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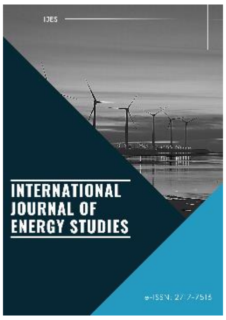


Research Article

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# Examination of combustion behaviors and emissions of hydrogen enriched propane/methane fuel under external acoustic application

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**Highlights**

- Investigating combustion behavior of hydrogen enriched propane/methane fuel
- Investigation flame instability under different acoustic stress
- Measurement of temperature and emission under different mixture and external acoustic enforcement
- Flame temperature and its brightness increases for all hydrogen enriched propane/methane fuel conditions

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## ABSTRACT

In this study, the instability and emission changes of hydrogen-enriched methane-propane fuel under external acoustic application in a premixed and vortex assisted system were investigated. In the experiment, 67% -33% and 63,5% -31,5% -5% were studied under different acoustic stresses as fuel mixtures. It is known that hydrogen can reduce the emission parameters polluting the environment and its effect on combustion stability. For this reason, interest in the use of hydrogen fuel with other fuels has increased. It may be possible to improve the combustive performance properties of compatible methane and propane mixtures by adding hydrogen. Also, the effects of acoustic applications were examined. Addition of hydrogen to the methane/propane flame increased the heating value of the mixture and caused flame instability due to the increase in laminar flame velocity. There was an increase of 12.2% in light intensity. When the amount of hydrogen increased, the flame was more resistant to acoustic stress. High dynamic pressure fluctuations occurred with 90 Hz acoustic forcing. The emission capacity of the mixture to which hydrogen is added by acoustic forcing has consistently higher values. This was attributed to the change in reaction kinetics due to the increased content.

**Keywords:** Propane, Methane, Hydrogen enriched, Acoustic enforcement, Emissions

## 1. INTRODUCTION

The increasing population in the world reveals the need for more energy every day. The increase and consumption of energy resources cause an increase in emissions. Many scientists contribute with different studies to reduce the emission hazard. One of them is the more efficient use of hydrogen. Hydrogen is preferred because it is a renewable fuel type. Hydrogen addition is an important and current method to reduce the emission rate to low levels. Hydrogen has a higher calorific value by mass than other hydrocarbon fuels.

In this experiment, hydrogen addition to fuel mixtures were investigated numerically. Thermodynamic analysis of hydrogen addition was carried out. It was stated that laminar combustion rates increased with hydrogen fractions [1]. The effect of hydrogen gas on methane flame chemical kinetics and explosion parameters was investigated. Consequently, the flammability limits expand with the addition of hydrogen [2]. In this article, it is investigated how hydrogen addition affects combustion parameters in a MILD model combustor with methane fuel. With the addition of hydrogen, the stable operating range is narrowed [3]. When the hydrogen ratio was increased by 40%, the flame front velocity and explosion pressure were greatly affected [4]. Fuel elasticity and combustion parameters of methane/hydrogen mixtures under flameless conditions were investigated numerically and experimentally. When hydrogen addition to methane fuel is increased, combustion performance increases and ignition delay time is shortened [5]. The stability and emission values of hydrogen supported oxymethane flames in a model gas turbine burner were investigated. It expands the burner operability limits (higher throttling rate).

$CO$ emission increased with the increased hydrogen amount. The addition of $H_2$ increases reaction rates under high equivalence ratios [6]. The effect of hydrogen enrichment on methane and syngas fuels in a MILD burner was numerically investigated. The volume of the high temperature zone increased with hydrogen doping. Compared to the methane gas, the effect of hydrogen on the synthesis gas was observed more [7]. The effect of hydrogen additive on the flame of low calorie gaseous fuels was investigated. In the results, it was stated that the volumetric efficiency of the engines increased [8]. The effect of hydrogen on premixed propane/air combustion in a microplanar combustor was investigated. In the results, a more stable combustion occurred with the addition of $H_2$ [9]. Combustion parameters were investigated experimentally and numerically by enriching the $CH_4$-$O_2$-$CO_2$ mixture with hydrogen in a model gas turbine burner. In the results of the study, the reaction rates have increased and the flames are more compact and intense [10].

Combustion of pure methane and natural gas in a unmixed burner system was investigated. In hydrogen enrichment, the flame structure expanded and decreased carbon emissions and increased $NO$ emissions [11]. Addition of hydrogen to biogas mixtures on laminar combustion rate was studied. It has been stated that the laminar burning rate increases linearly [12]. Hydrogen enrichment of oxygen-rich methane-propane mixtures was investigated. It was observed that the ignition temperature of the mixture increased by 140 K [13]. The instability of hydrogen addition to oxygen-enriched fuel mixtures and combustion properties under acoustic stress were investigated. The increase of both oxygen and hydrogen additions increased the instability. It was stated that the $CO$ emission rate increased [14].

The combustion instability effect of hydrogen is still a topical issue. The aim of this study is to support the development of burners with lower carbon emissions by focusing on the stable combustion of propane fuel in premixed and vortex assisted burners. For this reason, he experimentally investigated the variation of methane/air combustion with hydrogen addition. Flame reaction increased with the effect of hydrogen in laminar flame. The heat release increased to the highest speed and the average temperature decreased. Combustion efficiency has increased [15]. The effect of hydrogen added to propane gas on combustion parameters was investigated. The dilution effect of hydrogen has been limited. The radiation fraction was slightly affected. The activation energy of the $C_3H_8/H_2$ mixture tended to decrease rapidly [16].

Despite these studies, there are deficiencies in the studies on methane/propane flame in different burners and conditions when compared to other hydrocarbon fuels. Thus, in this study, which is used in industrial burners, hydrogen was added to the combustion of methane and propane in a premixed and vortex supported burner, which is missing in the literature. To examine the addition of hydrogen on flame instability, the fuel was subjected to external acoustic forcing at different frequencies.

## 2. EXPERIMENTAL CONDITIONS AND EQUIPMENT

### 2.1. Experimental Conditions

Fuel mixtures containing 67% $CH_4$-33% $C_3H_8$ and 63,5% $CH_4$-31,5% $C_3H_8$-5% $H_2$ were burned under standard air conditions containing 21% $O_2$ by volume. Table 1 presents the physical values of propane, methane and hydrogen fuels used in the experiment. The air required for theoretical combustion was calculated using the stoichiometric combustion equation. First, the blowback and blowback limits of the mixture were determined. The flashback limit was determined as 1.57 equivalence rate, and the blowoff limit was determined as 0.65 equivalence rate. In this experiment, 1.1 equivalence ratio with stable combustion was kept constant throughout the experiment. A generator with a vortex number of 1.0 was used. The burner is powered by this swirl generator. The experiments carried out at 5 kW burner power. The test was carried out at room temperature and a pressure of 20 mbar. Air and fuel ignite in the burner surrounded by the combustion chamber, creating a flame. Fuels are supplied from tanks. These are $CH_4$, $C_3H_8$ and $H_2$ tanks, respectively. Firstly, the acoustic modes of the combustion chamber were determined. The resenounce values of the combustion chamber were found by following the abrupt dynamic pressure changes. These external acoustic modes for this combustion chamber values are 90, 160, 310 Hz.

**Table 1.** Propane, methane and hydrogen properties

| Chemical formula | $C_3H_8$ | $CH_4$ | $H_2$ |
|---|---|---|---|
| Molecular weight (g/mol) | 44.097 | 16.043 | 2.016 |
| Density (g/liter) | 1.8917 | 0.718 | 0.083 |
| Boiling point (°C) | -42.1 | 112,03 | -252.87 |
| Lower Heating Value (MJ/kg) | 46.4 | 50,050 | 119.93 |
| Flame Speed (m/s) | 0.4 | 0.54 | 0.77 |
| Stoichiometric air/fuel | 15.8 | 17.3 | 34.48 |
| Energy content (MJ/l) | 25.4 | 8.080 | 120.1 |
| Burning Velocity (cm/sec) | 32 in air | 35.6 | 325 |
| Wobble Index (MJ/Nm3) | 81.07 | 48.21 | 40.9 |

## 2.2. Experimental Equipment

The schematic diagram of the experimental setup is given in Figure 1, and a real section is given in Figure 2. The mixture of methane-propane enriched with 5% hydrogen was experimentally studied in a premixed and vortex supported system at Erciyes University. In the experimental system, the vortex generator part is designed as replaceable. The detailed view of the burner is shown in Figure 3. 1.0 Swirl number (1) was used for vortex. There are different inlets on the combustion chamber that allow taking emission and temperature values from different axial regions. There is a loudspeaker capable of external acoustic forcing on both extension arms. It creates a safe environment with its burner system, which works with an automatic system against an explosion. In a dangerous situation, gas cutting is done by itself. Mass flow controllers (MFCs) automatically regulate the amount of fuel and air supplied to the combustion chamber. Three of the thermocouples in the flame region can measure temperatures up to 1800 °C, while the other six can measure temperatures up to 1200 °C. There are two types of pressure gauges in the system. The piezoresistive pressure gauge can measure pressure changes between 0 and 10 bar. Dynamic pressure gauges (±622 Pa) continuously record pressure fluctuations under acoustic force. Measure of the gas emission were made by means of a portable flue gas analyzer. Values taken from the system are stored instantly with the software called ProfiSignal Go. All data are stored on the computer with the data logger.

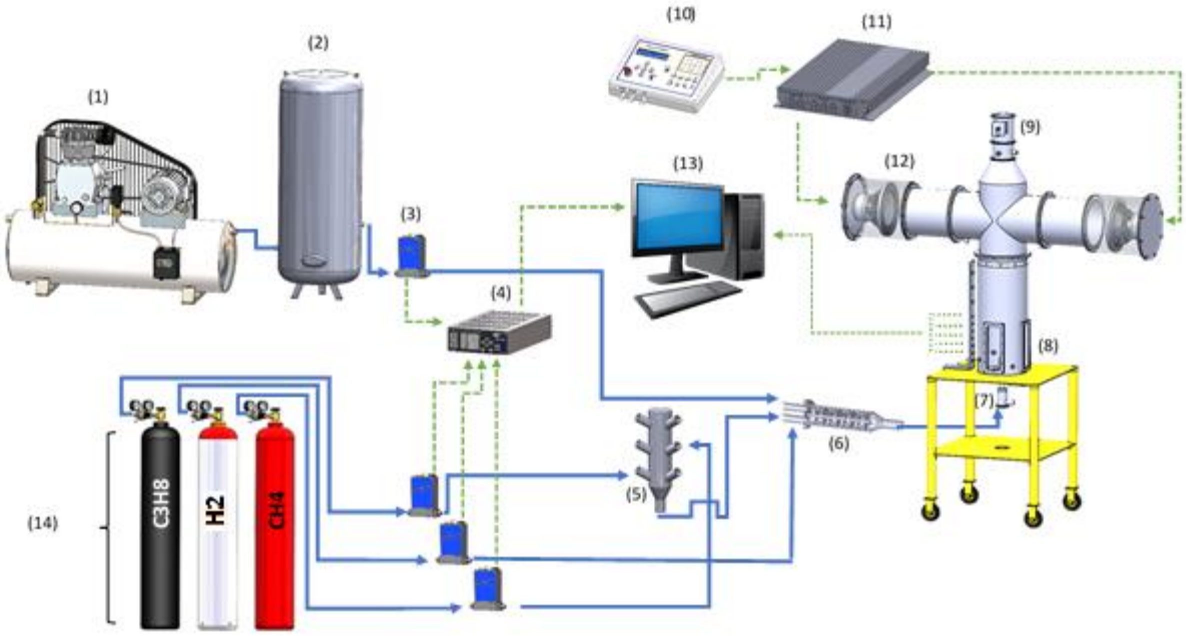


**Figure 1.** Experimental setup

1.Air Compressor 2. Air Vessel (1 $m^3$) 3. Mass Flowmeter Controller (MFC) 4. Vacuum System Controller 5. Gas Fuel Collector 6. Mixer 7. Premixed Burner 8. Combustion Chamber 9. Flue Signal 10. Generator 11. Amplifier 12. Loudspeaker 13. Computer 14. Gas Cylinders

**Figure 2.** A view of the experimental setup

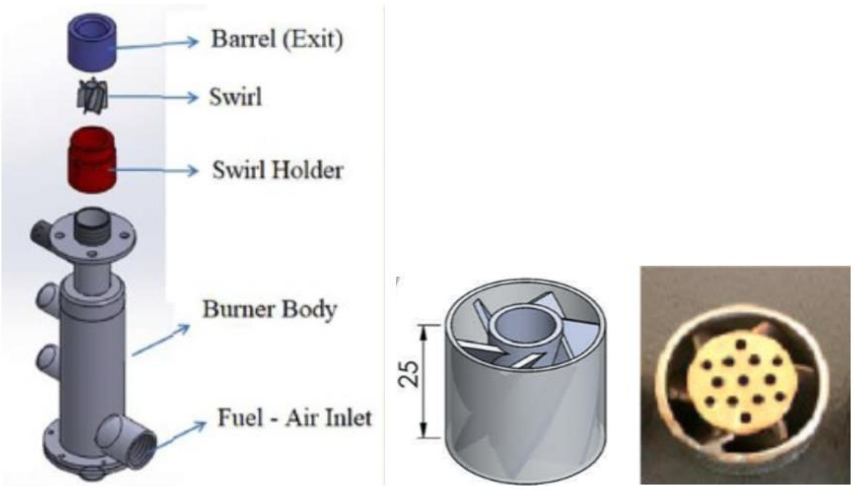


**Figure 3.** Burner and swirl generator detailed design

## 3. RESULTS AND DISCUSSION

This section focuses on the 2B thermocouple temperature, flue gas temperature, dynamic pressure, light intensity and $CO$ emission values of hydrogen addition (5%) and acoustic forcing.

### 3.1. Temperature, Dynamic Pressure, Luminous Intensity Values and Emissions

The values of the 2D thermocouple temperature under acoustic stress are shown in figure 4. The mixture with higher calorific value in gases (63,5% $CH_4$-31,5% $C_3H_8$-5% $H_2$) showed a higher temperature trend in the burner. Hydrogen has a high burning rate, so the reaction of carbon and hydrogen with oxygen accelerates and accordingly the flame temperature increases. Under the first stress (90 Hz), the temperature value decreased to the lowest level as a result of dynamic instability. Here the temperature was found to be 1115 K. In the case where the dynamic instability was removed, the temperature increased to the values at the unforced level (1129 K). The temperature increased with 160 Hz acoustic forcing and decreased again under 310 Hz forcing.

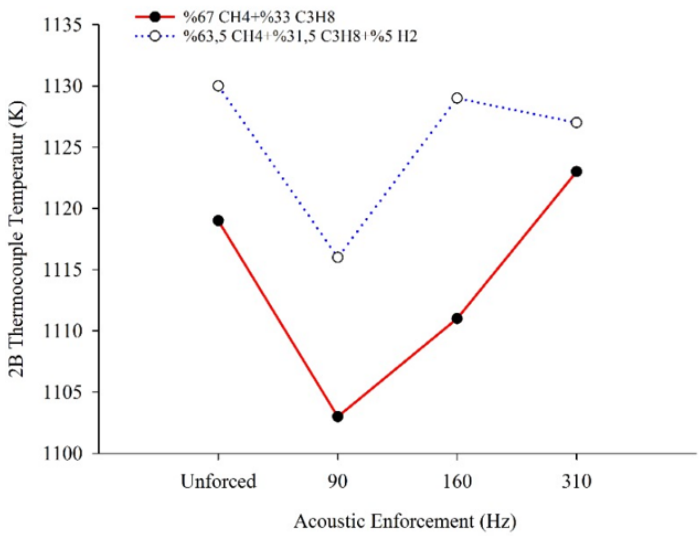


**Figure 4.** 2B thermocouple temperature for different acoustic enforcement

In Figure 5, the variation of flue gas temperature of 67% $CH_4$-33% $C_3H_8$ mixture and 63,5% $CH_4$-31,5% $C_3H_8$-5% $H_2$ mixture with acoustic forcing was investigated. The flue gas temperature values of the hydrogen mixture were generally higher. The highest temperature was measured 66 °C at 160 Hz forced condition in hydrogen-added fuel, and the lowest temperature was 142 °C in non-hydrogen mixture under unforced conditions. In addition, hydrogen has a high adiabatic flame temperature. More heat is released due to hydrogen. This is clearly seen in the graph.

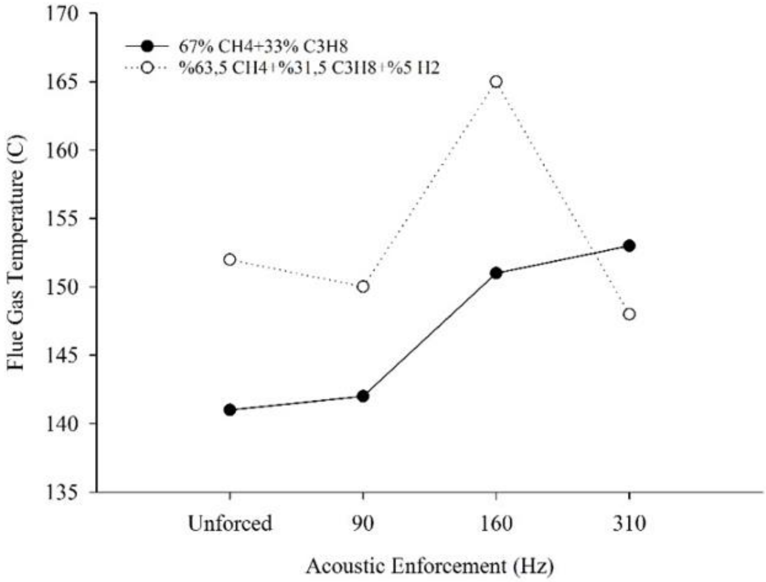


**Figure 5.** 2B flue gas temperature for different acoustic enforcement

Flame stability changes of the gas mixture (63,5% $CH_4$-31,5% $C_3H_8$-5% $H_2$) are interpreted using dynamic pressure, flame temperature and light intensity values. The dynamic pressure under acoustic stress are shown in Figure 6. Frequency values where pressure fluctuations increase significantly are the resonance regions where the flame is exposed to instability [17]. These values are frequencies of 90, 160 and 310 Hz. Thermo-acoustically unstable flames generate higher pressure fluctuations. With the low frequency resonance of 90 Hz, the dynamic instability reached its maximum values. Although the flame showed an unstable combustion at 90 Hz frequency, it clung to the burner and continued to burn. While the dynamic pressure fluctuation at the 90 Hz resonance frequency was measured as 673 Pa, the amplitude of 224 Pa at 160 Hz and 428 Pa at 310 Hz was determined with the increase in frequency. The lowest dynamic pressure change was observed at 160 Hz, which is the mid-frequency resonance region.

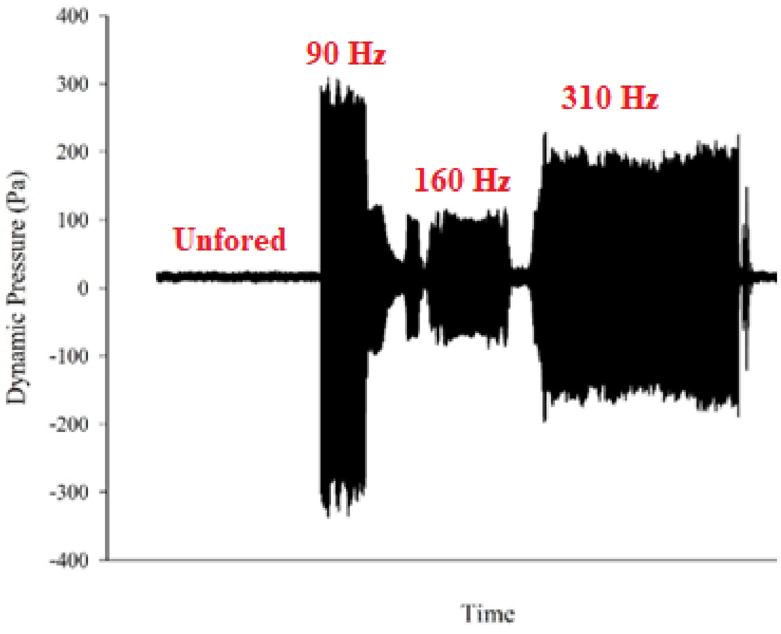


**Figure 6.** Natural acoustic mode of combustion chamber (63,5% $CH_4$-31,5% $C_3H_8$-5% $H_2$)

Figure 7 shows the dynamic pressure graph of 67% $CH_4$-33% $C_3H_8$ mixture under three different acoustic stresses. Dynamic stability was achieved at the highest level with 90 Hz forcing. Here, the dynamic pressure amplitude value was measured as 873.5 Pa. Dynamic pressure value was declined at 160 Hz. The dynamic pressure increased at 310 Hz compared to 160 Hz, but remained low compared to 90 Hz. Despite the persecuted, the flame continued to burn by maintaining its balance. The dynamic instability level is higher than the hydrogen added mixture. The increasing of hydrogen amount increases the flame stability.

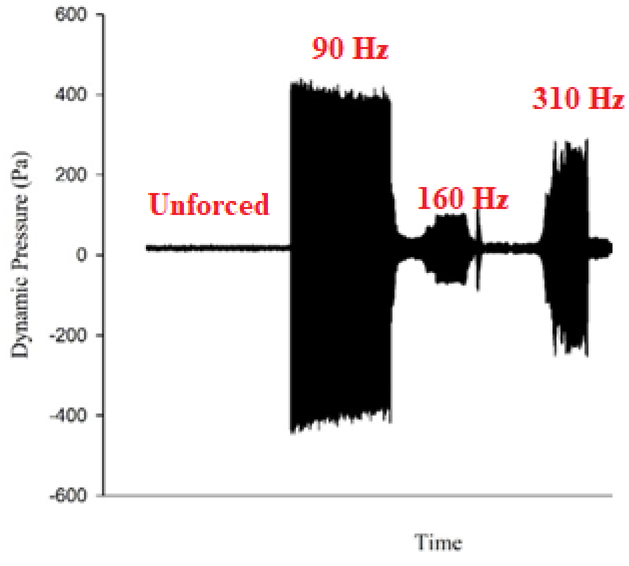


**Figure 7.** Natural acoustic mode of combustion chamber (67% $CH_4$-33% $C_3H_8$)

The luminous intensity values for both mixtures under acoustic forcing are presented in Figure 8. The increase in the thermal value caused an increase in the light intensity. There was a significant increase in light intensity as a result of hydrogen addition. Both mixtures showed the same trend under acoustic stress. For the hydrogen added mixture, the luminous intensity values of 94.32 mV, 109.67 mV and 110.7 mV were measured at the resonance frequencies of 90 Hz, 160 Hz and 310 Hz, respectively. For the normal methane/propane mixture, the luminous intensity values of 68.02 mV, 97.12 mV and 105.34 mV were measured at the resonance frequencies of 90 Hz, 160 Hz and 310 Hz, respectively. Luminous intensity under non-forced conditions was lower than the mid and high frequency resonance region values. This indicates that the acoustic forcing in the resonance regions has a positive effect on the light intensity.

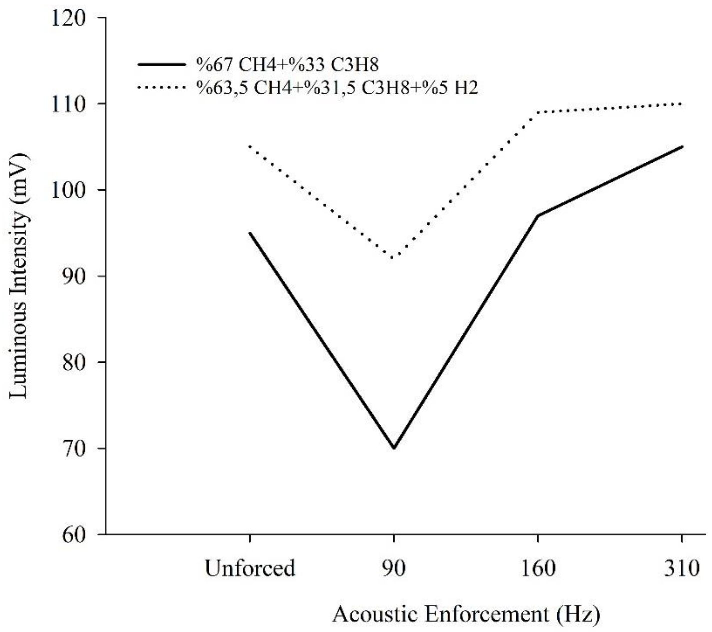


**Figure 8.** Luminous intensity under different acoustic stress

In Figure 9, the different emission graph trend of both mixtures is shown. Both mixtures, whose emission values are close to each other in the unconstrained environment, started to take different values at the beginning of the acoustic forcing. In the hydrogen added mixture, the emission value increased at each forcing level and the $CO$ values increased to the maximum level (725 ppm) in the high frequency level. Emission values of hydrogen-free methane/propane mixture decreased under all three acoustic stresses. The value which is 181 ppm in the low frequency is measured as 100 ppm. The $CO$ emission capacity of the hydrogen-added mixture was consistently higher. This was attributed to the change in reaction kinetic thanks to increased $H_2$ content. The high CO emission is due to reaction kinetics of the methane/propane/hydrogen mixture, low flame temperature and poor combustion conditions. Normally, the amount of $CO$ emissions decreases with the addition of hydrogen. With the addition of hydrogen, the carbon amount is reduced. With the addition of hydrogen, the reaction rate in its fractions increases, so the $CO$ concentration decreases [18]. But since the effect of acoustic forcing is very high, the $CO$ rate has increased a lot.

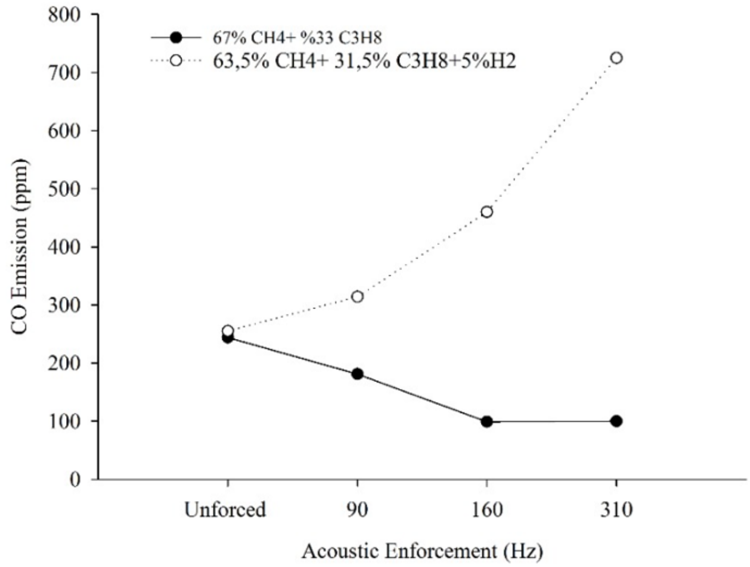


**Figure 9.** $CO$ emission for different acoustic enforcement

## 4. CONCLUSIONS

In the article, flame instabilities and emission of two fuel mixtures 67% $CH_4$-33% $C_3H_8$ and 63,5% $CH_4$-31,5% $C_3H_8$-5% $H_2$ under external acoustic stress were investigated. The results can be summarized as follows:

- The adding 5% hydrogen increased the flame stability and light intensity in the methane/propane mixture.
- Flame temperature and luminous intensity showed non-monotonic behavior because of dynamic instability.
- With acoustic forcing, the dynamic stability decreased in the resonance region (90 Hz) where the acoustic stress was high, and then increased.
- $CO$ emission value did not change much with the addition of hydrogen, but had a different tendency under acoustic stress. While the emission values with acoustic forcing had a negative effect in the mixture containing hydrogen addition, it had a positive effect in the mixture without hydrogen addition.

- Hydrogen additon positively affected the combustion chamber temperature of the methane-propane mixture.

## NOMENCLATURE

Hz: Hertz

mV: Millivolts

ppm: Parts Per Million

K: Kelvin

Pa: Pascal

°C: Celsius

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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

**Murat Tastan:** Bringing the idea, planning the method, numerical calculations, evaluation and interpretation of the results, final check of the paper template.

**Kamil Mutlu:** Numerical calculations, evaluation and interpretation of the results, preparation of the manuscript.

**Serdar Cetintas:** Conducting the literature review, evaluation and interpretation of the results, final check of the paper template, and proofreading.

## CONFLICT OF INTEREST

There is no conflict of interest in this study.

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