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The Effect of Hydrogen Ratio on Flame Temperatures in the Methane Combustion Reaction in the Burner

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ABSTRACT

Nowadays, with the increasing energy demand and concerns about environmental sustainability, hydrogen is regarded as a crucial energy carrier in reducing dependence on conventional fuels. Hydrogen plays a critical role in various fields, particularly in fuel cells. Therefore, due to the undesirable effects of pure hydrogen usage on temperature and emissions, as well as the challenges and high costs of storage, efforts are being made to blend it with conventional fuels in varying proportions to achieve optimal combustion conditions. The aim of this study is to investigate the effects of adding hydrogen gas at different concentrations, without pre-mixing, to the methane combustion reaction inside the burner on flame characteristics. The combustion reaction of CH_4 was carried out with six different H_2 concentrations (0%, 5%, 10%, 15%, 20%, 25%), and it was observed that as the H_2 ratio increased, the flame temperature rose and its shape became more stable. The maximum flame temperature was recorded as 2732.248 K with 15% H_2. At 25% H_2, the mixture exhibited behavior similar to that of a rich combustion mixture. The burner used in this study provides an alternative solution in the field of hydrogen burners.

Brülör İçerisinde Gerçekleştirilen Metan Gazı Yanma Reaksiyonunda Hidrojen Oranının Alev Sıcaklıklarına Etkisi

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ÖZ

Günümüzde artan enerji talebi ve çevresel sürdürülebilirlik kaygıları ile birlikte konvansiyonel yakıtlara bağımlılığı azaltma sürecinde hidrojen önemli bir enerji taşıyıcısı olarak görülmektedir. Hidrojen, yakıt hücreleri başta olmak üzere birçok farklı alanda kritik bir görev üstlenmektedir. Bu sebeple saf hidrojen kullanımının sıcaklık ve emisyon değerleri üzerindeki istenmeyen sonuçları ve depolamasının zor ve maliyetli olması sebebiyle konvansiyonel yakıtlara farklı oranlarda karıştırılarak optimum yanma koşulları oluşturulmaya çalışılmaktadır. Bu çalışmanın amacı brülör içerisindeki metan gazı yanma reaksiyonuna, önceden karıştırılmadan ve farklı konsantrasyonlarda hidrojen gazı eklenmesiyle oluşacak alev spesifikasyonları üzerindeki etkisinin incelenmesidir. Altı farklı H_2 konsantrasyonunun (%0, %5, %10, %15, %20, %25) CH_4 gazı yanma reaksiyonu gerçekleştirilmiş, H_2 oranının artmasıyla alev sıcaklığının yükseldiği ve şeklinin daha stabil bir hale geldiği gözlemlenmiştir. Maksimum alev sıcaklığı %15 H_2 kullanılarak 2732,248 K olarak elde edilmiştir. %25 H_2 kullanımında karışımın zengin karışım gibi reaksiyon verdiği gözlemlenmiştir. Çalışmada kullanılan bu brülör geliştirilen hidrojen brülörleri alanına farklı bir çözüm sunmaktadır.

1. INTRODUCTION

Changing energy demands, rising costs and environmental concerns have made hydrogen, a sustainable energy carrier, a significant focus of scientific and industrial research. In recent years, advancements in hydrogen production, storage, and utilization have positioned it as a promising alternative to conventional fossil fuels. Hydrogen, the lightest element found in nature and whose properties are shown in Table 1 [1,2], is colorless, tasteless and odorless. Due to its high energy density and its ability to generate electricity with zero carbon emissions when used in fuel cells, it is considered a key component of future energy systems.

Hydrogen, which is bound to compounds such as water and fossil fuels on the earth, is 14.4 times lighter than air [3]. The energy per unit mass of hydrogen is approximately three times that of gasoline and seven times that of coal. A comparison of some properties of hydrogen with various conventional fuels is presented in Table 2 [4].

Table 1. Properties of hydrogen [1,2]

Boiling point	˚C	-252.87
Melting point	˚C	-259.14
Flash point	˚C	-253
Density	kg/m^3	Gas: 0.089, Liquid: 70
Ionization energy	eV	13.5989
Lower heating value-LHV	Mj/kg	118.8
Adiabatic flame temperature	˚C	2107
Flammability range in air	vol%	4.0-75.0
Laminar flame velocity	m/s	3.06
Auto ignition temperature	˚C	585
Research octane number-RON		>130

Table 2. Comparison of properties of hydrogen with other fuels [4]

Parameters	**Units**	**Hydrogen**	**Methane**	**Propane**	**Methanol**	**Ethanol**	**Gasoline**
Chemical Formula		H_2	CH_4	C_3H_8	CH_3OH	C_2H_5OH	C_xH_y (x=4-12)
Molecular Weight		2.02	16.04	44.1	32.04	46.07	100-105
Density (NTP)	kg/m^3	0.0838	0.668	1.87	791	789	751
	lb/ft^3	0.00523	0.0417	0.116	49.4	49.3	46.9
Normal Boiling Point	˚C	-253	-162	-42.1	64.5	78.5	27-225
	˚F	-423	-259	-43.8	148	173.3	80-437
Vapor Specific Gravity (NTP)	air=1	0.0696	0.555	1.55	N/A	N/A	3.66
Flash Point	˚C	<-253	-188	-104	11	13	-43
	˚F	<-423	-306	-155	52	55	-45
Flammability Range in Air	vol%	4.0-75.0	5.0-15.0	2.1-10.1	6.7-36.0	4.3-19	1.4-7.6
Auto Ignition Temperature	˚C	585	540	490	385	423	230-480
in Air	˚F	1085	1003	914	723	793	450-900

Hydrogen is an abundant and versatile energy carrier that can be derived from various organic and inorganic sources, including water, biomass, fossil fuels, and other hydrocarbon-based materials. At the present time, the main source of hydrogen production is natural gas. Steam methane reformers using natural gas play an important role in the production of special hydrogen in the methanol and ammonia industries [5]. Hydrogen energy, which can be produced by many methods, is one of the most researched energy sources today. It can be produced by heating from natural gas, coal, petrol, methanol, or biomass; by photosynthesis from bacteria and algae; by breaking down water with electricity or sunlight [1].

A key challenge in utilizing hydrogen as an energy carrier lies in efficiently and economically isolating it from naturally occurring compounds. Several methods have been developed for hydrogen production and extraction [6]. Steam methane reforming (SMR) is a well-established industrial process that enables hydrogen generation from hydrocarbons and water, accounting for approximately 95% of the hydrogen produced in the United States. Another widely used method is electrolysis, which involves the application of an electrical current to dissociate water into its constituent hydrogen and oxygen molecules. The electricity required for electrolysis can be derived from various energy sources, including fossil fuels, nuclear power, and renewable energy.

When hydrogen (H_2) undergoes combustion in the presence of oxygen (O_2), it releases energy and forms water (H_2O) as the only by-product (Equation 1). Due to the absence of carbon-based emissions, the energy produced from hydrogen combustion is often referred to as "clean energy".

$$2H_2\,(g) + O_2\,(g) \rightarrow 2H_2O\,(g) + \text{energy} \tag{1}$$

Methane (CH_4) is a hydrocarbon compound that exists as a gas under standard temperature and pressure conditions. It is colorless and odorless in its natural state and constitutes a major component of natural gas, serving as a significant energy source. The complete combustion of one mole of methane in the presence of oxygen (O_2) results in the formation of one mole of carbon dioxide (CO_2) and two moles of water (H_2O), releasing approximately 55.5 MJ/kg of thermal energy (Equation 2).

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + \text{heat} \tag{2}$$

The combustion reaction of a hydrogen-methane mixture can be expressed as shown in Equation 3, assuming that air consists of 20.9% oxygen and 79.1% nitrogen [7].

$$(1-f_{H2}) \text{ x } CH_4 + (f_{H2}) \text{ x } H_2 + [2 \text{ x } (1-f_{H2}) + f_{H2}/2] \text{ x } (O_2 + 3.76 \text{ x } N_2) \rightarrow$$
$$(1-f_{H2}) \text{ x } CO_2 + (2-f_{H2}) \text{ x } H_2O + [2 \text{ x } (1-f_{H2}) + f_{H2}/2] \text{ x } 3.76 \text{ x } N_2) \tag{3}$$

Methane is both a hydrocarbon fuel and a greenhouse gas (GHG), serving as the primary constituent of natural gas. Due to its significant global warming potential, methane plays a critical role in influencing the earth's temperature and climate system. It is emitted into the atmosphere from a variety of anthropogenic and natural sources [8].

In the summer of 2020, the German Federal Government implemented the “National Hydrogen Strategy”, aligning with the European Commission’s objectives outlined in the Green Deal. The Green Deal seeks to achieve a fundamental transformation of the energy system, with the goal of reducing CO_2 emissions by 40% by 2030 and establishing Europe as a climate-neutral continent by 2050. As part of this initiative, the production of clean hydrogen is projected to reach one million tons by 2024. Hydrogen is thus envisioned not only as a critical component in mitigating climate change and facilitating the energy transition but also as a catalyst for technological innovation and economic growth [9]. Experimental studies conducted on compression ignition engines have investigated the effects of hydrogen addition to diesel fuel on exhaust emissions. The findings indicate that the use of hydrogen-enriched fuel mixtures leads to an increase in NOx emissions (nitrogen oxides), while a noticeable reduction in CO_2 emissions is observed [10,11].

Hydrogen burners exhibit a more complex structural design compared to conventional burners due to the distinct combustion characteristics of hydrogen. Several key specifications must be considered in their design to ensure efficient and reliable operation:

- **Enhanced flame stability** to accommodate the high reactivity of hydrogen.
- **High resistance to thermal damage**, given the elevated combustion temperature.
- **Compatibility with low-calorific secondary gas supplies**, ensuring operational flexibility.
- **Suitability for industrial applications**, providing durability and efficiency in high-demand environments.

A hydrogen burner should be designed individually or in conjunction with whatever fuel it is used for. Its material has to be resistant to high temperatures that will be released during combustion [12].

Toyota Motor Corporation has developed a versatile hydrogen burner designed for industrial applications [13]. In this study, the company successfully reduced the flame temperature by lowering the oxygen concentration to 19% during the primary combustion process, as illustrated in Figure 1.

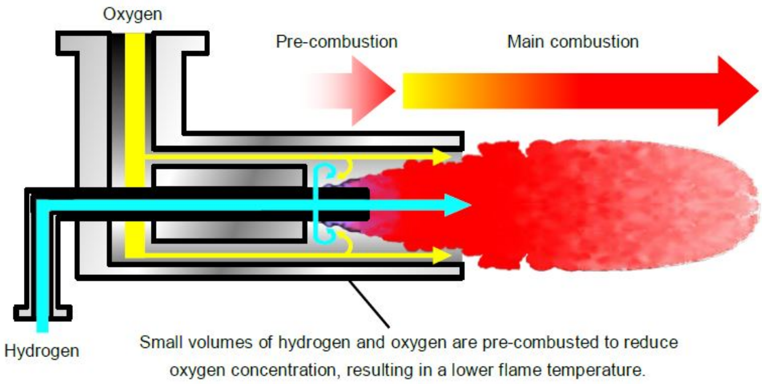


Figure 1. Toyota hydrogen burner [13]

To prevent fully mixing small holes are opened in the pipes that supply hydrogen to the burner. The new burners have greatly reduced NOx emissions (Figure 2).

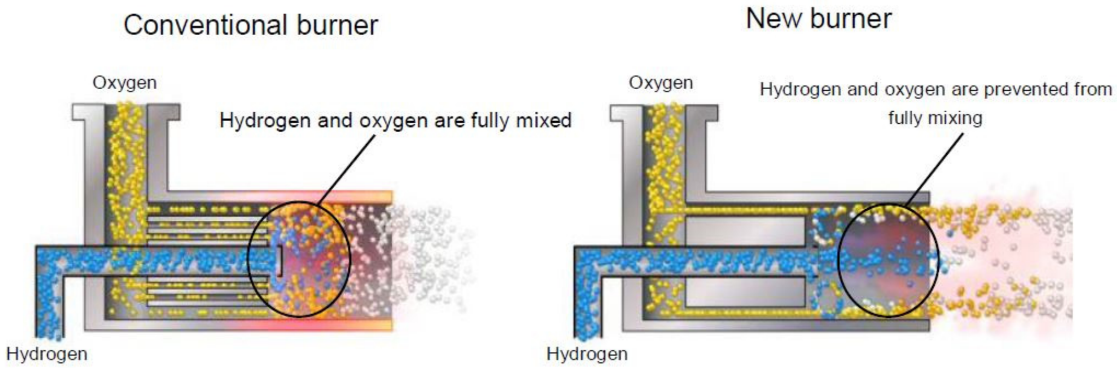


Figure 2. Difference between the conventional and new burner [13]

It is observed in the literature that studies on natural gas-hydrogen mixtures have intensified. In a study conducted on a conventional spark ignition engine, coke oven gas (COG) with high volumetric percentages of H_2 and CH_4 was compared with pure hydrogen and methane, yielding performance and emission results comparable to those of the pure gases [14]. In another study, the combustion of biogas-hydrogen mixtures was investigated in a conventional 100 kW natural gas burner. To improve flame stability, the biogas was enriched with hydrogen from 5% to 25% [15]. An integrated system has been designed to produce green hydrogen and blend it with the natural gas reserves potentially found in the Black Sea region of Turkey. Through this system, it has been observed that incorporating up to 20% hydrogen into the system reduces annual natural gas consumption, thereby extending the lifespan of the discovered reserves. Additionally, increasing the hydrogen ratio further has been found to reduce CO and CO_2 emissions while leading to an increase in NOx emissions [16]. In a study on a hydrogen-methane fuel blend used in a domestic boiler, it was observed that increasing the hydrogen content from 0% to 30% resulted in a rise in combustion chamber temperature [17]. Another study investigating the laminar burning velocities of hydrogen-air and various hydrogen-methane-air mixtures found that increasing the hydrogen concentration in the hydrogen-methane mixture enhanced the burning velocity and widened the flammability limits. This study also demonstrated that a 30% hydrogen and 70% methane gas mixture could serve as an alternative fuel for existing combustion systems [18].

Studies in the literature have generally been conducted on conventional combustion systems such as internal combustion engines, domestic natural gas boilers, and gas turbines, with hydrogen-methane mixtures typically utilized in a premixed configuration. For this reason, this study was conducted not on a conventional burner, but on a specially designed burner with the potential for industrial application. Furthermore, while previous experiments have predominantly employed premixed combustion, in this study, the burner was operated under non-premixed conditions in order to observe and evaluate the resulting performance and combustion characteristics.

2. MATERIAL AND METHOD

2.1. Burner Selection and Modeling

The selection of burners necessitates the consideration of various criteria, including fuel type, burner capacity, burner efficiency, combustion chamber dimensions, burner counter pressure, flame length and diameter, and altitude. Additionally, the mode of fuel combustion—whether with air or pure oxygen—plays a critical role in burner performance. When fuel combusts in the presence of air, the process is referred to as air-fuel combustion, whereas combustion with pure oxygen is termed oxy-fuel combustion. The oxy-fuel combustion technique results in a significantly higher flame temperature compared to air-fuel combustion. However, this elevated temperature may lead to excessive heating of the burner and combustor walls, potentially causing structural degradation. To mitigate this issue, burners should be constructed using materials capable of withstanding high temperatures associated with oxy-fuel combustion [19].

In this study, a specially designed burner suitable for the methane-hydrogen combustion reaction was used. This burner has dimensions of 100×500 mm and features one methane inlet, two hydrogen inlets, and two air inlet ports. As schematically illustrated in Figure 3, the burner is made of a high-temperature-resistant material, ensuring appropriate test conditions.

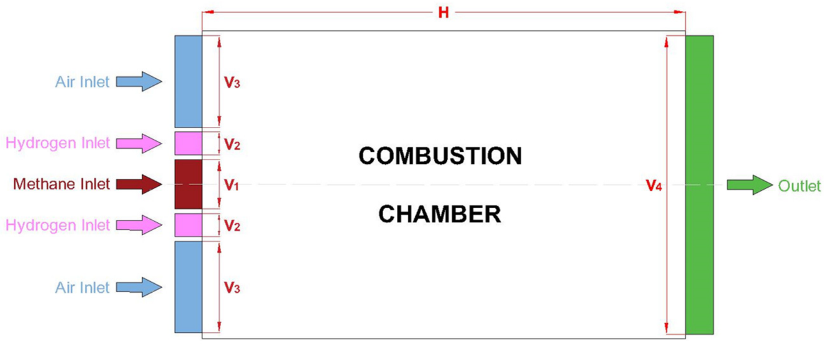


Figure 3. Schematic model of burner for non-premixed combustion

Investigations were conducted on the flame temperatures resulting from the addition of hydrogen at six different concentrations (0%, 5%, 10%, 15%, 20%, 25%) to the methane combustion reaction. Additionally, ten equidistant points along the burner axis, as schematically illustrated in Figure 4, were identified. Temperature variations at these points were observed, and relevant interpretations were made based on the obtained results.

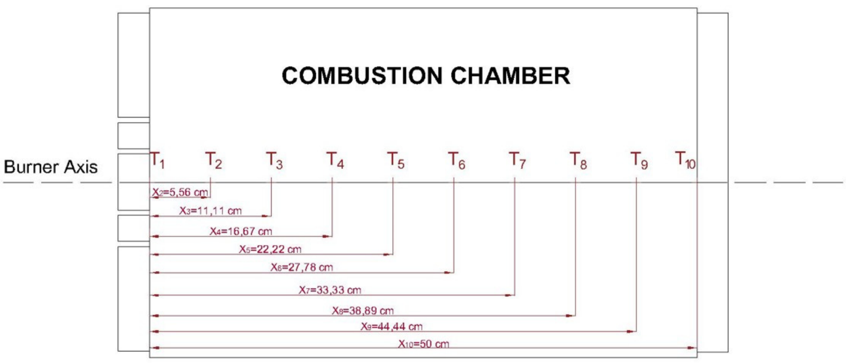


Figure 4. Schematic model of distance on the burner axis

2.2. Numerical Solution

All numerical calculations for this specially designed burner have been conducted using the Ansys Fluent CFD (Computational Fluid Dynamics) software. CFD software, based on the Navier-Stokes equations, is a computational modeling and simulation approach used to analyze fluid flow and heat transfer phenomena. Its applications include assessing combustion stability, regulating combustion rates, and characterizing flame dynamics [20].

A mesh is divided into smaller cells with this property to accurately represent the geometry of the object being simulated in the CFD program. Higher-quality mesh enables more precise and realistic results. The mesh structure of the combustion chamber, as illustrated in Figure 5, was determined based on the grid independence test presented in Figure 6. For the case with 18 divisions at the methane inlet, the mesh consists of 162162 nodes and 161000 elements.

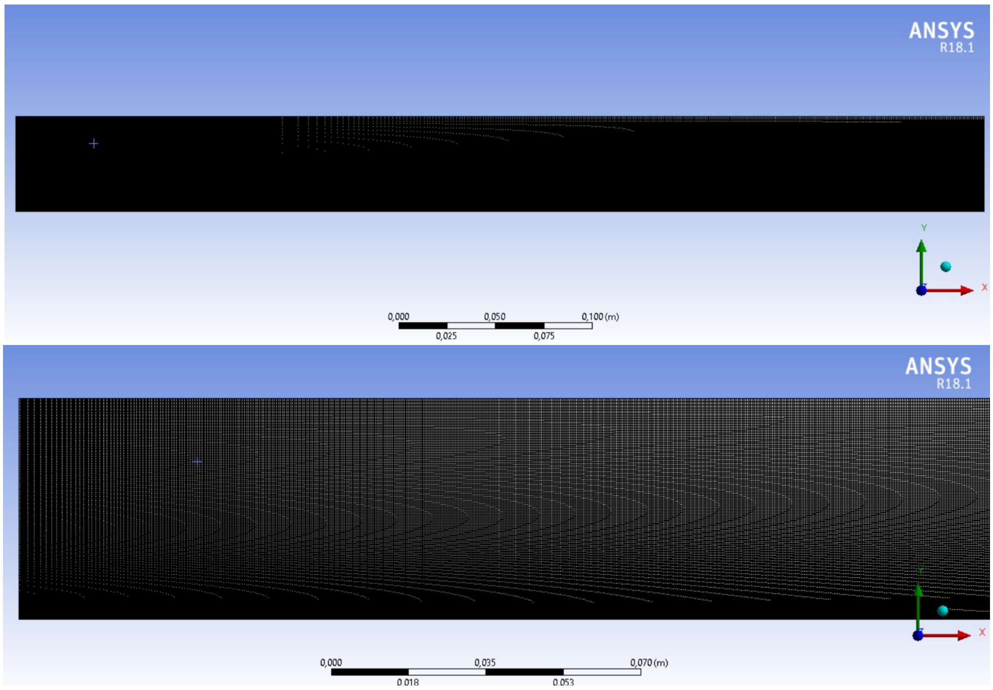


Figure 5. Mesh structure overview

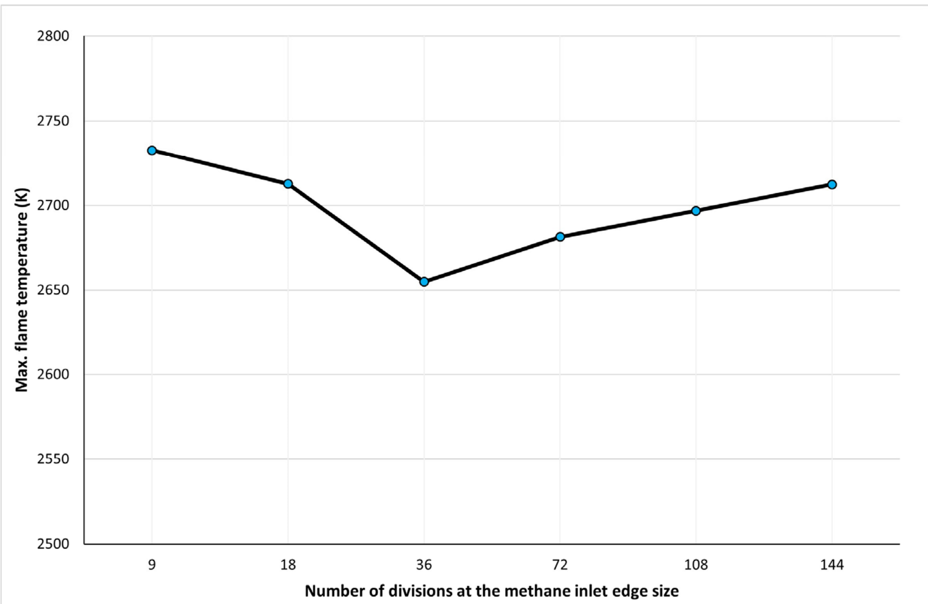


Figure 6. Grid independence test

In the numerical analysis, the realizable k-ε turbulence model (Equations 4 and 5) was used, as it more accurately predicts the spreading rate of jets with different structures (planar and circular). The term "realizable" indicates that the model satisfies specific mathematical constraints on the Reynolds stresses, ensuring consistency with the physics of turbulent flows. In contrast, neither the standard k-ε model nor the RNG k-ε model is realizable [21]. Furthermore, the P1 radiation model was employed in the study to achieve computational efficiency and enhanced numerical stability.

The realizable k-ε model is considered more practical for industrial applications due to its improved accuracy and closer alignment with physical reality compared to other turbulence models [22]. It is frequently preferred in high-temperature combustion flows such as burner design, combustion chambers, and gas turbines. Studies have shown that the realizable model delivers the best performance among the k-ε model variants in validating separated flows and flows with complex secondary flow features [21]. However, it falls short in scenarios involving near-wall flow details and laminar-to-turbulent transition, where other models may perform better [23]. Two-equation turbulence models are also limited in their ability to capture the subtle relationships between turbulent energy production and turbulent stresses caused by anisotropy in normal stresses [24]. Another limitation of the realizable k-ε model arises in domains involving both rotating and stationary fluid regions, where it may produce non-physical turbulent viscosities [21].

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}(\rho k u_j) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\varepsilon - Y_M + S_k \tag{4}$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_j}(\rho \varepsilon u_j) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + \rho C_1 S\varepsilon - \rho C_2 \frac{\varepsilon^2}{k+\sqrt{\nu\varepsilon}} + C_{1\varepsilon}\frac{\varepsilon}{k}C_{3\varepsilon}G_b + S_\varepsilon \quad \text{where}$$
$$C_1 = max\left[0.43, \frac{\eta}{\eta+5}\right], \eta = S\frac{k}{\varepsilon}, S = \sqrt{2S_{ij}S_{ij}} \tag{5}$$

The simulation was conducted under steady-state conditions. The fundamental governing equations are provided as follows: the conservation of mass (continuity) in Equation 6, the conservation of momentum in Equation 7, the conservation of energy in Equation 8, and the conservation of species in Equation 9 [25].

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_i)}{\partial t} = 0 \tag{6}$$

$$\frac{\partial(\rho u_j)}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_i u_j - \tau_{ij}) = \frac{\partial p}{\partial x_j} \tag{7}$$

$$\frac{\partial(\rho h)}{\partial t} + \frac{\partial(\rho u_i h)}{\partial x_i} = \frac{\partial(\lambda_f \rho T_f)}{\rho x_i} - \sum j \frac{\partial(h_j J_j)}{\partial x_i} + \sum j h_j R_j \tag{8}$$

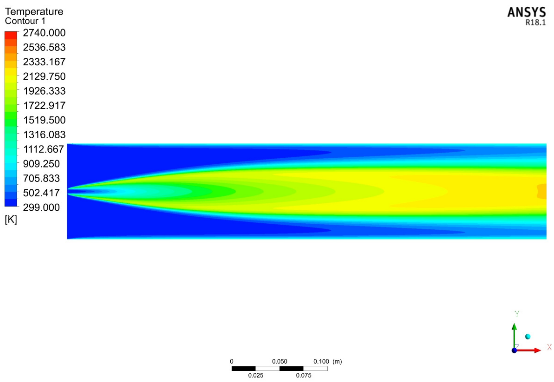
$$\frac{\partial(\rho Y_i)}{\partial t} + \frac{\partial(\rho u_i Y_i)}{\partial x_i} = \frac{\partial J_j}{\partial x_i} + R_i \tag{9}$$

When fuels reach their ignition temperature and oxygen is present in the environment, they undergo a chemical reaction, releasing heat along with certain byproducts. This process is referred to as combustion. One of the most critical parameters in a combustion process is the air-fuel mixture ratio. The minimum amount of air required to achieve complete combustion is defined as stoichiometric air. The excess air ratio (λ) is determined by dividing the actual air-fuel ratio by the stoichiometric air-fuel ratio (Equation 10). Under stoichiometric combustion conditions, the excess air ratio is equal to 1. The equivalence ratio (φ) is obtained by dividing the stoichiometric air-fuel ratio by the actual air-fuel ratio, serving as an indicator of the fuel content in the mixture. When $\varphi > 1$, the mixture is fuel-rich, whereas when $\varphi < 1$, the mixture is fuel-lean. In the case of $\varphi = 1$, a stoichiometric mixture is achieved [17].

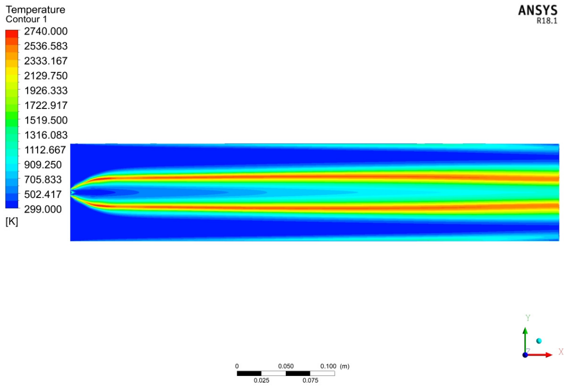
$$\lambda = \frac{\dot{m}\, air}{\dot{m}\, air{,}stockiometric}\ x\ 10 \tag{10}$$

3. RESULTS AND DISCUSSION

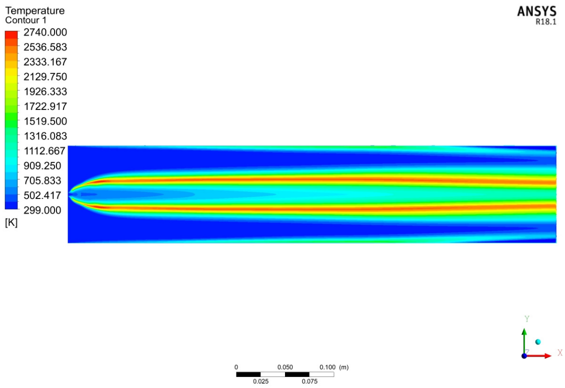
Hydrogen is currently being investigated as an additive to various conventional fuels to examine its effects on combustion characteristics and emission levels. To achieve this, burners with different specifications and characteristics have been designed. By varying the hydrogen concentration in the fuel, optimal combustion conditions have been sought. In this study, hydrogen gas was injected at different concentrations into a specially designed burner, with dimensions of 100 × 500 mm, to analyze combustion temperature variation trends. The burner includes two air inlets, two hydrogen inlets, and one methane gas inlet. CFD analyses of the flame temperatures and characteristics resulting from combustion were conducted using ANSYS Fluent. The analysis results indicate that the flame distribution structure varies depending on the hydrogen concentration, as illustrated in Figure 7.



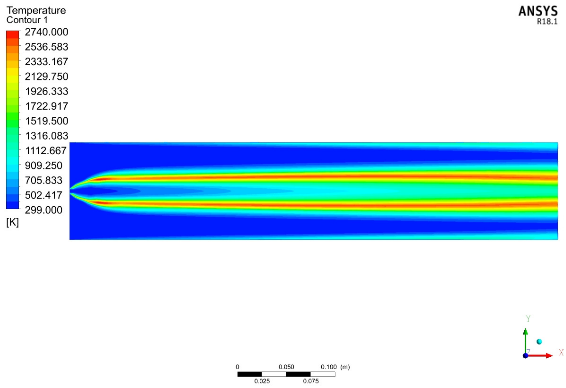
a) 0 % Hydrogen – 100 % Methane



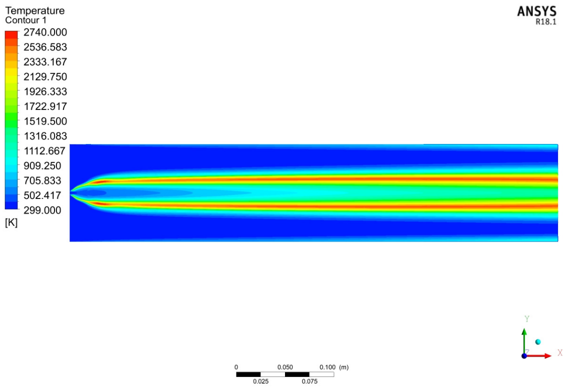
b) 5 % Hydrogen – 95 % Methane



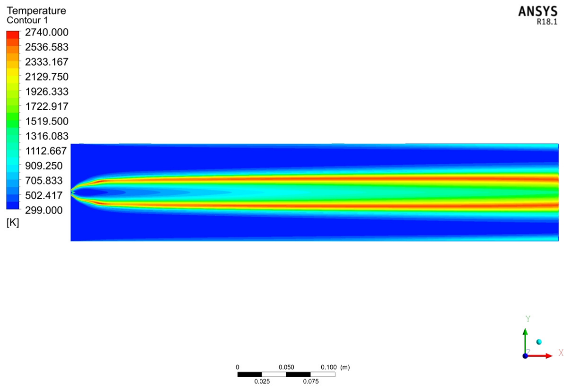
c) 10 % Hydrogen – 90 % Methane



d) 15 % Hydrogen – 85 % Methane



e) 20 % Hydrogen – 80 % Methane



f) 25 % Hydrogen – 75 % Methane

Figure 7. Combustion temperature distributions at different fuel input rates

The analysis of the flame distribution structure shown in Figure 7 reveals that increasing the hydrogen concentration in the combustion reaction enhances flame stability. Temperature was observed to increase both above and below the central axis of the burner. In the case of 10% hydrogen utilization, a noticeable increase in temperature distribution toward the burner tip was observed. This indicates that as the hydrogen content in the mixture increases, the temperature profile tends to become more homogeneous and exhibits an increasing trend along the burner axis.

To understand why an increase in hydrogen concentration leads to a rise in temperature, it is essential to first examine the physical and chemical properties of hydrogen. When these properties are considered, it is known that the lower heating value of hydrogen is 118.8 MJ/kg, whereas this value for methane is 55 MJ/kg. Therefore, during combustion, hydrogen releases significantly more energy compared to an equivalent amount of methane, resulting in a greater increase in reaction temperature. Hydrogen combustion occurs very rapidly, with a reported laminar flame speed of approximately 2.75 m/s. This is nearly seven times higher than that of methane, which has a laminar flame speed of around 0.38 m/s [26]. This rapid combustion leads to higher energy density and, consequently, elevated temperatures. Additionally, due to its chemical structure, hydrogen exhibits highly reactive characteristics. It rapidly generates radicals such as H, O, and OH, which accelerate the reaction kinetics and result in a more intense energy release within a shorter time frame. Moreover, hydrogen's high diffusivity enables better mixing with oxygen, promoting more homogeneous combustion. As a result, the increase in hydrogen concentration leads to a corresponding rise in temperature.

Table 3 presents the temperature values measured at ten different points along the central axis of the burner for various hydrogen concentrations in the combustion reaction. Additionally, the table includes the maximum temperature recorded within the combustion chamber. The study found that the highest flame temperature, 2732.248 K, was achieved with 15% hydrogen concentration. In general, temperature distributions exhibited an increasing trend as the hydrogen concentration in the burner increased while the methane concentration decreased. Further examination of the table reveals that with 25% hydrogen concentration, the temperature decreased by 1.07% compared to the maximum temperature recorded at 15% hydrogen concentration, resulting in a value of 2703.032 K. This decrease is attributed to the mixture exhibiting a rich combustion characteristic. The effect of radiation observed at 15% hydrogen utilization, where the maximum burner temperature is achieved, is presented in Figure 8. A study on combustion indicated that as the hydrogen concentration in the fuel mixture increases, heat loss due to radiation from the flame is expected to decrease. The study also determined that existing natural gas burners can operate with fuel containing up to 30% hydrogen without requiring major modifications [27].

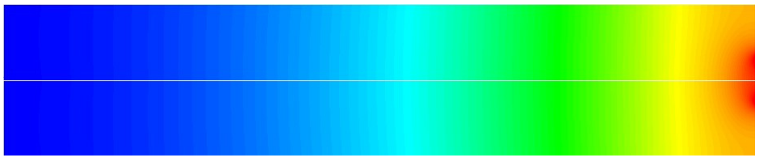


Figure 8. Distribution of the radiation effect on the burner

Table 3. Temperature values were recorded at specific points along the burner axis and the maximum temperature value in the burner

	Gas content in the burner (%)					
Temperatures (K)	**%0 H_2 - %100 CH_4**	**%5 H_2 - %95 CH_4**	**%10 H_2 - %90 CH_4**	**%15 H_2 - %85 CH_4**	**%20 H_2 - %80 CH_4**	**%25 H_2 - %75 CH_4**
T_1	300.000	300.000	300.000	300.000	300.000	300.000
T_2	846.356	420.192	548.655	415.883	563.238	492.367
T_3	1309.076	538.336	628.512	549.855	645.169	659.923
T_4	1584.09	612.154	729,468	710.943	767.798	811.846
T_5	1776.327	725.953	836.356	789.441	899.474	947.881
T_6	1921.585	780.979	898.485	898.862	990.212	1071.044
T_7	2032.659	884.156	1011.111	995.965	1066.588	1181.576
T_8	2118.059	916.273	1043.712	1052.264	1170.008	1259.003
T_9	2186.650	980.662	1140.946	1124.573	1216.471	1336.614
T_{10}	2238.233	1096.498	1101.336	1155.742	1232.348	1459.458
T_{max}	2238.407	2731.520	2712.677	2732.248	2724.279	2703.032

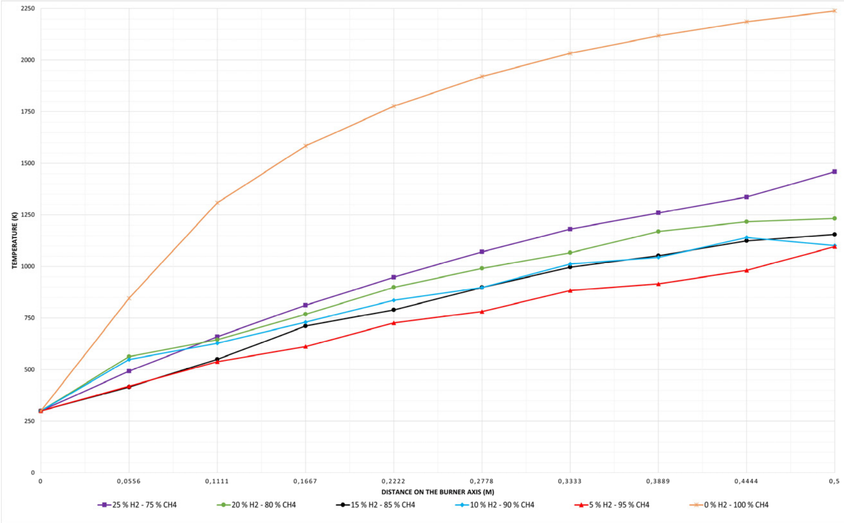
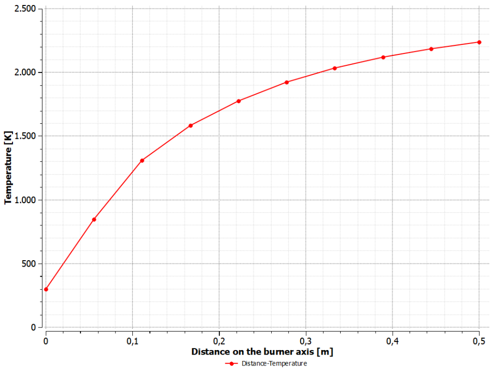
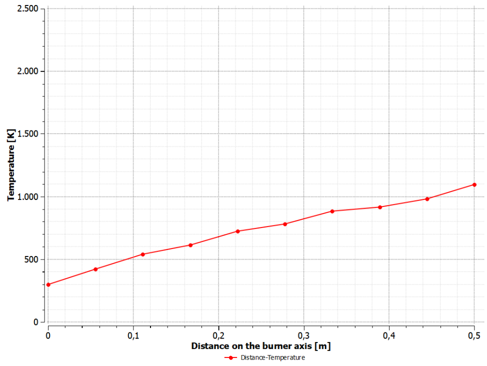


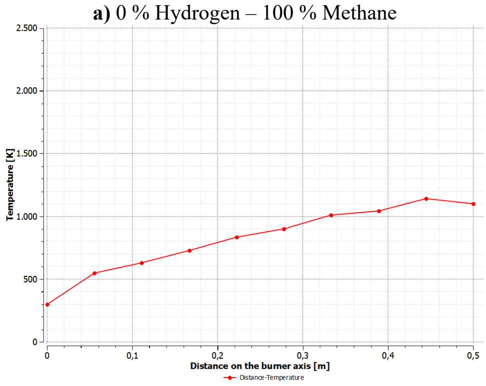
Figure 9. Comparison distance-temperature charts



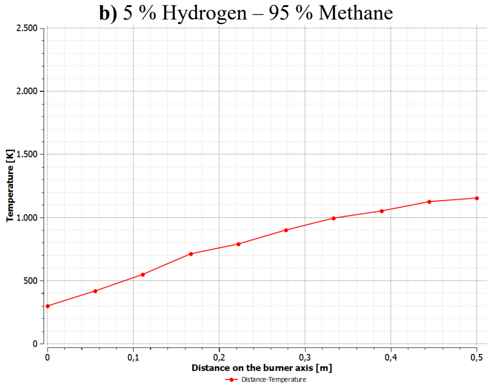
a) 0 % Hydrogen – 100 % Methane



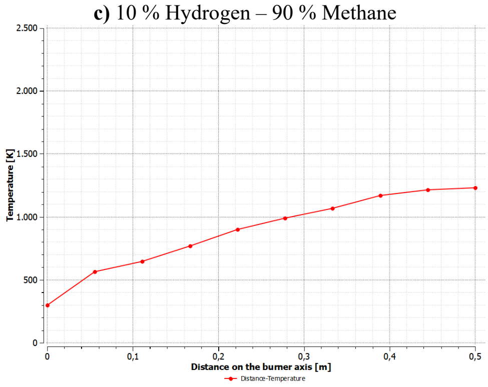
b) 5 % Hydrogen – 95 % Methane



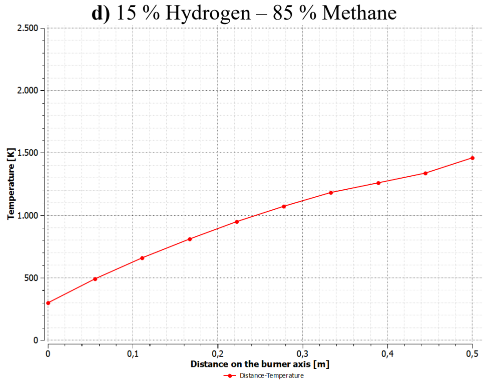
c) 10 % Hydrogen – 90 % Methane



d) 15 % Hydrogen – 85 % Methane



e) 20 % Hydrogen – 80 % Methane



f) 25 % Hydrogen – 75 % Methane

Figure 10. Distance-temperature charts on the burner axis

Figures 9 and 10 graphically compare the variations in flame temperature at ten equidistant points along the central axis of the burner. It has been observed that temperature tends to increase at these points as the hydrogen concentration rises. Studies examining the combustion specifications and emission characteristics of natural gas-fueled household gas stoves with hydrogen concentrations of 0%, 10%, 20%, and 30% [28,29], gas water heaters [30,31], and wall-mounted gas boilers [32] have shown that an increase in hydrogen concentration leads to a gradual decrease in the primary air coefficient, heat load, and CO and NOx content in the exhaust gases [33,34], while thermal efficiency progressively increases.

4. CONCLUSIONS

This study examines the effects of adding hydrogen (H_2) in different proportions on the flame characteristics resulting from the combustion of methane (CH_4). Hydrogen and methane gases were introduced into the combustion chamber through a specially designed burner, with separate ports for each gas, without pre-mixing. CFD analyses were conducted using Ansys Fluent, considering hydrogen concentrations of 0%, 5%, 10%, 15%, 20%, and 25%. The comparisons revealed that the highest temperature (2732.248 K) was recorded at a hydrogen concentration of 15%, and a gradual increase in temperature was observed with higher hydrogen concentrations. However, at a 25% hydrogen concentration, the mixture exhibited combustion characteristics similar to those of a rich fuel mixture.

Hydrogen, recognized as an environmentally friendly fuel due to its lack of emission gases during combustion, reduces the consumption rate of that fuel when used in combination with a secondary fuel, thereby decreasing dependence on fossil fuels and contributing to global sustainability. However, as the hydrogen concentration increases, the resulting rise in combustion chamber temperatures leads to a corresponding increase in NOx emissions. The burner used in this study offers an alternative solution within the field of hydrogen burner development and allows for parameter modifications through optional design adjustments. Our future work will explore varying hydrogen concentration levels within the fuel and investigate its applications with different conventional fuels.

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NOMENCLATURE

NTP	Normal temperature and pressure
CFD	Computational fluid dynamics
x_i, x_j	Directions
u_i, u_j	Velocity of i and j
μ	Viscosity
μ_t	Eddy viscosity
$\sigma_k, \sigma_\varepsilon$	Turbulent Prandtl numbers
R_i, R_j	Net production rates of species i and j by reaction

S_k, S_ε	User-defined source terms
S	Modulus of the mean rate-of-strain tensor
S_{ij}	Mean rate-of-strain tensor
G_k	Generation of turbulence kinetic energy due to the mean velocity gradients
G_b	Generation of turbulence kinetic energy due to buoyancy
Y_M	Contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate
$C_1, C_2, C_{1\varepsilon}, C_{3\varepsilon}$	Formula constants
λ	Excess air ratio
λ_f	Thermal conductivity
h	Enthalpy
k	Turbulence kinetic energy
ε	Turbulence dispersion ratio
ρ	Density
ν	Component of the flow velocity
η	Effectiveness factor
p	Pressure
t	Time
φ	Equivalence ratio
f_{H2}	The volume fraction of hydrogen
$\dot{m}\ air$	Air mass flow rate
τ_{ij}	Stress tensor
T_f	Temperature
J_j	Diffusion flux of species j