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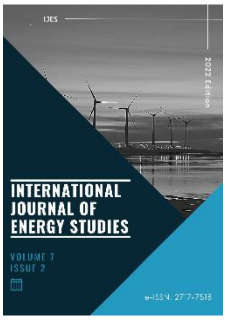

Research Article

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Effect of helium dilution on the dynamic stability of lean premixed methane flame in a model gas turbine combustor

Buğrahan Alabaş[a,*], Adem Altınay[b]

[a]*Faculty of Aeronautics and Astronautics, Department of Aeronautical Engineering, Erciyes University, 38039, Kayseri, Turkey, Orcid Number: 0000-0002-1040-1110*

[b]*THY Teknik A.Ş.*

*(*Corresponding Author: bugrahanalabas@erciyes.edu.tr)*

Highlights

- The effect of helium dilution at different volumetric ratios on flame instability was investigated.
- It was determined that low helium dilution did not have a significant effect on flame instability.
- It has been found that high helium dilution reduces flame instability.
- As a result of helium dilution, the burner outlet temperature decreased monotonically.

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ABSTRACT

Today, where clean, renewable and high efficiency energy production gains importance, methane gas draws attention due to its low carbon content. In this study, flame instability and temperature of methane gas were tested in a premixed model gas turbine combustor at different helium dilution conditions. The burner power was kept constant as 3 kW and the equivalence ratio as 0.7. In addition, a swirl generator with a swirl number of 1 is placed at the burner outlet. The dynamic pressure values of the flame were recorded under external acoustic enforcements at different frequencies applied to the flame and thermo-acoustic combustion instability was interpreted. Methane flame diluted with Helium at 10, 20, 30, 40 and 45 volumetric ratios showed the following results. If helium dilutions of up to 20% did not significantly affect flame instability, instability increased at 30% He. After this critical value, when 45% He dilution was tested, the lowest instability value was determined. In addition, the burner exit temperature of the flame decreased at all helium dilution ratios.

Keywords: Methane, combustion instabilities, helium dilution

1. INTRODUCTION

Methane gas is one of the most widely used fossil fuels today. Methane gas, which has a low carbon/hydrogen ratio. This gas is used in thermal power plants, land vehicle engines, home heating and industrial furnaces. Researchers are conducting an intensive study on methane combustion because of the low carbon/hydrogen ratio and the cleaner products at the flue gas emissions, especially compared to solid fuels [1]. In studies on methane flame, the effect of different burners and combustion conditions was investigated. At the same time, different alternative fuels, enrichers or diluent inert gases were added to the methane gas in these studies.

Wang et al., [2] have numerically simulated premixed turbulent methane/hydrogen combustion. The results showed that the turbulence intensity increased with the flame propagation speed. The flame propagation speed increased with the increase in the hydrogen ratio. Guessab et al., [3] investigated the combustion of methane and biogas fuels in a model gas turbine burner. In the study where the addition of CO_2 at different rates was tested, it was observed that the increase in the CO_2 ratio increased the flame stability. In addition, as the CO_2 ratio increased, the flame temperature decreased, leading to a decrease in NO emissions. Liu et al., [4] compared the combustion of methane and hydrogen-enriched methane in a laboratory-scale gas turbine combustor. The results showed that hydrogen enrichment caused boundary layer flashback. Valera-Medina et al., [5] studied the swirled combustion of a methane/ammonia flame in a gas turbine burner. In the study, flame stability and emission behavior were determined at different ammonia addition rates. In the study, it was determined that high swirl number increased the instabilities in ammonia combustion.

In addition to these studies, there are also current studies in the literature on flame instability and flue gas emissions of methane gas under the influence of different diluents. Chouraqui et al., [6] experimentally and numerically investigated the effect of N_2, Ar, He, Xe dilutions on premixed methane combustion in a micro-burner. Experimental results were supported by numerical simulations in the study. As a result of the dilution applied to the stoichiometric methane flame, its effect on the thermodynamics of the mixture was determined. Yılmaz et al., [7] investigated the effect of N_2 dilution on biogas flame instability and emission behavior. Results; showed that dilution up to 30% by volume N_2 reduces combustion instability. In addition, it was observed that NO_x emissions decreased up to 20% N_2, while an increase was observed after this value. Tao and Zhou [8] investigated the effects of CO_2, Ar, N_2 and He dilutions on combustion dynamics and emission behavior in a premixed microjet flame. The results showed that CO_2 gas has higher performance in reducing combustion instability than other gases. Fan et al., [9] investigated the effect of helium dilution on hydrogen combustion efficiency in a micro-burner. The results showed that the combustion efficiency was up to 98% in case of He dilution. In addition, the low thermal capacity of Helium caused a higher flame temperature compared to N_2 dilution. Kozubkova et al., [10] investigated the effect of nitrogen and argon dilution on laminar methane flame. Chemical kinetic models were made to determine the temperature and flue gas emissions of the methane flame at different diluent ratios according to the premixed combustion mechanism. Zhang et al., [11] studied the MILD (Moderate or Intense Low-Oxygen Dilution) combustion model in methane flame using CO_2 and N_2 diluents. In the study, it was observed that CO_2 gas was much more effective than N_2 gas in providing MILD combustion conditions. In addition, CO_2 gas reduces both the flame temperature and the overall reaction rate more.

As can be seen from the literature, the combustion behavior of different fuels under different diluents, especially methane combustion, is a current issue. Among these diluents, we encounter helium, especially with its low thermal capacity in volume. In this study, unlike those in the literature, helium gas dilutions between 0% and 40% at intervals of 10% by volume were tested in a swirl-supported, premixed model gas turbine combustion chamber. In addition, the experiment was carried out at the maximum helium rate of 45% He, at which stable combustion can be sustained under the specified conditions. As a result of dilution, external acoustic enforcement was applied to the flame through the speakers located in the combustion chamber arms, and dynamic instabilities caused by the noise were determined. Thanks to this study, for the first time in the literature, the effect of Helium dilution on thermo-acoustic combustion instability in a swirl-supported, premixed burner was investigated. This study aims to burn methane gas, which is used extensively in today's industrial systems, with high stability.

2. TEST PROCEDURE

Figure 1 shows the model gas turbine combustion chamber used in the experimental study. Fuel, air and other diluent gases are mixed in the premixer before entering the combustor. Then, the first ignition is made with the pilot fire in the burner and combustion is ensured. External acoustic enforcement is applied on the flame by means of the speakers located in the combustion chamber arms. Dynamic pressure fluctuation that occur as a result of forcing at different frequencies are recorded instantly with pressure measuring devices.

Gas masses entering the combustion chamber can be controlled by means of the mass flow controllers located on the fuel, air and diluent lines to be supplied to the combustion chamber. In this way, different volumes of diluents are sent to the combustion chamber precisely. For the safety of the system, there are non-return valves on the fuel supply lines. Thanks to the safety systems, as soon as the flame flashback, the fuel flow is completely stopped. In addition, there are thermocouple devices around the combustion chamber to detect the flame temperature change at different diluent ratios.

Figure 1. Premixed model gas turbine combustion chamber

In this study, some test parameters were kept constant in order to evaluate the effect of different diluent ratios on combustion instability. The thermal power of the model gas turbine burner was determined as 3 kW, at the same time the swirl number of the swirl generator at the burner outlet was kept constant as 1. Blowoff and flashback limits of pure methane combustion were determined before starting the experiments in which the dilution effect was observed. The flashback limit for pure methane combustion was 0.91, while the blowoff limit was 0.55. According to these determined limits, 0.7 was determined as the equivalence ratio in which pure methane burned stable within the lean combustion limits and was kept constant in all experiments. In order to provide 3 kW of thermal power, 5006 sccm (standard cubic centimetre per minute) was supplied as pure methane fuel. Because determination of air flow, stoichiometric combustion equation was used. This equation was presented at Eq 1. In order to provide 0.7 equivalence ratio, 68087 sccm air flow is provided. In cases of helium dilution, the dilution of the total fuel and diluent mixture is started to be 10% by volume Helium. Then, dilutions of 20%, 30%, 40% and 45% He, respectively, were tested. As a result of dilution, both instability and temperature data of the flame were obtained. The uncertainty analysis of the experimental system used in this study was calculated as % 0.1169 [12].

$$CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 7.52N_2 \quad \text{Eq 1.}$$

3. RESULTS AND DISCUSSION

In this study, firstly, dynamic instabilities of pure methane combustion at 3 kW burning power were determined. Acoustic resonances occurred at frequencies that are the natural mode of the model gas turbine combustion chamber and large dynamic pressure fluctuation were detected. These oscillation zones were determined as 95 Hz and 160 Hz. Studies in the literature were used to determine the ranges in which resonance frequencies were detected. Wang et al [13] divided the acoustic frequency ranges under 170 Hz and above, in which instability was investigated in their study. In this study, resonance values below 170 Hz frequency were studied. The resonance situation at these frequencies is detected both by the high pressure oscillation and the data received with the sensors, and it is also heard with the ear. Figure 2 shows the dynamic pressure fluctuation amplitude in case of pure methane combustion. External acoustic enforcement can be initiated by the device at a frequency of 37 Hz. Although the dynamic pressure oscillations start to increase at this frequency due to forcing, a significant instability does not occur. The situation where the main flame becomes unstable and is forced to extinguish is in the range of resonance frequencies. When the acoustic forcing frequency was brought to 95 Hz, a great instability occurred and the flame started to oscillate with a dynamic pressure amplitude of 858 Pa. After moving away from the resonance region, it first went down to the range of about 480 Pa, and after completely separating from the resonance frequencies (105 Hz), it took a position close to the initial state. At 160 Hz, the next resonance frequency of the system, a dynamic pressure fluctuation occurred on the flame again and the difference between the highest and lowest dynamic pressure values was measured as 215 Pa.

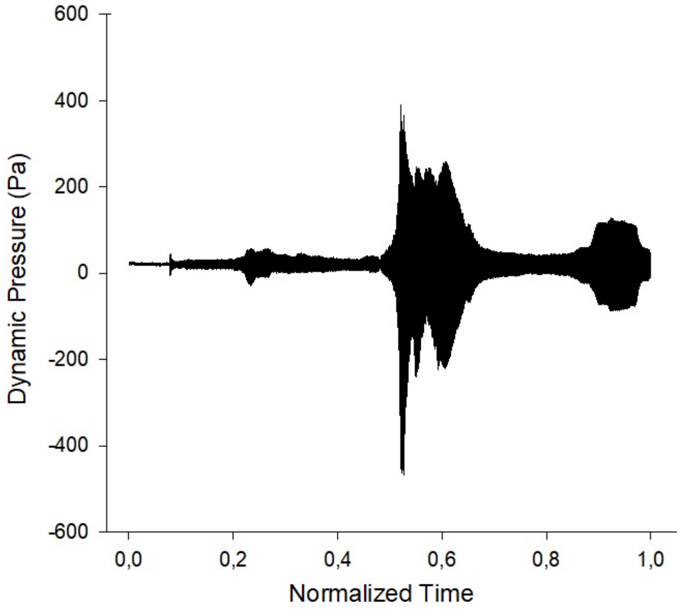

Figure 2. Dynamic pressure fluctuation of pure methane flame under acoustic enforcement

In order to see the effect of helium dilution, first of all, the characteristics of pure methane combustion were determined. In the second stage, Helium was added to the methane gas at different volumetric ratios and its effect on dynamic instabilities was investigated. Figure 3 shows the dynamic pressure amplitude of the mixture flame containing 10% He. In the flame with increasing dynamic pressure fluctuation amplitude under external acoustic enforcement, instability increased at 95 Hz frequency and a pressure amplitude of 841 Pa was determined. As in the pure methane flame, the pressure amplitude decreases to 491 Pa values as we move away from the 95 Hz frequency, and after the 105 Hz frequency it completely ceases to resonate. The difference between the highest and lowest dynamic pressure values was measured as 239 Pa at a frequency of 160 Hz, which was found to have a lower disruptive effect in pure methane flame.

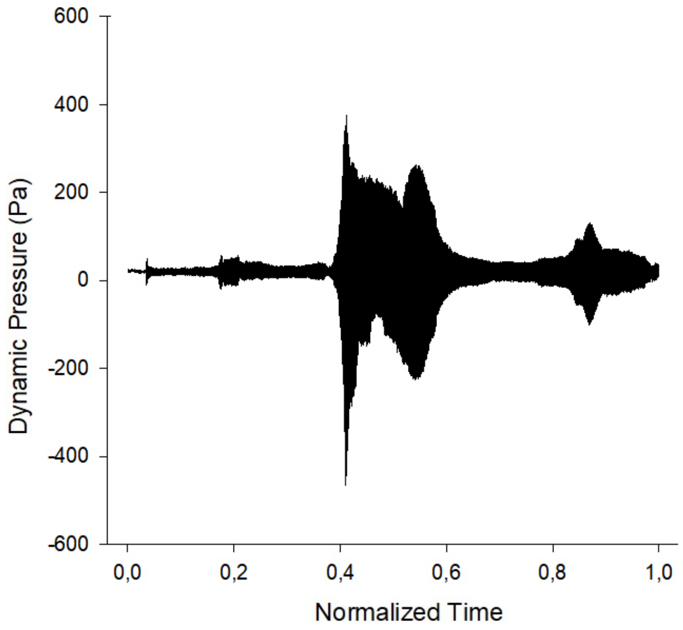

Figure 3. Dynamic pressure fluctuation of a 10% He diluted flame under acoustic enforcement

The volumetric dilution ratio has been increased to more clearly reveal the effect of helium dilution on dynamic instabilities. The dynamic pressure fluctuation graph of the mixture containing 20% He is presented in Figure 4. When an external acoustic enforcement is applied to the methane flame diluted with helium, a dynamic pressure oscillation of 840 Pa occurs at the moment of resonance at 95 Hz. The pressure oscillation, which decreases as it moves away from the resonance region, reaches 225 Pa when it comes to 160 Hz frequency again. When the dynamic pressure values are compared up to the pure methane flame and 20% helium dilution by volume, it is seen that there is no significant stability change. This can be explained by the low molecular weight and density of helium gas. Although there is a 20% helium ratio by volume, the density of methane gas is 0.717 kg/m3, while the density of helium gas is 0.1785 kg/m3 under standard conditions and 1 atmosphere pressure [14]. For this reason, little amount of helium gas added as a diluent did not cause a significant change in the properties of the methane flame.

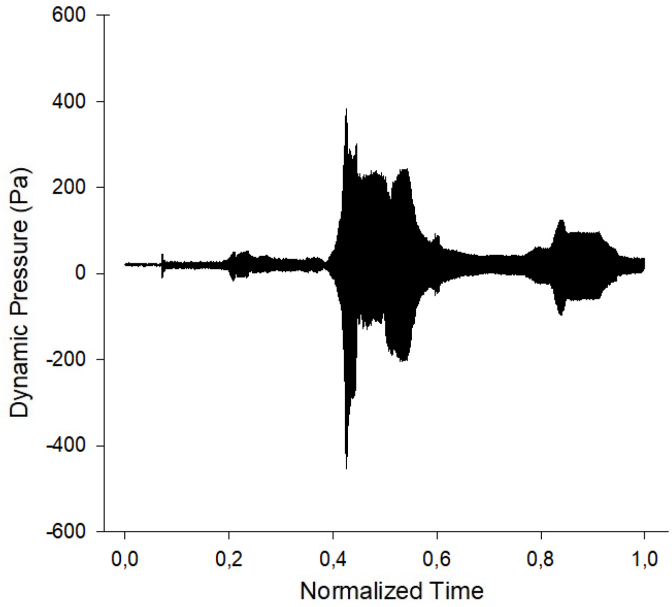

Figure 4. Dynamic pressure fluctuation of a 20% He diluted flame under acoustic enforcement

Higher helium dilution ratios were tested after seeing that the addition of Helium up to 20% by volume did not cause a significant change in stability. Figure 5 shows the dynamic pressure change of a methane flame containing 30% He. At 95 Hz, where the external acoustic forcing coincides with the natural frequency mode of the combustion chamber, a great dynamic instability occurred in the flame, resulting in a pressure amplitude of 1068 Pa. This value is the highest dynamic pressure fluctuation amplitude ever measured. On the other hand, the dynamic pressure value at 160 Hz resonance frequency was measured as 217 Pa. Tao and Zhou found in their study that the sound pressure oscillation frequency of Helium gas is higher than gases such as especially N_2, Ar and CO_2 [8]. For this reason, it is thought that the dynamic instability of the methane flame diluted with 30% helium under external acoustic enforcement is high.

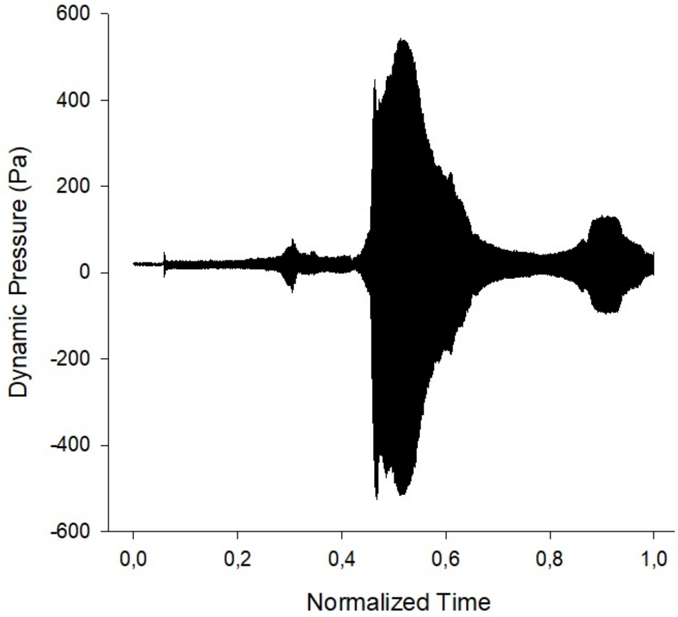

Figure 5. Dynamic pressure fluctuation of a 30% He diluted flame under acoustic enforcement

In the studies on combustion stability, it is seen that while the instability decreases up to the critical values for different burners in enrichment and dilution conditions, after this critical value, an adverse effect is observed and increases. Again, monotonous changes are not always observed in both emission values and characteristic features such as flame temperature. In this study, although flame instability increased in case of 30% Helium dilution, it was deemed necessary to test higher Helium dilutions and to examine the effect on instability. Figure 6 shows the dynamic pressure fluctuation of the methane flame diluted with 40% by volume He. There is a 988 Pa difference between the lowest and highest dynamic pressure values under the 95 Hz external acoustic enforcement frequency, which is the lowest resonance frequency of the combustion chamber. 247 Pa dynamic pressure oscillation was measured at 160 Hz frequency, where the forcing effect is lower due to the high frequency and low decibel effect.

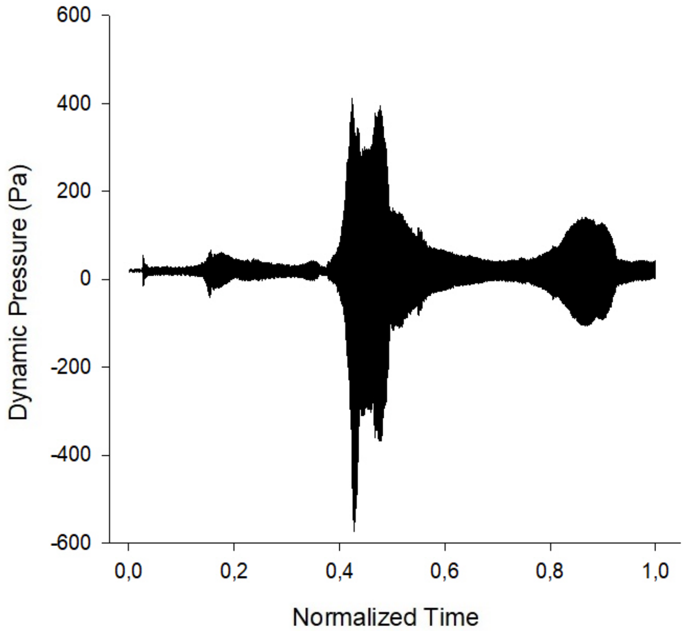

Figure 6. Dynamic pressure fluctuation of a 40% He diluted flame under acoustic enforcement

In this study, in which the effect of helium dilution on pure methane flame was observed, the volumetric helium ratio continued to be increased. Although it was desired to increase the dilution rate to 50%, after 46%, due to dilution, the methane flame fell below the lean combustion limits and experienced blowoff instability and could not continue to burn. For this reason, the flame containing 45% He, which is the highest dilution rate at which stable combustion can continue, was tested. Figure 7 shows the dynamic pressure oscillations of the flame at different acoustic forcing resonance frequencies. While the difference of 675 Pa was measured between the highest and lowest dynamic pressure values of the flame in external acoustic forcing at 95 Hz frequency, a value of 207 Pa was determined at 160 Hz, which has a lower forcing effect due to the decreasing decibel effect.

When pure methane combustion and tests performed up to 45% by volume were compared, it was observed that low dilution of Helium did not have a significant effect on thermo-acoustic instabilities of methane combustion. In fact, a negative effect has occurred due to the high sound pressure oscillation frequency of helium at the rate of 30% He. After the volumetric 30% He ratio, a critical turn occurred and the diluting effect of helium emerged more dominantly. Especially at the rate of 45% He, the dynamic pressure fluctuation amplitude in the flame was greatly reduced. This is explained by the lower molecular weight and density of helium compared to other diluents such as CO_2, N_2. For this reason, it reveals a significant effect only at high dilutions.

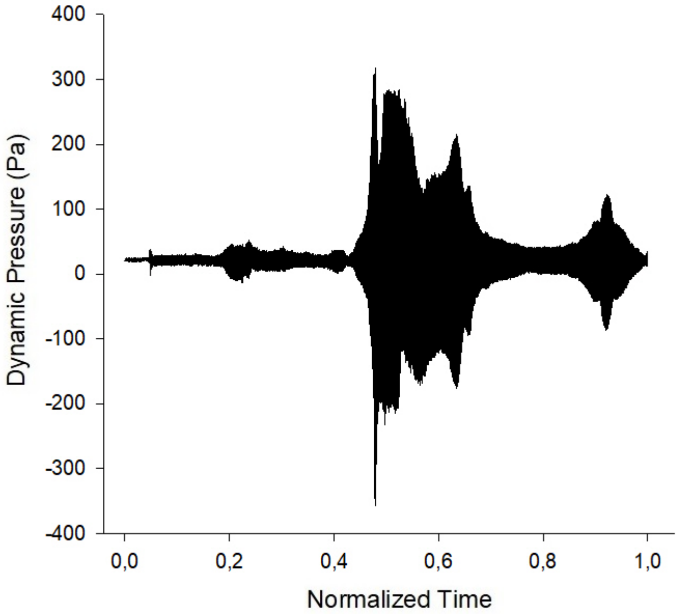

Figure 7. Dynamic pressure fluctuation of a 45% He diluted flame under acoustic enforcement

Figure 8 shows the effect of helium dilution on the burner outlet temperature of the methane flame. The flame temperature data obtained with the thermocouple placed 5 cm above the burner outlet are examined. When the data are examined, it is clearly seen that the flame temperature, which is 1054.9 K in pure methane combustion, experiences a monotonous decrease with dilution. 1050.5 K, 1043.4 K, 1010.9 K, 984.8 K and 980.4 K values were measured at 10%, 20%, 30%, 40% and 45% He ratios, respectively. Since helium has no calorific value and is used as a diluting gas, it is expected that the flame temperature will decrease. In addition, the flame temperature reduction trend was low up to 20% He, where there was no significant change in the flame stability data, while a greater decrease in temperature was observed after 30% He dilution.

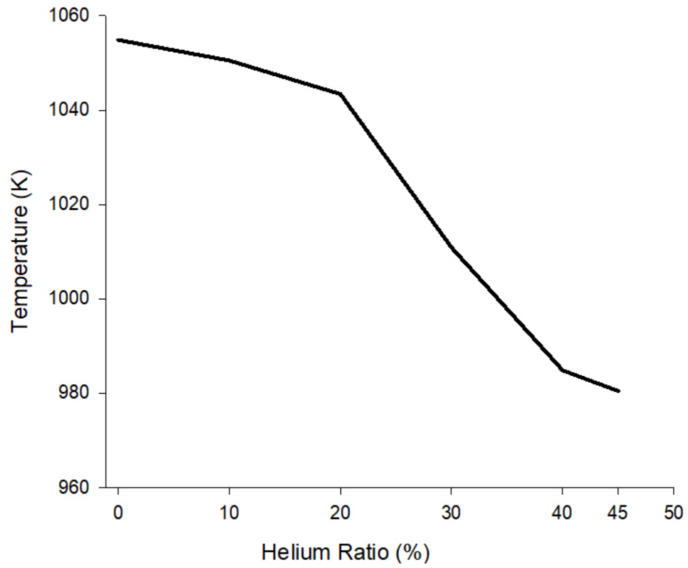

Figure 8. Effect of Helium Ratio on Flame Temperature

4. CONCLUSION

In the study where the effect of helium dilution on the combustion instability and flame temperature values of pure methane flame at 3 kW burning power and 0.7 equivalence ratios, the following results were determined;

- It has been determined that due to the low density of helium gas, it does not have a significant effect on instability at low dilution ratios.
- High instability was detected at 30% He dilution due to the high sound pressure oscillation of helium.
- At high helium dilution ratios, the sound wave pressure suppression feature is more prominent, and the helium 45% He reduces the instabilities.
- Pure methane flame could not be further diluted after 46% He and fell below the lean burning limit and experienced blowoff.
- While helium dilution monotonically lowered the flame temperature at all increase rates, the temperature decrease rate increased after 30% He.

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DECLARATION OF ETHICAL STANDARDS

The authors of the paper submitted declare that nothing which is necessary for achieving the paper requires ethical committee and/or legal-special permissions.

CONTRIBUTION OF THE AUTHORS

Buğrahan ALABAŞ: Performed the experiments, analyse the results and wrote the manuscript.
Adem ALTINAY: Performed the experiments.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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