



Numerical investigation of hydrogen enrichment and equivalence ratio on the biogas combustion

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ABSTRACT

While energy plays an indispensable role in every aspect of life, consumption is increasing rapidly with the increasing world population and technological developments. This situation necessitates the efficient use of limited resources, the shift towards renewable energy sources and the control of greenhouse gas emissions. Biogas emerges as an important resource, and increasing its calorific value, especially by mixing it with different fuels, will help expand its areas of use. In this study, the effects of different equivalence ratios and different inlet temperatures on adiabatic flame temperatures were investigated by adding hydrogen, which has high flammability and calorific value, to biogas. Expanding the use of renewable energy sources and investigating the use of biogas without making any changes to existing combustion systems are also among the objectives of the study. Numerical analyses were performed with Python using the GRI 3.0 mechanism. Different analyses were performed with hydrogen at 0-50% rates, CO₂ at 0-40% rates, equivalence ratios in the range of 0.5-1.5 and inlet temperatures in the range of 300-600 K. It was observed that the addition of hydrogen increased the calorific value of biogas and thus increased the adiabatic flame temperatures. The highest temperatures were obtained at stoichiometric conditions.

1. INTRODUCTION

Energy plays an indispensable role in every aspect of life, from daily activities to industrial production. Energy is a necessity for basic human needs such as lighting, cooking, heating, cooling and transportation. It is important not only for sustaining our lives, but also for technological progress, economic growth and increased social welfare. The increase in the number of new technologies and new habits that have entered our lives as a result of R&D studies, the increase in the world population, and

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the inability to use existing energy resources effectively and efficiently cause a significant increase in energy consumption. Considering that energy resources are limited, the importance of energy is increasing especially for developing countries. In addition to the importance of access to energy, greenhouse gas emissions that directly affect human health must also be controlled. These situations have necessitated the efficient use of existing resources, the search for new energy sources, new energy production methods, and especially turning to renewable energy sources. In a world where resource and resource access problems are increasing day by day, diversification of energy resources is an important issue. In addition, due to the increasing use of fossil fuels, CO₂ emissions are increasing, which causes the greenhouse effect and global warming. While countries' turning to their own energy resources will ensure their supply security, especially if these resources are renewable, it will help reduce global warming and environmental pollution.

In this context, biogas attracts attention because it does not cause environmental pollution and provides sustainability. It is seen as a suitable and important energy source because it can be obtained everywhere and helps socio-economic development, especially in rural areas. Biogas is a gas mixture consisting of CO₂ and small amounts of other gases, which are produced as a result of the decomposition (anaerobic fermentation) of organic waste/waste in an oxygen-free environment (IEA, 2025). It is used in combustion systems to obtain energy with its 50-70% methane in its composition, thus providing energy from waste. The calorific value of biogas varies according to its methane content, but may not be sufficient for sustainable energy. Although using biogas as biomethane by removing impurities from its content is a method, the costs of these processes are high.

At this point, there are studies on using biogas by mixing it with different fuels to increase its calorific value and expand its areas of use. Among these, hydrogen is particularly notable due to its properties such as high ignition ability and high calorific value. The important objectives are to obtain efficient and stable combustion by mixing hydrogen, which is a clean source with high calorific value, with biogas and to ensure its use without the need for changes in combustion systems.

Yıldız (2024) numerically investigated the effect of biogas-hydrogen mixture on flame temperatures and emissions for different equivalence ratios in his study. It was observed that flame temperatures increased with the addition of hydrogen to biogas, especially in rich mixture conditions, and reached the highest value. In addition, it was concluded that the amount of CO₂ decreased and the amount of NO increased with the increase of the hydrogen ratio in the mixture. Gee et al. (2024) carried out a study on flashback and blow-off limits with a mixture of natural gas, CO₂ and hydrogen. In the study, different injector diameters were also used and their effects on flashback and blow-off limits and NO_x emissions were also investigated. It was observed that the limits could be extended by increasing the injector diameter, and the addition of hydrogen to the fuel mixture also extended the extinction limits. It was concluded that the amount of NO_x increased with the enlargement of the injector diameter and the addition of hydrogen, but decreased with the addition of CO₂. Amez et al. (2021) investigated the combustion performance of biogas-hydrogen mixture in a conventional natural gas burner. In the experiments; different proportions of biogas were used and studies were carried out with new mixtures by adding hydrogen from 5% to 25% to biogas. In the studies, it was observed that as the CO₂ ratio in the mixture increased, combustion efficiency decreased and ignition problems occurred at CO₂ ratios above 40%. Although an increase in combustion efficiency was observed with the addition of hydrogen, the efficiencies obtained with natural gas could not be achieved. As a result of the experiments, it was seen that biogas is not suitable for high-power combustion systems. In the study conducted by Zhen et al. (2016), the combustion characteristics and thermal performances of a stoichiometric biogas and hydrogen mixture flame were evaluated. The dependence of flame stability on the hydrogen and CO₂ ratio was analyzed in terms of fuel property and flow aerodynamics change. In the experiments, it was observed that the pure biogas flame was not stable. It was observed that in order to achieve flame

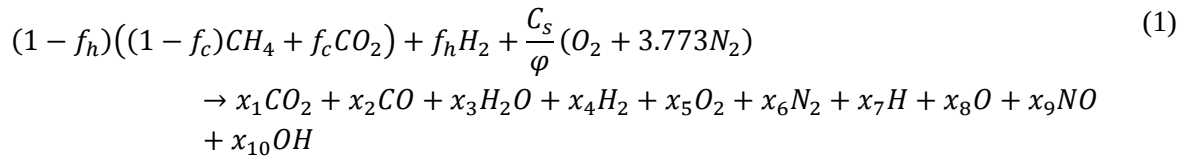
stability in biogases with high CO₂ content, the hydrogen content had to be higher than the others. It has been observed that as the CO₂ ratio increases, the number of operating conditions in which the flame is stable decreases, and as the hydrogen ratio increases, the flame temperature increases. Li et al. (2017) conducted a study on the combustion characteristics of biogas enriched with hydrogen and oxygen. It was observed that the reaction rates increased by increasing the hydrogen and oxygen ratio, and accordingly the heat release rate of biogas increased. İlbaş and Yılmaz (2012) experimentally investigated the temperature and emission values for two different hydrogen-methane mixtures. It was concluded that flame temperatures and NO amount increased with the increase in hydrogen ratio, and CO amount decreased with the decrease in C/H ratio. Zhao et al. (2024) investigated the effects of hydrogen and inlet temperatures on emissions using the simplified San Diego mechanism. It was observed that the amount of NO increased and the amount of CO and CO₂ decreased with the increase in hydrogen. It was found that the amount of NO and CO increased with the increase in the inlet temperature. Attia et al. (2018) numerically studied the effect of methane and hydrogen combustion on the combustion parameters. It was observed that flame temperatures increased and CO emissions decreased with hydrogen. Xiang et al. (2020) numerically studied the effects of hydrogen addition to methane and ethane on the combustion characteristics of laminar premixed flame. The effects of different inlet temperatures and pressures were also investigated in the study. It was observed that the increase in inlet temperatures increased the laminar flame speed (LFS), while the increase in inlet pressure decreased it. It was concluded that the addition of hydrogen greatly increased the LFS and partially increased the adiabatic flame temperature. Yadav et al. (2018) investigated the effects of biogas and hydrogen mixture on adiabatic flame temperatures (AFT) and laminar burning velocity numerically and experimentally. It was observed that AFT decreased with the increase in CO₂ and increased with the increase in hydrogen in the mixture. In addition, it was concluded that the amount of CO₂ was more effective on AFT, especially at high equivalence ratios. Mariani et al. (2018) numerically studied the effects of methane-hydrogen and biogas-hydrogen mixtures and preheating on the indicated mean effective pressure, engine efficiency, and pollutant emissions in a controlled auto-ignition engine. It was observed that the autoignition temperature decreased with the addition of hydrogen, and a higher equivalence ratio was required for biogas compared to methane to obtain the same IMEP. It was concluded that the decrease in inlet temperatures achieved with the addition of hydrogen also reduced the NO_x rates. Boulahlib et al. (2021) experimentally investigated the effect of adding hydrogen to natural gas in a domestic boiler with staggered combustion and high equivalence ratios on combustion parameters and emissions. It has been observed that at high equivalence ratios (>2) temperatures and NO_x values decrease independently of hydrogen, but better results are obtained with staged combustion when the equivalence ratio is <2. Sish et al. (2014) numerically investigate the effects of hydrogen content in methane/hydrogen blended fuels on combustion performance in a box-type combustor, simulating conditions for an innovative micro gas turbine. The findings show that moderate hydrogen fractions can increase flame temperature and combustion efficiency, but higher percentages require design changes due to potential power loss at constant heat input or increased NO_x emissions at constant fuel flow rate. In their experimental and numerical study on laminar premixed methane-hydrogen-air flames, Hu et al. (2009) concluded that the laminar burning velocity increases with hydrogen fraction, causing its peak to shift towards the rich mixture side. They also observed that Markstein length increases with the equivalence ratio but decreases with hydrogen fraction, and that the enhanced chemical reactions due to hydrogen addition correlate strongly with higher concentrations of H, O, and OH radicals in the reaction zone.

In this study, the effects of adding hydrogen to biogas at different rates on adiabatic flame temperatures are investigated using different equivalence ratios and different inlet temperatures. Adiabatic flame temperature is important as it will show the limits in the design of the combustion system. In the study,

numerical analyses were performed with Python using the GRI 3.0 mechanism. It was aimed to see the effects of both hydrogen ratio, CO₂ ratio, equivalence ratio and different inlet temperatures by performing different analyses such as hydrogen at 0-50% rates, equivalence ratio between 0.5-1.5, CO₂ at 0-40% rates. The aim of the study is to show that renewable, low calorific value fuels such as biogas can be used instead of conventional fuels.

2. METHODOLOGY

Since biogas consists largely of methane and carbon dioxide, the mixture in combustion modeling was created with methane, carbon dioxide and hydrogen. The chemical reaction model is given in below (Yıldız, 2024):



where, f_h and f_c are the H₂ fraction in the fuel blend and the CO₂ proportion in biogas, respectively. The x_i (i=1 to 10) represents the mole numbers of each product. The ϕ and C_s denote the equivalence ratio and the stoichiometric molar air-fuel ratio.

Hydrogen is a very low density gas and its critical temperature is -239.91 C. As seen in Table 1, it has a lower calorific value than methane on a volume basis but a higher value on a mass basis (Mariani et al. 2018).

Table 1. Methane and hydrogen properties (Mariani et al. 2018)

	CH ₄	H ₂
Density [kg/Nm ³]	0.7064	0.0888
Lower Heating Value [MJ/kg]	50	119.9
Lower Heating Value vol. [MJ/Nm ³]	35.32	10.64
Auto-ignition temperature [°C]	813	858
Laminar flame speed at stoich. conditions [m/s]	0.38-0.40	2-2.2
Flammability limits in air [%vol.]	5.3-15	4-75

One of the important properties in combustion is the equivalence ratio, which is the normalization of the actual fuel-air ratio to the stoichiometric fuel-air ratio (Benaissa et al. 2022).

$$\phi = \frac{Actual\ F/A}{Stoichiometric\ F/A} \quad (2)$$

In the study, a numerical model was created using the combustion mechanism GRI 3.0 with Python. GRIMech 3.0 is the most widely used because of its detailed NO formation reactions and high accuracy in predicting combustion characteristics (Zhao et al. 2024). GRI-Mech 3.0 is a widely used chemical kinetics model optimized for the combustion of natural gas (primarily methane) and similar light hydrocarbons. This mechanism consists of 53 chemical species: fuels (methane, hydrogen, etc.),

oxidants (oxygen, nitrogen), intermediates and combustion products (carbon dioxide, water, carbon monoxide, nitrogen oxides, etc.) and 325 basic reactions that define how these species interact and transform with each other. Table 2 and Table 3 show the combustion reactions for CH₄ and H₂.

Table 2. CH₄ combustion reactions according to the chemical kinetics of Gri-Mech 3.0 (Okten et al. 2025)

No	Reaction	Arrhenius factor	β_r	Ea (kJ/mol)
1	$CH_4 + 0.5O_2 \leftrightarrow CO + 2H_2$	$7.82e^{13}$	0	$30.0e^3$
2	$CH_4 + H_2O \leftrightarrow CO + 3H_2$	$0.30e^{12}$	0	$30.0e^3$
3	$H_2 + 0.5O_2 \leftrightarrow H_2O$	$1.21e^{18}$	-1	$40.0e^3$
4	$CO + H_2O \leftrightarrow CO_2 + H_2$	$2.75e^{12}$	0	$20.0e^3$

Table 3. Chemical reaction mechanism of H₂/air combustion (Okten et al. 2025)

No	Reaction	Arrhenius factor	β_r	Ea (kJ/mol)
1	$O_2 + H \leftrightarrow OH + O$	$5.10e^{13}$	-0.82	69.1
2	$H_2 + O \leftrightarrow OH + H$	$1.80e^7$	1.00	37.0
3	$H_2 + OH \leftrightarrow H_2O + H$	$1.20e^6$	1.30	15.2
4	$OH + OH \leftrightarrow H_2O + O$	$6.00e^6$	1.30	0.0
5	$H_2 + O_2 \leftrightarrow OH + OH$	$1.70e^{10}$	0.00	200.0
6	$H + OH + M \leftrightarrow H_2O + M$	$7.50e^{17}$	-2.60	0.0
7	$O_2 + M \leftrightarrow O + O + M$	$1.90e^8$	0.50	400.1
8	$H_2 + M \leftrightarrow H + H + M$	$2.20e^9$	0.50	387.7
9	$H + O_2 + M \leftrightarrow HO_2 + M$	$2.10e^{12}$	-1.00	0.0

The simulation process in numerical calculations is shown in Figure 1. The first step in combustion modeling is the creation of a chemical mechanism where reaction components, rates and pathways are defined using tools Cantera (Sadeq, 2024). Initial conditions (gas ratios, temperature, etc.) are specified to set the state of the system before combustion. Then, simulations are performed using reactor models that calculate species concentrations and temperature over time, thereby simulating the combustion process. In the analysis phase, combustion characteristics such as temperature distributions examined. Parameters are adjusted to improve performance and ensure the validity of results by aligning them with data from literature.

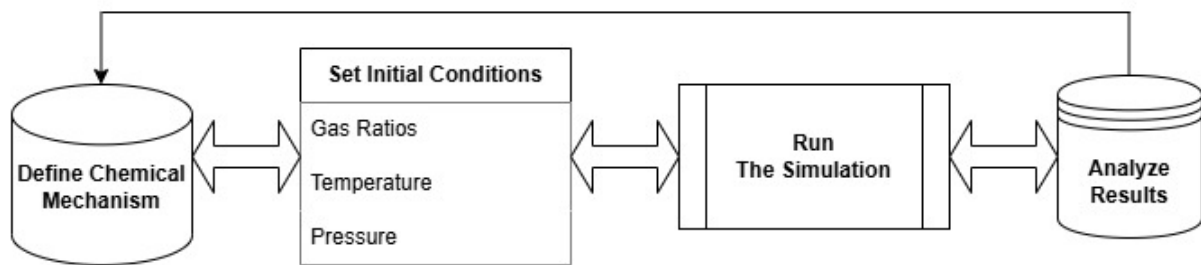


Fig 1. Simulation process

3. MODEL VALIDATION

The model was compared with different studies from the literature. The boundary conditions in the selected studies for validation vary from each other. For model validation, analyses were performed and results were compared by considering different conditions.

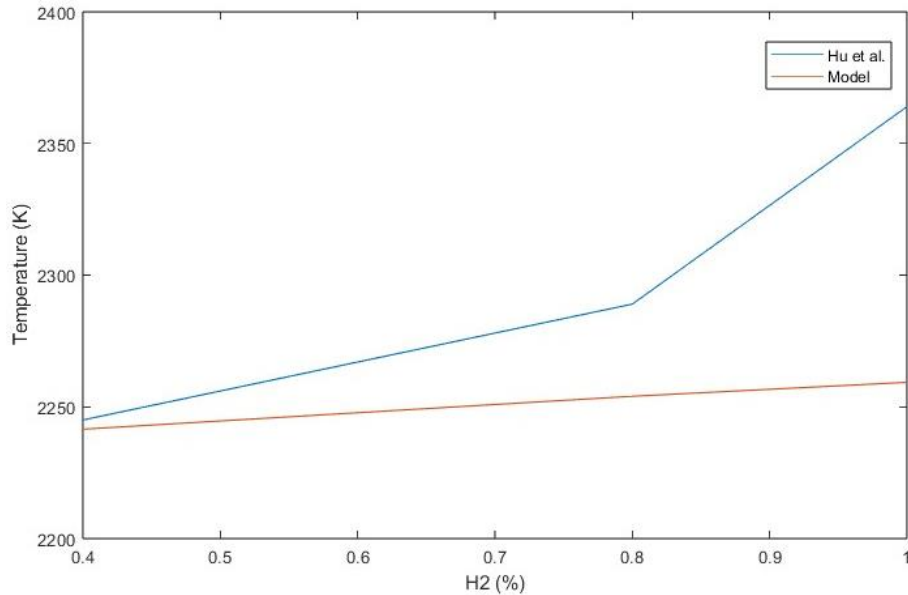


Fig 2. Model validation with the study by Shih & Liu (2014).

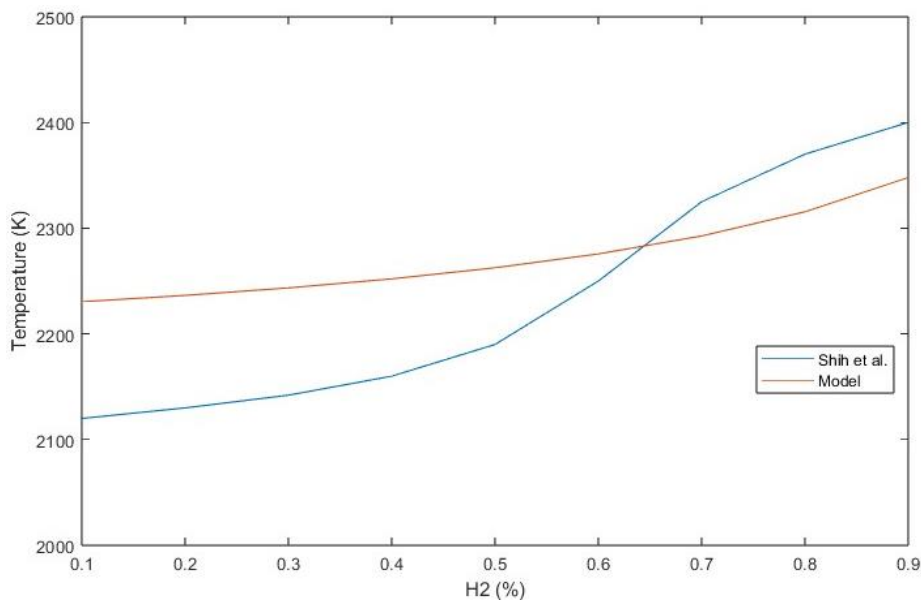


Fig 3. Model validation with the study by Hu et al. (2009)

The results from both Shih & Liu (2014) and Hu et al. (2009) studies are seen to be compatible with the model. When the two studies are compared, it is seen that there is an increase in temperature with the increase in hydrogen. It is observed that the results are more convergent, especially at low H_2 ratios, but the temperatures differ even though the trends are the same at high H_2 ratios. This situation is probably related to the kinetic scheme used. However, since analyses were not performed with very high H_2 ratios in this study, this will not affect the analysis results.

4. RESULTS

The effects of equivalence ratio and inlet temperatures on the adiabatic flame temperature (AFT) for the biogas and hydrogen mixture were investigated. The initial temperature was set to 300 K, and the combustion process was assumed to occur at a constant pressure of 1 atmosphere.

The adiabatic flame temperature, representing the theoretical peak temperature in an isolated combustion system, is a critical factor influencing both how fast and in what way a combustion reaction proceeds. To optimize burning processes for reduced pollution and improved performance, a fundamental understanding of the adiabatic flame temperature is essential. Since the adiabatic flame temperature indicates the upper limit of heat attainable during combustion in the absence of heat transfer, it serves as a vital piece of information for fine-tuning combustion to minimize undesirable emissions and maximize efficiency.

4.1 Effects of Hydrogen Addition

The fuel ratios used in the analyses to see the hydrogen effect are given in Table 4. The change in AFT with the addition of hydrogen up to 50% for a biogas with 60% methane content is shown in Figure 4. It is clearly seen that the addition of hydrogen to biogas has a significant effect on increasing the adiabatic flame temperature. While the adiabatic flame temperature for biogas was obtained as 2103 K, it was obtained as 2185 K in the analysis performed with 50% H₂ addition.

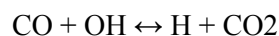
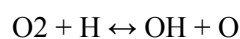
Table 4. Fuel ratios for different cases

Case	H ₂ %	CH ₄ %	CO ₂ %
0	0	60	40
1	10	60	40
2	20	60	40
3	30	60	40
4	40	60	40
5	50	60	40

It is seen that AFT increases regularly with the increase in hydrogen content since it has a high reactivity and heat release rate with its high lower heating value.

Hydrogen accelerates combustion by reacting to elevate the molar concentration of reactive radicals (O, H, OH, etc.). This, in turn, expands the branched chain reactions inherent in combustion, leading to a faster rate.

The two most critical elementary reactions for fostering the temperature rise of methane are (Xiang et al. 2020):



Gaseous fuels are primarily characterized by their Wobbe Index, heating value, and interchangeability (Amez et al. 2021). The heating value quantifies the heat produced during combustion per unit of mass or volume, influencing adiabatic flame temperature. For gas mixtures, the heating value can be readily estimated if the molar fraction of each component is known. Heating values calculated with different H₂ and CO₂ ratios according to the basic data are shown in Figure 5 to compare.

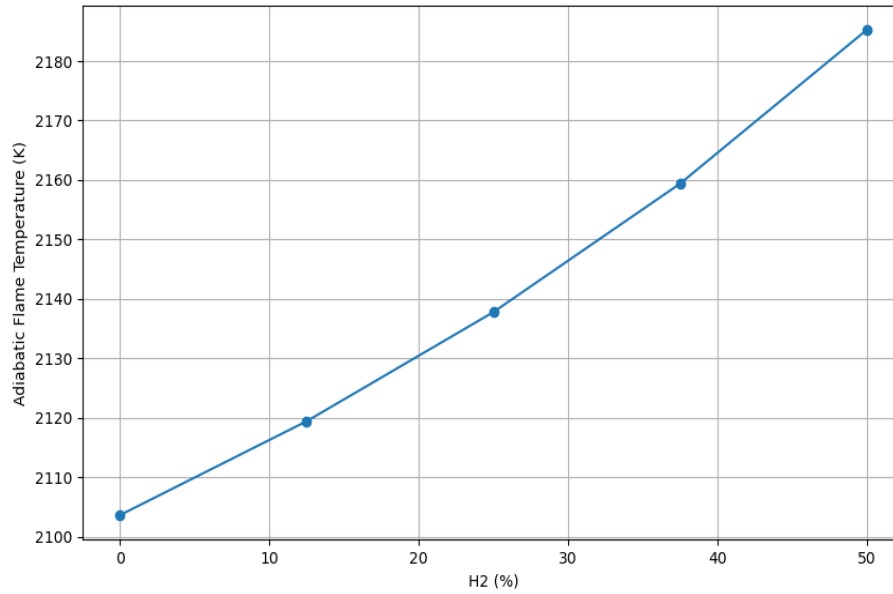


Fig 4. Effect of H₂ addition on biogas (CH₄ 0.6 & CO₂ 0.4) for equivalence ratio 1

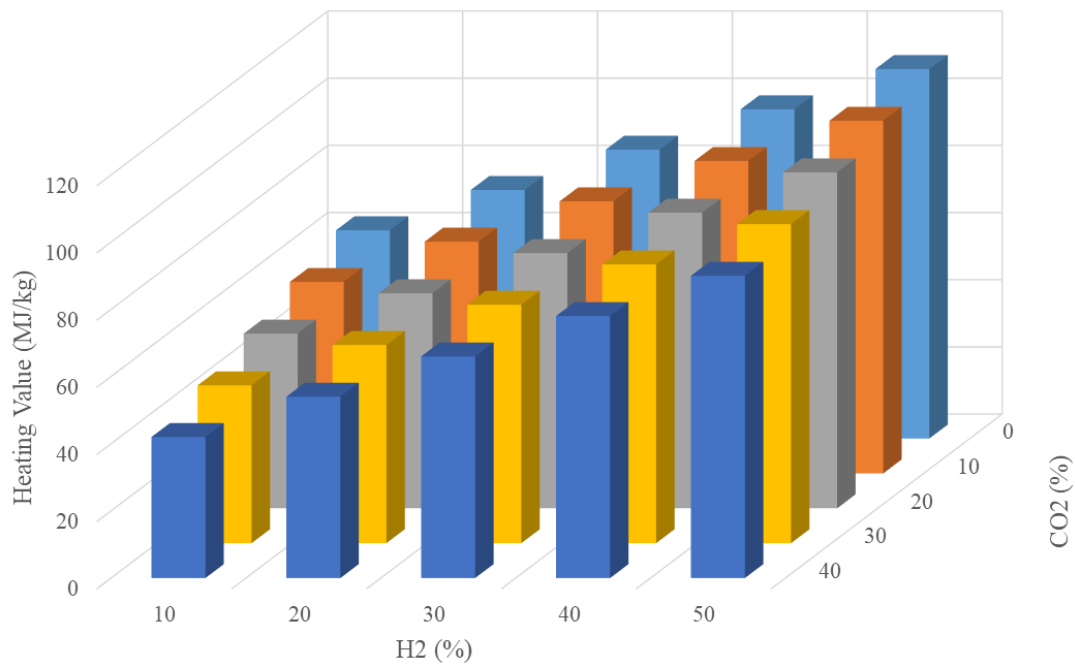


Fig 5. Heating value comparison of biogases depending on hydrogen content

Figure 6 shows the adiabatic flame temperatures for mixtures with different heating values (with different H₂ and CO₂ ratios).

It can be observed from Figure 6 that, increasing H₂ ratios leads to higher adiabatic flame temperatures, while increasing CO₂ ratios leads to lower temperatures.

This reduction is due to the presence of CO₂, which captures H through $\text{CO} + \text{OH} \leftrightarrow \text{CO}_2 + \text{H}$, with $\text{H} + \text{O}_2 \leftrightarrow \text{O} + \text{OH}$ as the main branching reaction (Yadav et al. 2018).

The mixture's specific heat capacity increases with the increase in CO₂ rate. Due to this increase in specific heat, the thermal effect becomes more dominant than dilution and chemical effects (Yadav et al. 2018).

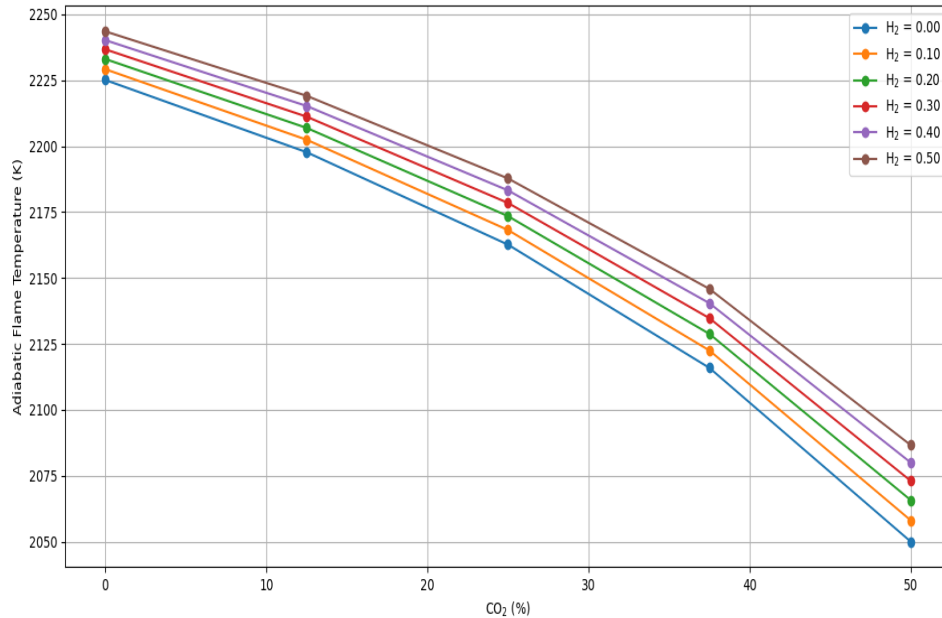


Fig 6. Effect of H₂ and CO₂ for equivalence ratio 1

The results imply that even small amounts of hydrogen in Low Calorific Value fuels such as biogas may be a viable option to increase their AFT leading to improvement in chemical reaction rates. Enhancing biogas fuels with hydrogen has potential to improve their thermo-chemical properties, potentially making them a viable alternative to conventional and nonrenewable fuels with reduced pollutant emissions.

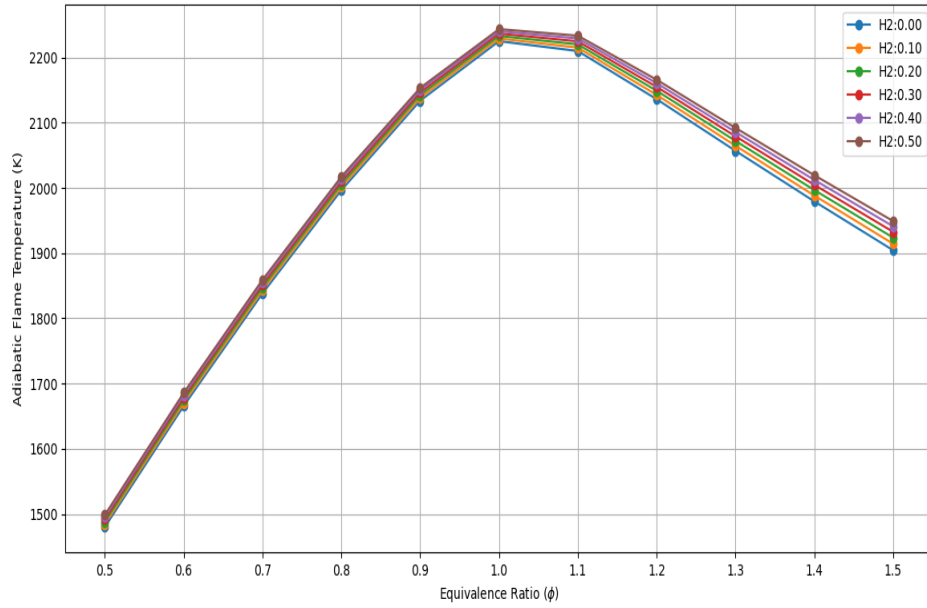
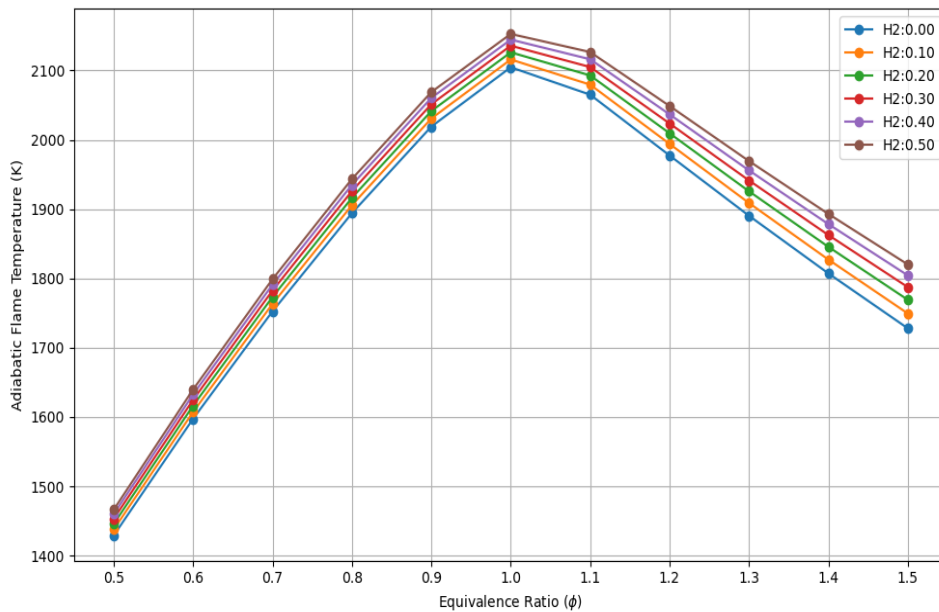
4.2 Effects of Equivalence Ratio

Understanding the effects of the equivalence ratio is crucial in designing and operating combustion systems to achieve optimal performance, minimize pollutant emissions, and ensure stable operation. The ideal equivalence ratio often represents a compromise between these competing factors, and its optimal value can depend on the specific application and fuel used. Analyses were carried out with different H₂ ratios to understand the effect of the equivalence ratio on the adiabatic flame temperature. The effect of hydrogen addition on both biogas (CH₄ 60%-CO₂ 40%) and methane (100%) was investigated.

It is seen from Figure 7 that adiabatic flame temperatures are lower in the rich and lean mixture regions than in stoichiometric combustion.

It is observed that temperatures decrease as the fuel mixture becomes richer. This is primarily because the higher fuel content makes complete and efficient combustion more challenging (Boulahlib et al. 2021). On the other hand, the fuel mixture becomes leaner excess air acts as a diluent, absorbing heat and lowering the adiabatic flame temperature compared to stoichiometric conditions. However, the relationship is not strictly linear, and other factors like dissociation at high temperatures play a role.

It is seen that there are no major differences between the temperature results obtained with different H₂ ratios. It's important to note that the very low molecular weight of hydrogen is the simple reason for its small effect on the adiabatic flame temperature of these fuels (Ren et al. 2019).

Fig 7. Effect of H₂ and equivalence ratio for CH₄ 100%Fig 8. Effect of H₂ and equivalence ratio for CH₄ 0.6 & CO₂ 0.4

When the two figures are evaluated together, the CO₂ ratio in biogas and the equivalence ratio are the determining factors on the level of effect of H₂ addition.

4.3 Effects of Inlet Temperature

To conserve energy and improve thermal efficiency in fuel combustion, industrial practice typically involves using waste heat to preheat the fuel and oxidant before they enter the combustion chamber. (Xiang et al. 2020). In the study, the effects of both inlet temperatures and hydrogen ratio were investigated separately. Analyses were carried out with different H₂ ratios at inlet temperatures of 300 K, 400 K, 500 K and 600 K.

As seen in Figure 9, flame temperatures increase as inlet temperatures increase. The main reason for this is that the increasing air temperature triggers the combustion reaction rate. Higher temperatures notably increase reaction rates, as known from the Arrhenius equation.

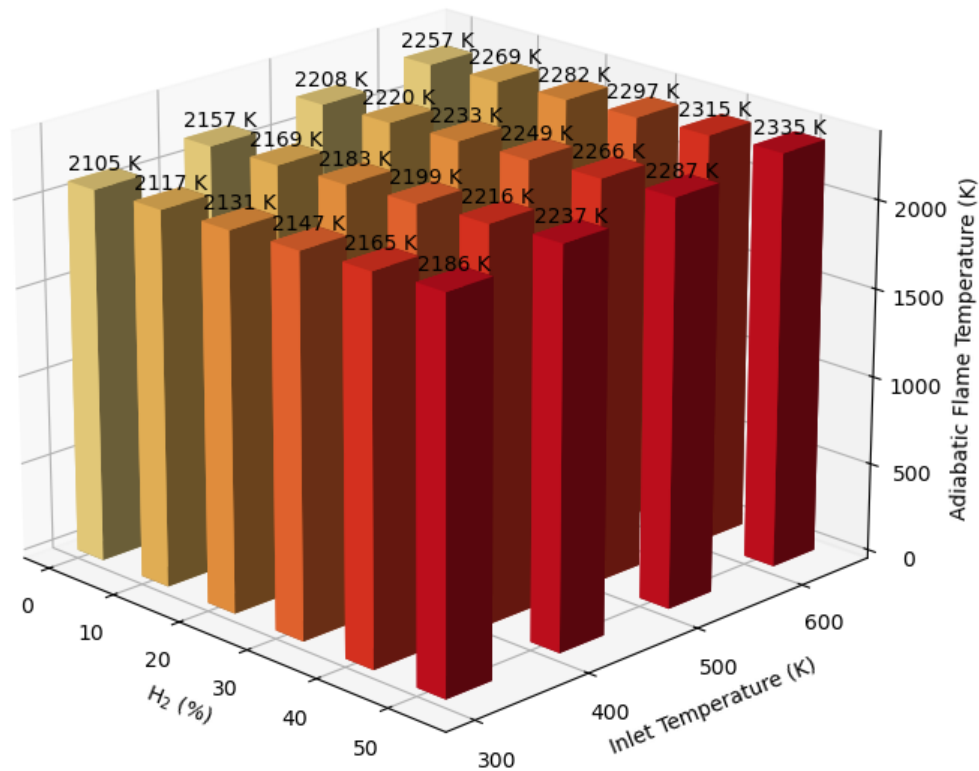


Fig 9. Effect of H₂ and inlet temperature for CH₄ 0.6 & CO₂ 0.4

The increase in inlet temperatures increases the fuel and oxidizer enthalpy and thus the energy input of the flame. It also causes the fuel-air mixture to mix homogeneously and rapidly. This results in a high combustion temperature.

The exponential dependence of reaction rates on temperature also explains these results, as a higher initial temperature of the flammable mixture would greatly promote fuel pyrolysis and subsequent reactions (Ren et al. 2019).

It is also seen in Figure 9 that the AFT value increases with the increases in inlet temperatures for all hydrogen ratios. For example; under conditions where 10% H₂ is added, 2117 K AFT is obtained with 300 K inlet temperature, while 2269 K AFT is obtained with 600 K inlet temperature.

However, increases in flame temperatures also significantly increase the formation of NO_x, a detrimental pollutant (Pehlivan & Altın, 2024). The optimal inlet temperature is therefore a trade-off, depending on the specific application and the relative importance of efficiency, stability, and emissions. Optimum conditions can be achieved by conducting detailed studies on this subject, specifically for the output to be prioritized for combustion.

5. CONCLUSIONS

In this study, the effects of adding different amounts of hydrogen to biogas on adiabatic flame temperatures were investigated. Since it is known that the equivalence ratio and inlet temperature have an important effect on combustion, analyses were also conducted in this context. Numerical analyses

were performed with Python using the GRI 3.0 mechanism. The model enables the calculation of adiabatic flame temperature. It was aimed to see the effects of both hydrogen ratio, CO₂ ratio, equivalence ratio and different inlet temperatures by performing different analyses such as hydrogen at 0-50% rates, equivalence ratio between 0.5-1.5, CO₂ at 0-40% rates. The results could be summarized as follows:

- The addition of hydrogen to biogas has a significant effect on increasing the adiabatic flame temperature. AFT increases regularly with increasing H₂ ratio. Hydrogen, which has a high reactivity, reacts to increase the molar concentration of reactive radicals, accelerating combustion.
- In the analyses performed with different equivalence ratios, the highest adiabatic flame temperature was obtained at the stoichiometric ratio. It was evaluated that adiabatic flame temperatures were lower than stoichiometric because excess fuel in the rich mixture and excess air in the lean mixture prevented complete combustion.
- It is determined that the adiabatic flame temperature levels increase with the inlet temperature (preheating effects) for each fuel mixture. Increased inlet temperatures raise the enthalpy of fuel and oxidizer, boosting the flame's energy input. This also promotes rapid and homogeneous mixing of the fuel-air mixture, leading to a higher combustion temperature.

In conclusion, in this study, it has been numerically demonstrated that flame temperatures can be increased with the hydrogen addition of biogas, and thus it can be used in different combustion systems. In this way, biogas that can be quickly produced can be replaced with conventional fuels such as natural gas, which is continuously running out and not evenly distributed worldwide, in combustion systems.

NOMENCLATURE

AFT	Adiabatic flame temperature [K]	IMEP	Indicated mean effective pressure
CH ₄	Methane	K	Kelvin
CO ₂	Carbon dioxide	R&D	Research and development
H ₂	Hydrogen	φ	Equivalence ratio

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