemical, biological, chemical, and photolytic processes. The main hydrogen production pathways are illustrated in Figure 1 (Alhuyi et al., 2022). Currently, fossil fuel reforming—particularly natural gas reforming—remains the dominant method of hydrogen production worldwide (Alhuyi et al., 2022; Hosseini, 2020). However, the present study does not focus on hydrogen production technologies. Instead, the primary objective is to investigate the use of hydrogen as a supplementary fuel in gas turbine combustion systems.

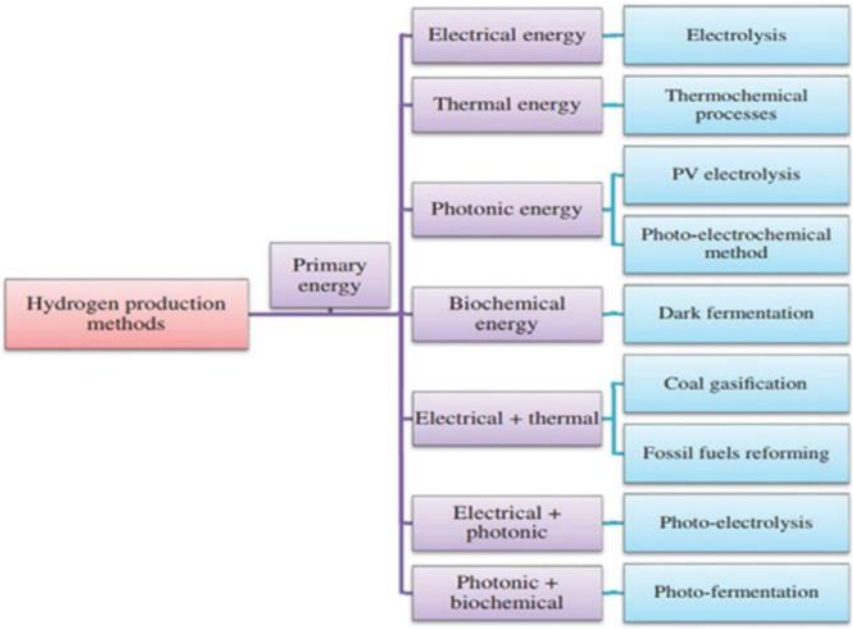


Figure 1. Hydrogen product application methods (Alhuyi et al., 2022).

Fuel type can cause different types of $CO_2$ emissions. $CO_2$ emissions regarding the burning of fossil fuels per unit of energy output for diesel and heating oil, coal (anthracite), gasoline (without ethanol), propane, and natural gas are around 163.45, 228.60, 155.77, 138.63, and 116.65 pounds/Btu, respectively (Alhuyi et al., 2022). When comparing fossil fuels to hydrogen energy, it is cleaner than the others. Hydrogen is used for different purposes, like power generation, transportation, heating, and other alternatives in recent years to accelerate the decarbonization strategies (Parra et al., 2019). On the other hand, nowadays hydrogen has been started to use as fuel in internal and external combustion engines due to its low emission of harmful gases (Guilbert and Vitale, 2021; Johnston et al., 2005). That is why hydrogen and other fuels could be mixed in the combustion chamber to solve the $CO_2$ emission problem (Gültekin and Ciniviz, 2023).

From an especially environmental point of view, the advantages of using hydrogen with other fuels in the combustion chamber of GTs can reduce greenhouse emissions. By using hydrogen with conventional fuels, can affect the performance of GTs through operating conditions and system configuration. In this paper, hydrogen and natural gas burned in a combustor chamber have been analyzed to understand the performance of hydrogen-fired GTs.

## II. MATERIAL AND METHOD

### *A. Type of Combustion Chambers in Gas Turbines*

Under normal operating conditions, gas turbines draw fresh air from an inlet guide vane (IGV) located at the turbine inlet to regulate the air flow rate. It adjusts the flow rate of the air entering the turbine in accordance with the power output. After that compressed air (compressed in the compressor side) is mixed with fuel in the combustion chamber, where ignition occurs, resulting in a significant increase in thermal energy. The high-pressure and high-temperature combustion gases produced in the combustor are subsequently directed toward the turbine section. In the turbine, the expansion of these hot gases generates mechanical energy by rotating the turbine blades, which in turn drives the generator shaft to produce electrical power, as illustrated in Figure 2 (Toklu et al., 2019). After passing through the turbine, the exhaust gases exit the system at relatively lower pressure and temperature. In simple-cycle gas turbines, these exhaust gases are typically released into the atmosphere. However, in combined-cycle power plants, the exhaust gases are utilized to recover additional energy. In such systems, the hot exhaust gases are used to heat demineralized water in a heat recovery steam generator (HRSG), producing steam.

The generated steam then drives a steam turbine to generate additional electricity. This combined-cycle configuration significantly enhances the overall efficiency and power output of the plant.

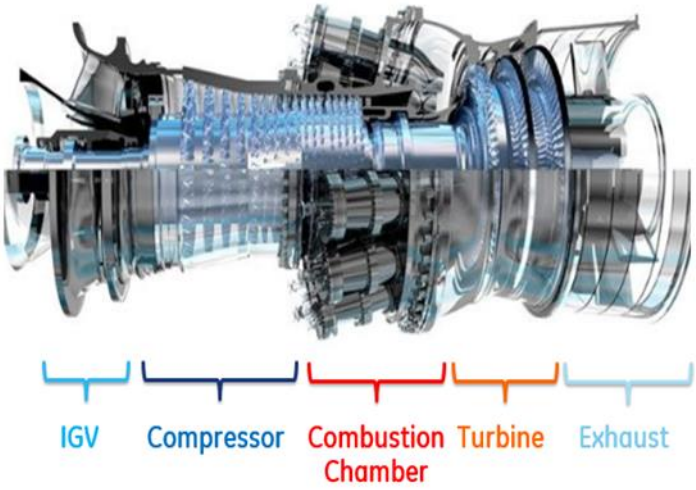


Figure 2. Gas turbine view (Toklu et al., 2019).

Regarding the design shown an intensive figure after the inlet compressor section starts, in normal conditions, two types of compressors consist of centrifugal compressors and axial compressors. Blades are used for compressing air. The shapes of the blades are designed with regarding to the flow of the air path. They are fixed on the disc and coupled together like a shaft. They compress the fresh air for a feeding combustion chamber (Gerengi and Polat, 2022).

The combustion system consists of several parts. Fuel is managed from the fuel nozzles and guided into the chamber. If the fuel and air are mixed into the chamber, this means a non-premix chamber. If fuel and air mix out of the chamber and are guided to the combustion, this means premix. The fuel-air mix ignites with electric igniters or spark plugs. After the burn reaction starts, the combustion process is self-sustaining as long as fuel and air are available. There are two types of combustion chambers, annular and can-annular. Figure 3 (Meher-Homji, 2007) shows the parts of the GE gas turbine can-annular combustion chamber.

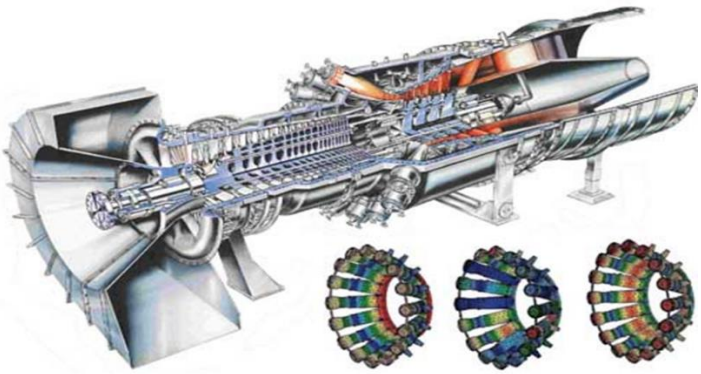

Figure 3. Can-annular type combustion chamber (Meher-Homji, 2007).

Some manufacturers did some design changes, and instead of a can-annular combustion chambers they use an annular combustion chamber. Instead of 18 or 16 combustion chamber there is just one combustion chamber around the unit shown in Figure 4 (Ansaldo, 2024).

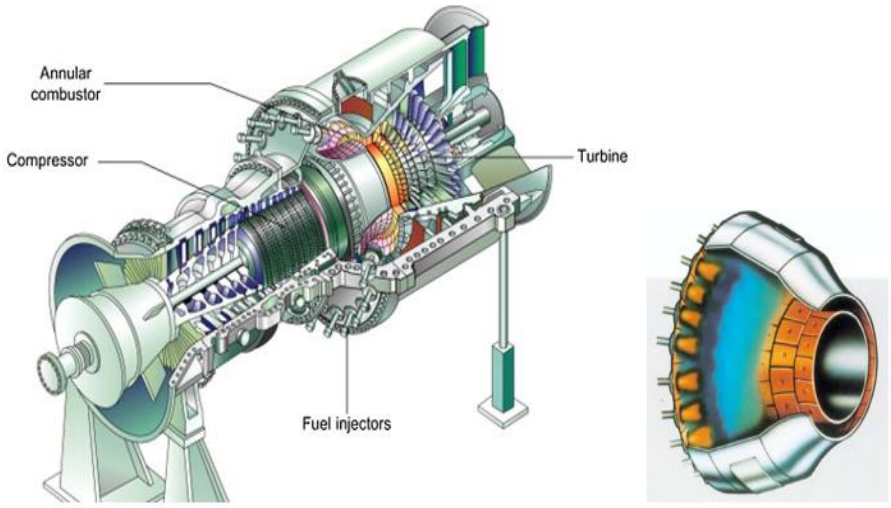


Figure 4. Annular-type combustion chamber (Ansaldo, 2024).

Annular-type gas turbines seem simpler than can-annular types regarding maintenance activities. These types of units need 25,000 and 50,000 EOH (operation hours) maintenance activities. At 25,000 maintenance hot gas path parts are replaced. The next outage for 50,000 EOH outage all hot gas path parts and some compressor parts are replaced. Otherwise, chamber materials and turbine side blades start to burn.

*B. Analysis Method*

GTs can use natural gas, coal, and oil as fuel to produce power generation. These types of fuels can cause emissions of greenhouse gases, such as $NO_x$, carbon monoxide, and carbon dioxide. Several approaches have been applied to solve or minimize the environmental problem related to fossil fuel-using GTs. Renewable energy sources, like solar, wind, and heat recovery boilers for preheating from exhaust gases, are a few alternative methods. In addition, changing the fuel type or modifaying alternative fuels can decrease the emission of greenhouse gases. Hydrogen is one of the alternative fuels. Regarding Table 1 below, the properties of hydrogen are better than those of the other fossil fuels.

Table 1. View of Marc V unit start.

| | **Diesel** | **Gasoline** | **Methane** | **$H_2$** |
|---|---|---|---|---|
| Density (kg/m$^3$) | 830[I] | 730-780[I] | 0.72[I] | 0..89[I] and 71[II-III] |
| Stoichiometric air demand $L_{st}$ ($kg_{air}/kg_{fuel}$) | 14.5 | 14.7 | 17.2 | 34.3 |
| Lower heating value (MJ/kg) | 42.5 | 43.5 | 50 | 120 |
| Boiling temperature[III](˚C) | 180-360 | 25-215 | -162 | -253 |
| Ignition limits[IV] (λ) | 0.5-1.3 | 0.4-1.4 | 0.7-2.1 | 0.14-10 |
| Minimum ignition energy [III,IV,V] (Mj) | 0.24 | 0.24 | 0.29 | 0.02 |
| Self-ignition temperature ($^0$C) | ~250 | ~250 | 595 | 585 |
| Specific heat ratio [III,VII] (γ) | | 1389 | 1354 | 1401 |
| Laminar flame speed [IV,V](cm/s) | 40-80 | 40-80 | 40 | 200 |
| Quenching distance [III,IV,V] (mm) | | 2 | 2.03 | 0.64 |
| Carbon content (Mass-%) | 86 | 86 | 75 | 0 |

I at 1.013 bar, 0 ˚C; II at -253 ˚C; III at 1.013 bar; IV in air; V λ=1; VI at 20 ˚C; VII at 300 K

In this study, hydrogen is introduced into the natural gas fuel stream under typical operating conditions of the gas turbine system. The primary objective is to investigate the influence of hydrogen enrichment on flame behavior within the combustion chamber. The incorporation of hydrogen as a supplementary fuel may require adjustments in key operating parameters such as mass flow rate, pressure ratio, and fuel–air mixing conditions. In addition, the combustion characteristics associated with

hydrogen may necessitate structural modifications in certain combustor components to ensure stable and safe operation.

However, the present study focuses on the analysis of the existing combustion system without implementing structural modifications. Instead, the current combustor configuration is evaluated to assess its performance under hydrogen-enriched fuel conditions, and recommendations for potential improvements are proposed based on the simulation results. In the numerical analysis, hydrogen is introduced through either the pilot fuel line or the premix line, depending on the operating scenario. All simulations are performed using operational parameters and boundary conditions derived from real field operating data to ensure that the results reflect realistic gas turbine operating conditions.

### *C. Collecting Data*

This research was conducted on an annular-type combustion chamber of a gas turbine currently operating under real field conditions. The gas turbine considered in this study belongs to a heavy-duty industrial class (e.g., Siemens, GE, Mitsubishi, or similar manufacturers) with a power output of approximately 280 MW or less. Operational data were collected from multiple monitoring sources during normal plant operation. The use of real operational data significantly increases the practical relevance and reliability of the study. As is well known, studies conducted solely under laboratory conditions may not always accurately represent real operating environments. This discrepancy can lead to various challenges when the system is implemented under actual field conditions. Therefore, in this study, operational parameters were obtained directly from the running gas turbine unit. These parameters were then used as boundary conditions for the numerical analyses in order to reflect realistic operating scenarios. Operational data can be obtained from various plant monitoring and control systems. These operational programs enable continuous monitoring, recording, and analysis of key performance parameters during the turbine's operation. As illustrated in Figure 5 the GE (General Electric) Marc V control system is shown.

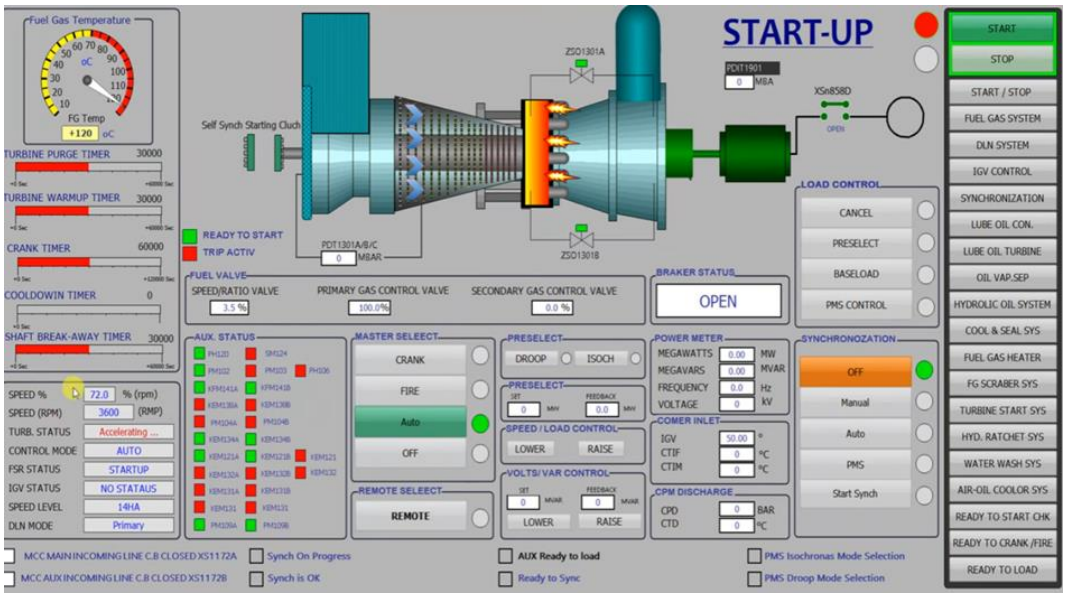


Figure 5. View of Marc V unit start.

The natural gas system view is seen in Figure 6 (Siemens T3000 fuel gas control system). The system consists of control valves, flow meters, pressure gauges, and temperature gauges. All these pieces of equipment are used for system safety and control. Control valves are hydraulic, electrical, or pneumatic and they open and close the valves according to the power request from the control logic. If they received a signal from the system to take the load the system automatically opens the valves regarding the gas request.

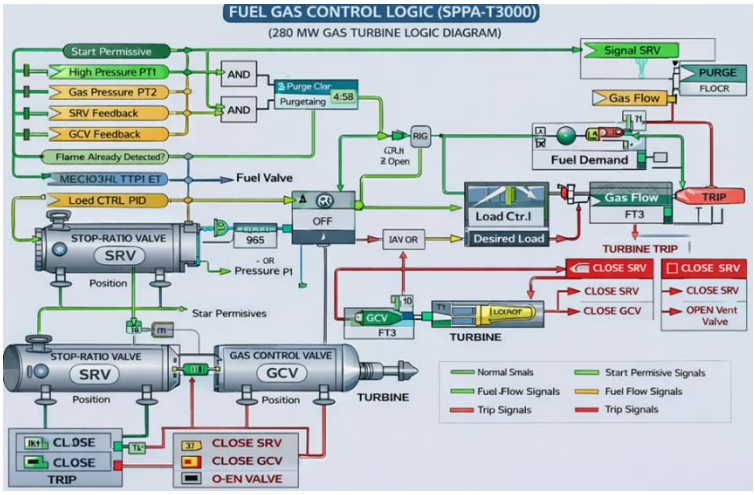


Figure 6. Siemens T3000 gas turbine fuel gas control system.

After natural gas burns in the combustion chamber, the exhaust gases pass through the gas turbine exhaust. In these waste gases, there are some gases that harm nature. One of them is NO and CO. As it is known, $NO_x$ values and CO values in existing systems are very harmful to nature. Therefore, the use of $H_2$, which is an alternative energy source, comes to the force for use in the system. CO and NO values are automatically measured in the system. In this study, the CO and $NO_x$ values resulting from the use of $H_2$ will be compared with the values in the current system. Figure 7 shows the points where the field values are taken. In Figure 7, $NO_x$ and CO values have been taken from Emission monitor units. These values are connected directly to the chimney and measured automatically.

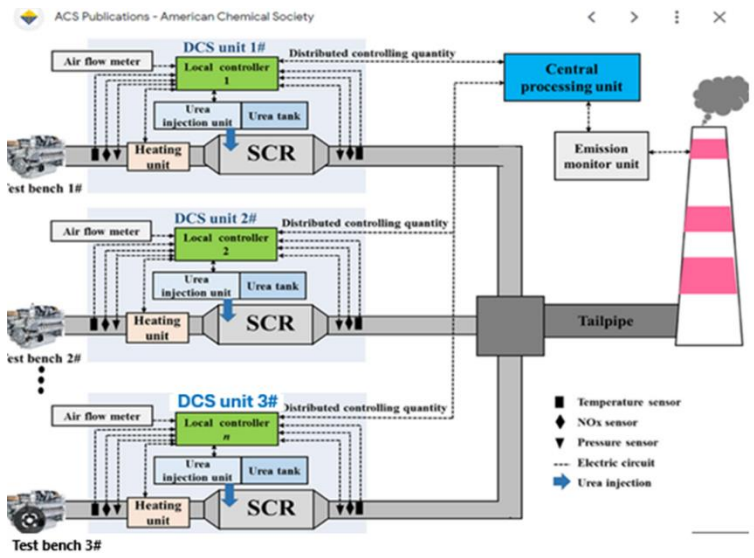


Figure 7. $NO_x$ and CO are measured from the system.

*D. Model Description and Simulation Details*

As can be seen in Table 2, the main natural gas is fed from the premix line. The Premix line is the main line for feeding the natural gas. Table 2 shows the flow rate of the gas with respect to the power output of the gas turbines. On the other hand, for getting the best solution for this study, values have been taken from different power plants. This issue makes the study of the application of the different power plant that has the annular-type combustion chamber. Most of the power plant operating conditions are similar to each other.

In order to balance the combustion event, in most of the power plants, a low amount of natural gas is fed from the second pilot line during operation. This process makes the combustion stabilization. During

the simulation studies, $H_2$ gas will be fed from the second line depending on the situation. If this line is not sufficient, reinforcement will be made directly to the premix line.

Table 2. Current values of the power output.

| **Power Output (MW)** | **245 MW** | **250 MW** | **260 MW** | **266 MW** |
|---|---|---|---|---|
| Premix Fuel Mass Flow Gas Request(kg/s) | 12.24 | 12.54 | 12.88 | 12.99 |
| Fuel Gas Pressure Premix Header (bar) | 19.90 | 20.18 | 19.98 | 20.55 |
| CV Pilot 1 Gas Mass Flow (kg/s) | 0.0 | 0.0 | 0.0 | 0.0 |
| CV Pilot 1 Gas Pressure (bar) | 16.94 | 17.22 | 17.22 | 17.87 |
| Pilot 2 Gas Flow Mass (kg/s) | 1.14 | 1.11 | 1.16 | 1.19 |
| Fuel Gas Pressure Pilot 2 Header (bar) | 16.29 | 16.78 | 17.15 | 17.22 |
| CO Emission Measure (ppm) | 0.770 | 0.770 | 0.772 | 0.770 |
| NOx Emission Measure (ppm) | 15.946 | 13.948 | 17.773 | 18.943 |

An annular-type combustion chamber is chosen for analysis in this study. There are 24 fuel nozzles around the chamber that will be simulated. They are distributed symmetrically around the combustion chamber, and each one has its own gas pipe connection. At each gas pipe connection, one is the main natural gas connection, the other one is the premix pipe connection, and the last one is the pilot pipe connection. During the simulation the premix line is going to be used for natural gas feed connections, and the pilot line is going to be used for hydrogen connections.

The basic dimensions and geometry of the annular-type combustor chamber are shown in Figure 8. The size of the combustor is 1215 mm in the X direction and 939 mm in the Y direction. The 3D model required for CFD Fluent is modeled by using the SolidWorks design module. The model is imported into ANSYS for further modifications.

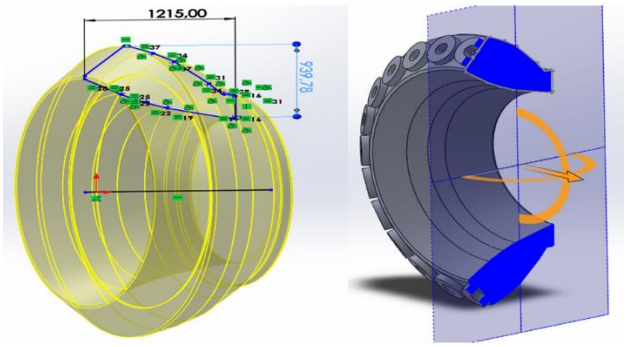


Figure 8. Size of the combustion chamber.

D.1. Meshing The Model

The mesh is generated using an orthogonal-type element with a fine element size. The meshing parameters of the combustion chamber for solving the model using the Fluent combustion code are given in Table 3. Into the Mesh process, the complex volume breaks into small segments for better solution simulation. As a definition of the Mesh, it is consists of cells and points. The geometry can have any size, and shape and Partial Differential Equations is used to solve complex shapes. For better analysis solutions, a high mesh quality is needed. The Mesh is done in the ANSYS program and shown in Figure 9.

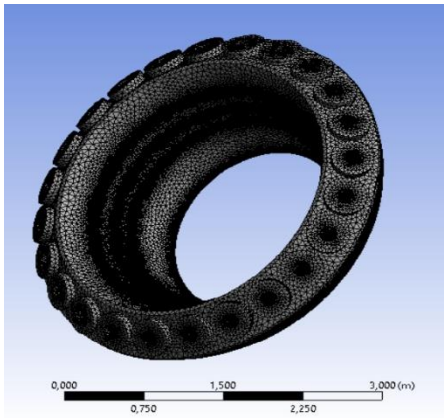


Figure 9. Size of mesh.

Table 3. Values of the mesh

| | |
|---|---|
| Nodes | 652698 |
| Mesh Metric | Orthogonal Quality |
| Elements | 3424630 |
| Volume | 5,3607 $m^3$ |
| Surface Area | 2,5826$m^2$ |
| Part Tolerance | 0,00000001 |
| Type of parts | Geometry (chamber) |

D.2. Model Domain

The model domain consists of three inlets: one for natural gas ($CH_4$), one for hydrogen ($H_2$), and the last one for air shown in Figure 10. All boundaries have been defined in ANSYS. Dimensions and other applications have been done regarding real gas turbine annular-type combustion chambers. [34].

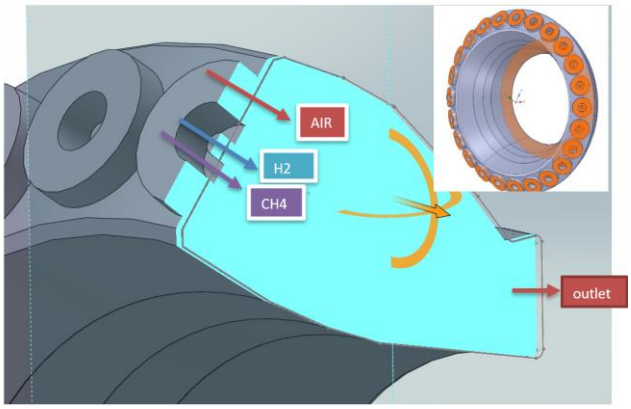


Figure 10. Fuel enters and is used in the chamber

In the chamber, there are 24 fuel nozzle surrounds, and they are controlled by numeric valves. Computer-aided controlled numeric valves controlled the amount of air, natural gases, and hydrogen. Normally, there isn't any hydrogen used on the unit, but the pilot entrance of the line has been used for hydrogen to perform the ANSYS simulation.

D.3. Simulation Parameters

Simulation parameters have been taken regarding real side conditions from the different power plants. That is why this study is very realistic and fact-related to the side conditions. The parameters are seen in Table 4. A simulation has been done regarding non-premix flame conditions. As seen in Figure 10, fuel and air are not mixed before the combustion, and they are mixed within the combustion chamber. That is why this kind of flame is called a non-premix flame.

Table 4. Simulation parameters

| **Modal** | **Non-Premix** |
|---|---|
| Fuel | Methane ($CH_4$) |
| Fuel | Hydrogen ($H_2$) |
| Mass flow of $CH_4$ (kg/s) | 0.51 for each nozzle (92%) |
| Mass flow of $H_2$ (kg/s) | 0.04 for each nozzle(8%) |
| Mass flow of air (kg/s) | 8.46 (Standard of the manufacturer) |
| The pressure of $CH_4$ (bar) | 21 |
| The pressure of $H_2$ (bar) | 17 |
| Tempereture of $CH_4$ (˚C) | 95 |
| The temperature of $H_2$ (˚C) | 32 |
| The pressure of the air inlet (bar) | 18 |
| The temperature of the air inlet (˚C) | 450 |
| ANSYS Fluent Launch | 3D Double Precision |
| Viscous | k-omega |
| Radiation | P1 |
| Heat Exchanger | off |
| Species Modal | Non-Premixed Combustion |
| Energy Treatment | Non-Adiabatic |
| Specify Fraction | Mass Fraction |
| Flamelet-mixture | C, H, O, N |
| Cell Zone | Combustion |
| Radiation | P1 |
| Iteration | Hybrid |
| Unit | SI Units=m, C, Kg/s, m/s, bar |

D.4. Computational Fluid Flow Simulation

The computational fluid dynamics (CFD) analysis was carried out using ANSYS Workbench Fluent to investigate the flow, combustion, and emission characteristics within the gas turbine combustion chamber. The three-dimensional geometry of the combustor was created in SolidWorks and subsequently imported into the ANSYS environment. Following the geometry transfer, a high-quality computational mesh was generated and refined to ensure numerical accuracy and solution stability. Special attention was given to mesh quality parameters such as skewness and element distribution in critical regions, particularly near the fuel injection and combustion zones. Regarding the side condition, a maximum of 8% $H_2$ and 92% of $CH_4$ are used for the analyses. Under normal field conditions, an 8% $CH_4$ mixture is used in the pilot pipeline section to ensure stable combustion. In our study, $H_2$ was supplied via the pilot pipeline instead of this 8% $CH_4$ mixture. This situation is more realistic for side- running conditions. During the analyses temperature, pressure, velocity, mass flow, and other parameters have been checked. All these values have been shown in Figure 11.

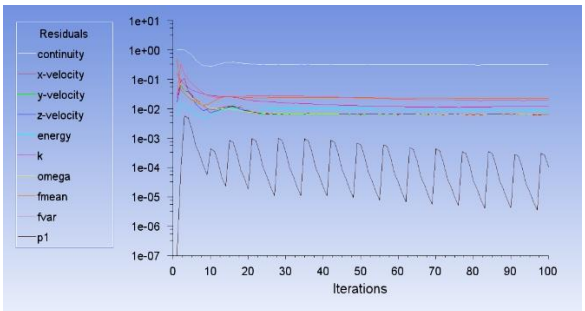


Figure 11. Iteration values of calculated parameters.

As seen on the graphic, x, y, z velocity, energy, fraction, k, and other values have been calculated on the ANSYS Workbench Flow program. Graphics are very slight, and this means that all calculated values

are real values and match each other in a continuous way. A three-dimensional, steady-state simulation approach was adopted under double precision settings to enhance the accuracy of the numerical solution. The governing equations for mass, momentum, and energy conservation were solved using the finite volume method. Turbulent flow behavior was modeled using an appropriate turbulence model (e.g., k–ε model), which is widely used for industrial combustion applications due to its robustness and computational efficiency.

The most important parameters for pollutants like $NO_x$ and $SO_x$ have been checked. These parameters have been compared with parameters that used $H_2$ as fuel. As it is known NO, and SO consist of nitrogen and peroxidant chemicals that pollute the environment. That is why such values have to be dropped regarding environmental threat conditions. See Figure 12.

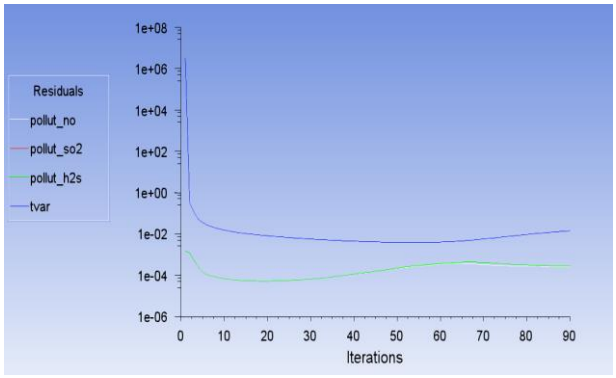


Figure 12. Pollutant values.

The $NO_x$ value is about 0.0113 ppm, and the CO value is about 0.101 ppm. These results show that the values can be decreased further by adjusting the values of hydrogen and natural gases.

The results obtained from the CFD simulations were analyzed to assess the influence of hydrogen enrichment on flame characteristics, combustion efficiency, and emission reduction potential. This methodology provides a reliable framework for evaluating alternative fuel strategies in existing gas turbine combustion systems.

## III. RESULTS AND DISCUSSION

All parameters, such as temperature, pressure, mass fraction of hydrogen, and mass fraction of natural gas, have been analyzed. The results have been evaluated.

### *A. Total Temperature*

The temperature of the combustion chamber has been increased after using hydrogen 2160 ˚C. The result is shown in Figure 13.

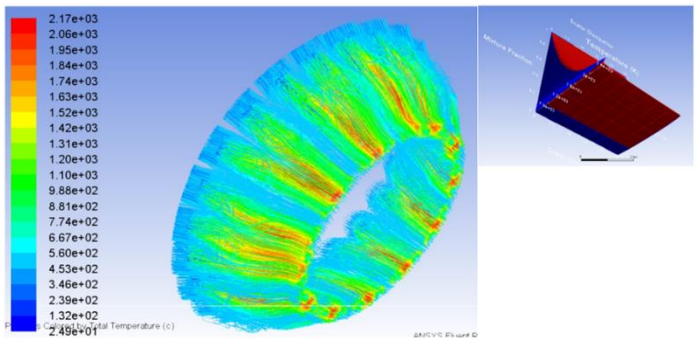


Figure 13. Total temperature.

An increase in temperature is a good result for converting mechanical energy to electrical energy in the turbine section. At normal operating condition, the combustion chamber temperature is about 1200 ˚C. The exhaust temperature is about 570 ˚C. If the combustion chamber temperature increases the exhaust temperature also increase. This means that the total combined cycle power will be increased.

*B. Velocity Profile*

The velocity value is shown in Figure 14.

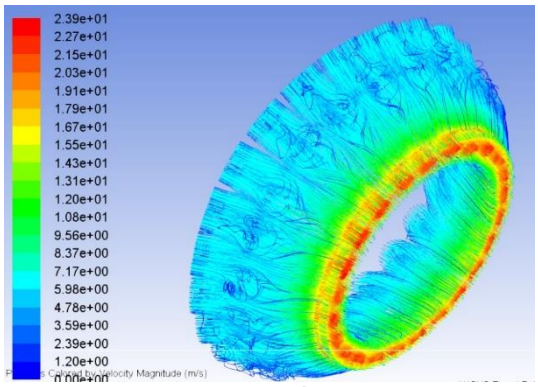


Figure 14. Velocity.

The velocity magnitude is about 24 m/s. This means that after the turbine section the velocity is going to increase and pass to the normal operating conditions. At normal operating conditions, the velocity of exhaust after the turbine section is about 52-55 m/s.

*C. Pressure Contours*

The pressure value is given in Figure 15.

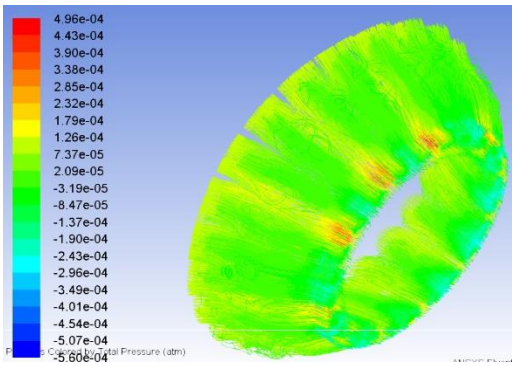


Figure 15. Total pressure.

At normal operating condition exhaust pressure after the turbine section is about 5 mbar. The calculated pressure before the turbine section is about 5 mbar. This means that the pressure is going to increase after the turbine section.

*D. Turbulent Intensity*

The Intensity of the turbulence regarding the simulation is shown in Figure 16.

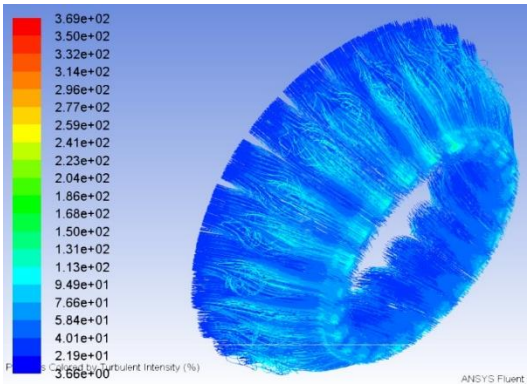


Figure 16. Turbulent intensity.

As seen in the figure, the flow is laminar and does not have any turbulence inside the chamber. The min Intensity is about 3.65%, and the max is 3.68%. These results show that the acceleration of the combustion chamber is very low. At normal operating conditions, if high turbulence increases in the chamber unit will trip regarding the acceleration.

## E. *Mass Fraction of Hydrogen*

The mass fraction of hydrogen in the simulation is shown in Figure 17.

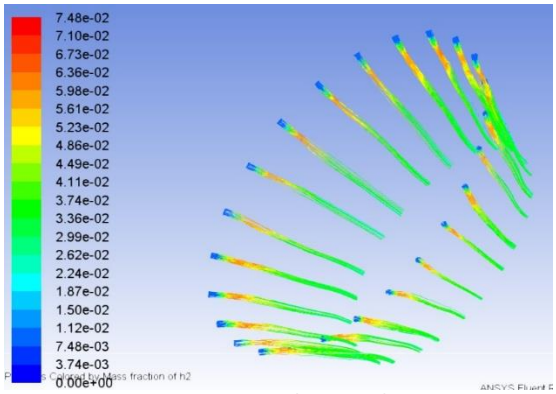


Figure 17. Mass fraction of $H_2$.

Min mass fraction of hydrogen is about 0.00, and the max is about 0.0747 kg/s

## F. *Mass Fraction of Natural Gas ($CH_4$)*

The mass fraction of $CH_4$ is shown in Figure 18. Mass fraction of $CH_4$ is about min:0 and max: 0.845 kg/s.

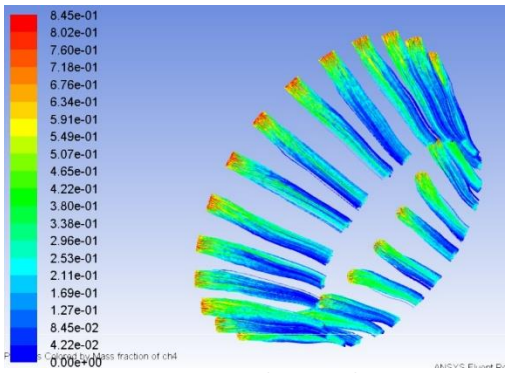


Figure 18. Mass fraction of $CH_4$

### *G. Mass Imbalance of Natural Gas ($CH_4$), Air, and Hydrogen ($H_2$)*

The mass imbalance of $CH_4$, $H_2$, and air is shown in Figure 19. The mass imbalance of air, $CH_4$, and $H2$ is about min: -2.91E-5 and max: 2.35 E-5 kg/s. This shows good results. If the mass balance is not sufficient, it means that we may have flame loss and acceleration. This balance can be adjusted from the regulation valves in the control system.

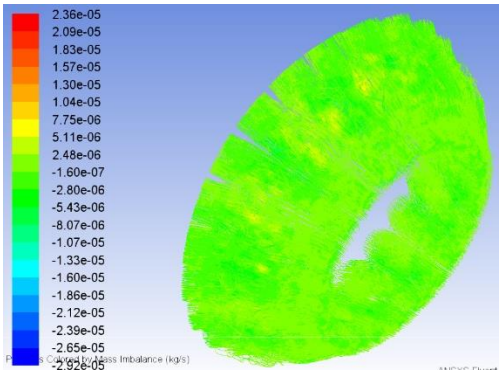


Figure 19. Mass imbalance of $CH_4$, $H_2$ and air.

### *H. Incident Radiation*

Incident radiation in the combustion chamber is shown in Figure 20. The incident radiation is about min: 255154 W/m$^2$ and max: 265139 W/m$^2$

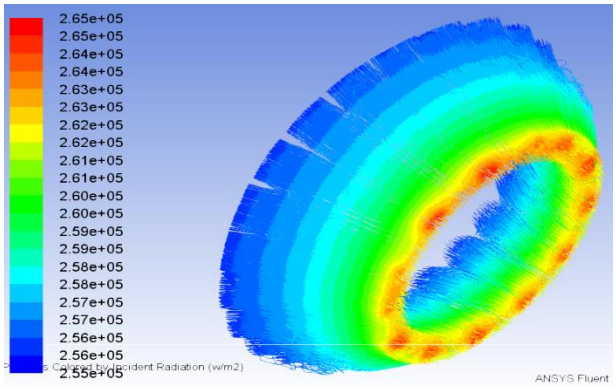


Figure 20. Incident radiation.

### *İ. Mass fraction of $CO_2$ (Carbon dioxide)*

The mass fraction regarding the calculated values is shown in Figure 21. $CO_2$ mass fraction is about min:0 and max: 0.103 ppm.

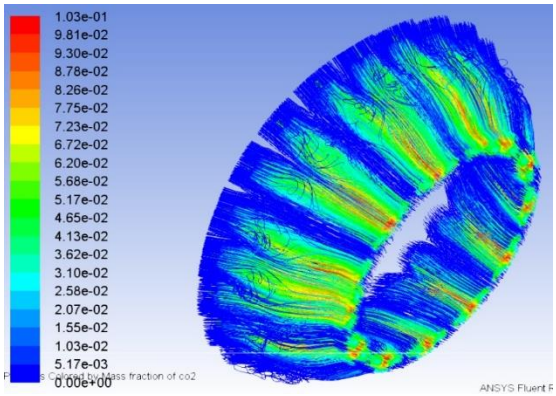


Figure 21. Mass fraction of $CO_2$.

### *J. Mass fraction of CO (Carbon Monoxide)*

The mass fraction regarding the calculated values is shown in Figure 22. CO mass fraction is about min:0 and max: 0.101 ppm.

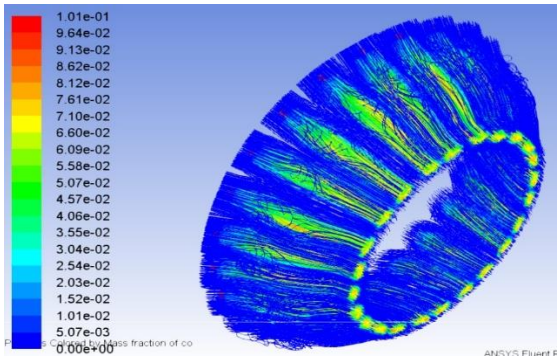


Figure 22. Mass fraction of CO.

### *K. Mass fraction of Pollutant ($NO_x$ and $SO_x$)*

The mass fraction regarding the calculated values for a pollutant is shown in Figure 23.

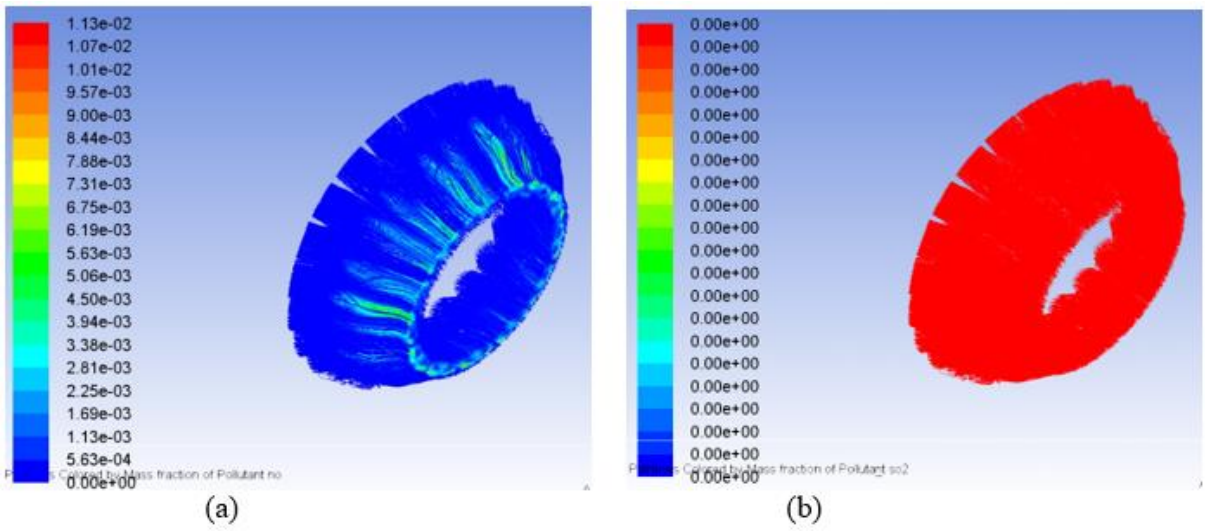


Figure 23. Mass fraction of pollutant a) $NO_x$, b) $SO_x$.

NOx (Nitrogen and oxygen) mass fraction is about min:0 and max: 0.0113 ppm. As seen in the figure, there is no pollutant for $SO_x$. If coal is used instead of $CH_4$, there may be a pollutant for $SO_x$.

## IV. CONCLUSIONS

Due to the environmental concerns associated with gas emissions from fossil fuels used in gas turbines, the use of hydrogen as an alternative fuel has been proposed in recent years. Numerous academic studies worldwide have investigated this issue. In the present study, the integration of hydrogen into natural gas-fired gas turbines has been reviewed. Standard operating conditions and baseline operational parameters were adopted for the analyses. Computational simulations were conducted using ANSYS Fluent. The key findings of the study can be summarized as follows:

- Adding hydrogen to the natural gas can decrease greenhouse gas emissions such as CO (carbon monoxide), $NO_x$, and SO regarding the simulation. NO value is about 0.0113 ppm, CO value is about

0.101 ppm, and SO value is 0 ppm. In normal operating conditions, the CO value is about 0.8825 ppm, and the NO value is about 35 ppm. As it is seen, the pollutant values remarkably decrease.

- Flame stability during the use of hydrogen is dependent on several factors, which are hydrogen enrichment and equivalence ratio. As it is seen in Figure 17, the mass fraction of air, hydrogen, and natural gases is in balance. If not, the combustion chamber will have acceleration, and the unit will trip regarding the protection system. The balance of the gases can be arranged by regulating the valves that are controlled by the DCS system. The value, pressure, and temperature of the gases can be regulated automatically by the control system.
- The internal combustion chamber temperature is increased when using hydrogen as an additional fuel. At normal operation conditions, the combustion chamber temperature is about 1200 $^0$C. Regarding the simulation, it increases by 2170 ˚C as the maximum value. This is expected. The hydrogen heating value, specific heat ratio, and laminar flame speed are higher than those of natural gas. These parameters increase the temperature. The temperature value can be decreased by decreasing the amount of hydrogen. Combustion chamber temperature increase can increase the mechanical energy. This means more mechanical energy will be converted to electrical energy in the turbine section.
- Combustion chamber temperature increase means high exhaust temperature will be transferred to the boiler. This issue is going to drop the time of water boil and gain more power from the steam turbine.
- As a simple approach, the addition of hydrogen as a fuel for the Gas turbines will affect the exergy efficiency of the system. The efficiency of the unit is going to increase by getting more power from the turbine section.
- The modification of the structure of gas turbine parts may be needed. Detailed analysis can be done on the structure. TBC (Thermal Barrier Coating) coating on the surface of the turbine blades may need modifications. As is seen in Figure 13, the total temperature increased by about 2160 ˚C. This means the turbine section temperature will be increased, and normal blade row materials may not be sufficient for the high temperature. They have been designed and manufactured for the 1200 ˚C of combustion chamber temperature.
- Using hydrogen in the gas turbine combustion chamber has many advantages regarding gas emissions and other parameters. As it is seen from the simulation, the natural gas uses may drop by adding hydrogen in the combustion chamber. The combustion chamber temperature increases and it gets more mechanical power from the turbine section. On the other hand, exhaust temperature increases and decreases the time the water boils. This means more power will be gained from the steam turbine side for the combined cycle of power plants.
- All these conditions show that hydrogen must be focused on for alternative energy in the future. The sources of the world are limited. That is why to save the environment, different works have to be done on more reliable alternatives. Energy is one of the top ten problems in the world.

## DECLARATIONS

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**Plagiarism Statement:** This article was checked by the plagiarism program. No plagiarism detected.

**Availability of Data and Materials:** The datasets analyzed during the current study are available from the corresponding author on reasonable request.

**Use of AI Tools:** The authors declare that Artificial Intelligence (AI) tools were used only for language editing and proofreading purposes. The authors take full responsibility for the content of the article.

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