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Research Article

Experimental Investigation of Different Shale Gases in a Premixed Combustion Chamber

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Abstract

The negative consequences of global climate change have increased day by day in the world. For this reason, it has been revealed that people should use fuels that produce less emissions. The aim of the presented study is to determine the effects of shale gas components on emission characteristics and temperature distribution. In this study, combustion and emission behaviors of shale gas mixtures with different CH_4/ C_3H_8 / CO_2 /N_2 contents were experimentally investigated. Emission and temperature measurements were performed at four different swirl numbers (0.2/0.6/1.0/1.4), at a thermal power of 4 kW and an equivalence ratio of 0.7. In the experiments, 6 different shale gas mixtures were used. As a result of this study, it has been seen that emission values vary greatly depending on the content of the shale gas. It has been also observed that all shale gases create more NO_x, CO and CO_2 values than pure methane. C_3H_8 value in the shale gas mixture caused an increase in NO_x amount, axial temperature values and flue gas temperature. As the CO_2 content increased, the CO value increased, while the NO, axial temperature and flue gas temperature values decreased.

Keywords : Shale gas, combustion, swirl, emission.

Ön Karışımlı Bir Yanma Odasında Farklı Kaya Gazlarının Deneysel Olarak İncelenmesi

Öz

Dünyada küresel iklim değişikliliğinin negatif sonuçları gün geçtikçe artmıştır. Bu sebeple insanların daha az emisyon üreten yakıtlara yönelmesi gerektiği ortaya çıkmıştır. Sunulan çalışmanın amacı; kaya gazı bileşenlerinin emisyon özellikleri ve sıcaklık dağılımı üzerindeki etkisini belirlemektir. Bu çalışmada, farklı CH_4/ C_3H_8 / CO_2 /N_2 içeriklerine sahip kaya gazı karışımlarının yanma ve emisyon davranışları deneysel olarak incelenmiştir. 4 kW ısıl güç ve 0,7 eşdeğerlik oranı ile dört farklı girdap değeri (0.2/0.6/1.0/1,4) kullanılarak emisyon ve sıcaklık ölçümleri incelenmiştir. Deneyde 6 farklı kaya gazı karışımı kullanılmıştır. Bu çalışma sonucunda kaya gazlarının içeriğine bağlı olarak emisyon değerlerinin büyük farklılıklar gösterdiği görülmüştür. Tüm kaya gazlarının metandan daha fazla NO_x, CO ve CO_2 değeri oluşturduğu gözlemlenmiştir. Kaya gazı karışımındaki C_3H_8 değeri NO_x değerinde, eksenel sıcaklık dağılımında ve baca gazı sıcaklığında artışa neden olmuştur. CO_2 oranındaki artışla CO değeri artarken NO, eksenel sıcaklık ve baca gazı sıcaklık değerleri azalmıştır.

Anahtar Kelimeler: Kaya gazı, yanma, girdap, emisyon.

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1. Introduction

People's perceptions of energy are constantly changing. Electronic tools and devices that we use in our social life are getting more and more involved in our lives every day. Each person consumes more energy than before. In addition, the amount of energy used in the sector should increase in order to meet the needs of people for a more comfortable and luxurious lifestyle. The future of energy resources, which are very limited in the world, leads countries to think differently. For this reason, there is a trend towards new and renewable energy sources that are more ecologically harmless. Shale gas is often considered a transition fuel for a low-carbon economy because it burns efficiently and cleaner than other fossil fuels (Rivard et al., 2014). With the prominence of the concept of energy efficiency in the world, research on alternative fuels and renewable energy sources is increasing. Shale gas, which is very popular today, is one of these alternative fuels. Shale gas, which is important for many countries, is more evenly distributed around the world than other oil resources (Ahıshalı, 2013). The presence of shale gas directly or indirectly causes changes in the political, economic and social fields (Stevens, 2012).

Shale gas is a mixture whose main ingredient is methane. (Contains more than about 80% methane) It also has heavier hydrocarbons such as ethane and propane, in addition to other inorganic gases such as nitrogen and carbon dioxide (Bullin and Krouskop, 2009). The composition of produced gas is not constant and it differs from formation to formation. Even between spaces in the same formation, the properties of the content can change (Al-Douri et al., 2017).

Shale gas reservoir areas consist of sedimentary rocks that are very rich in organic matter and have very fine-grained structures. Shale gas reservoirs are also composed of fissile, mudstone, indivisible material called shale. Shale can be a source rock alone, or it can be both source rock and reservoir rock (Kök and Merey, 2014). Under the influence of temperature and pressure, animal and plants remain undergo some transformations. These organic materials are converted into kerogen, oil, wet gas and dry gas under pressure and temperature. Gases in some shales can be released and rise to the surface through cracks and faults caused by natural expansion from the shale. However, sometimes the gases in the shale rocks cannot be displaced and become trapped in the source rock (Ratner and Tiemann, 2013). Shale gas is actually an unconventional natural gas (NG) (Karsli, 2015). In addition, shale gas is an important alternative energy source. Shale gas production is a method of extracting natural gas trapped between underground rocks at deeper distances. Shale gas production is mostly economical with horizontal drilling and hydraulic fracturing methods (Demirbaş et al., 2018). New techniques for the extraction of unconventional gas have been positively affecting the availability of natural gas in recent years. The most important technique is the combined use of horizontal drilling and hydraulic fracturing, which produces very high volumes of shale gas (Gomeza et al., 2017).

In the literature, there are more studies on the extraction of shale gas in general. Since it is a new type of fuel, there are very few studies on shale gas combustion in the literature. In a numerical study, Yilmaz investigated the effects of fuel composition and swirl number on the combustion and emission properties of shale gas mixtures in a laboratory scale combustor. Author observed that NO_x emission is highly dependent on gas composition and swirl number. It was also observed that axial temperature values and the reaction rate increased proportionally with the number of swirl (Yilmaz, 2019).

Ozturk studied turbulent and non-adiabatic combustion characteristics of shale gas and moist air mixture in a cylindrical combustor. Author investigated temperature and emission parameters, and diluting effects of CO_2, H_2O and N_2 (which were added to combustion air). The new Albany shale gas produced higher NO_x values because it has high C_2H_6 and C_3H_8 contents. Dilutions increased the CO mass fractions in all shale gases. CO_2 showed the greatest effect on the reduction of the reaction temperature (Ozturk, 2020).

Liu et al., investigated the variation of OH free radicals in the jet diffusion flame of two different shale gas mixtures and the effects of shale gas composition on methane mass fraction, combustion rate and temperature field. It was observed that shale gas formed a higher methane mass fraction at the flame peak during the diffusion combustion process. Shale gas with a mass ratio of 93.5% methane had the highest combustion temperature and the fastest burning rate (Liu et al., 2015).

El Sherif built an experimental set up to investigate CO, O_2 and NO_x concentrations and gas temperature. Author designed a model with a detailed representation of transport flows to predict experimental results. It has been seen that estimated and measured CO and NO_x values are very compatible. The flame structure and burning velocity of Egyptian natural gas varied greatly depending on the ethane ratio. NO_x increased with the increase of ethane content in Egyptian natural gas (El Sherif, 1998).

Seo et al. investigated flow and combustion characteristics of a shale gas-fired combustor in a commercial grade gas turbine using three-dimensional numerical simulation. It was determined that NO_x concentration in the city gas was higher than the other three shale gase mixtures. Thermal mechanism dominates NOx formation in shale gas 1 ($\%85CH_4$-$\%15N_2$) and shale gas 2 ($\%85CH_4$- $\%5C_3H_8$-$\%10N_2$) combustion. It was observed that local temperature increased as ethane and propane content increased (Seo et al., 2019).

Kakaee has conducted a research on how compositions in natural gas affect combustion and emission characteristics of internal combustion engines (ICEs). In general, they stated that fuels with higher wobbe number (WN) and larger energy content create more efficient fuel economy and emit less carbon dioxide (CO_2) emissions. Nitrogen oxide (NO_x) emissions also increased for gases with higher WN. It showed some decreases for total hydrocarbons (THCs) and carbon monoxide (CO) gases (Kakaee, 2014).

Vargas et al. investigated laminar combustion rates of three shale gas mixtures both numerically and experimentally. They also measured other properties such as the thickness of the flame fronts, low and high temperature values, Wobbe indices, flammability limits, dew points and adiabatic flame temperatures. The laminar combustion rate for all selected shale gas mixtures and methane showed very similar trends. The gas with the best Wobbe index was shale gas 1 (86% CH4– 14% C2H6), which does not contain inert gas (Vargas et al., 2016).

Cellek investigated soot formation of methane and various shale gas mixtures with different components in a combustion chamber under lean mixture conditions. Flame characteristics show that although flame temperatures are close to each other, they differ, albeit relatively. shale gas emitted the highest amount of soot during combustion. Although methane emits as much intermediate products as Barnett shale gas, methane emits the least soot. When the C/H ratio increases in hydrocarbon fuels, the amount of soot emitted from the flame also increases (Cellek, 2021).

Liu et al., investiagted effects of initial temperature, initial pressure and equivalence ratio on laminar combustion rate of shale gas. When an engine is fuelled by shale gas, combustion rate decreases and affects stability of the engine. At initial temperature, when the flame propagation velocity increased, the Markstein length slightly increased, the pre-flame stabilized, the adiabatic flame temperature increased (Liu et al., 2020).

In this study, effects of swirl number and gas composition on combustion and emission characteristics of six different shale gas mixtures were experimentally investigated at 4 different swirl number and at a fixed thermal power (4 kW) and equivalence ratio (0.7). For this purpose, a premixed combustion system that enables testing of different gas mixtures was built. First, pure methane was combusted at relevant conditions and achieved results were used as a baseline to compare results obtained from combustion of shale gas mixtures.

2. Material and Methods

In this study, shale gas mixtures were prepared separately by choosing different ratios of $CH_4/C_3H_8/CO_2/N_2$ contents. Tested shale gas mixtures are: K1-%85CH_4- %5C_3H_8- %0CO_2-%10N_2, K2-%85CH_4-%10C_3H_8- %0 CO_2- %5N_2, K3-%85CH_4-%5C_3H_8- %5CO_2-%5N_2, K4-%85CH_4 - %10C_3H_8 - %5CO_2-%0N_2, K5-%85CH_4 - %5 C_3H_8 - %10 CO_2-%0 N_2, K6-%80 CH_4 - %10 C_3H_8 - %5 CO_2 -%5 N_2.A 6-channel control station (MKS Series 946) was used to control the flow meters. The control station allows the desired amount of gas to pass through 4 different flow meters. Before starting the experimental measurements, the experimental setup was operated for 30-40 minutes to obtain a stable combustion regime. After the combustion was stable, emission and temperature measurements were made.

Table 1. The Properties of the Used Fuels

Gas Mixture	Gas Density (kg/m^3)	LHV (mj/m3)	HHV (mj/m^3)	Mass Flow Rate (kg/h)	Wobbe Index (MJ/m^3)
K1	0.808449024	35.13	38.37	0.331343671	47.83
K2	0.854762846	39.58	42.91	0.310934289	52.37
K3	0.856959047	35.17	38.37	0.350842822	46.84
K4	0.901035223	39.53	42.91	0.328172728	51.33
K5	0.903298521	35.06	38.37	0.370943286	45.90
K6	0.918760436	37.91	40.92	0.348953443	48.24

2.1. Equipment in the Test System

The schematic view of the experimental system is given in Figure 1. The test system shown in the figures has a gas supply line, a pre-mixer and a swirl burner so that different shale gas mixtures can be composed in the desired compositions. Air supply was provided by a compressor. The desired fuel mixture was formed using separate gas tanks (methane, propane, carbon dioxide and nitrogen). Emission and temperature measurement ports are located at different distances from the burner exit. Emission and temperature measurements were made using these ports. There is also a combustion chamber window that allows flame to be optically observed.

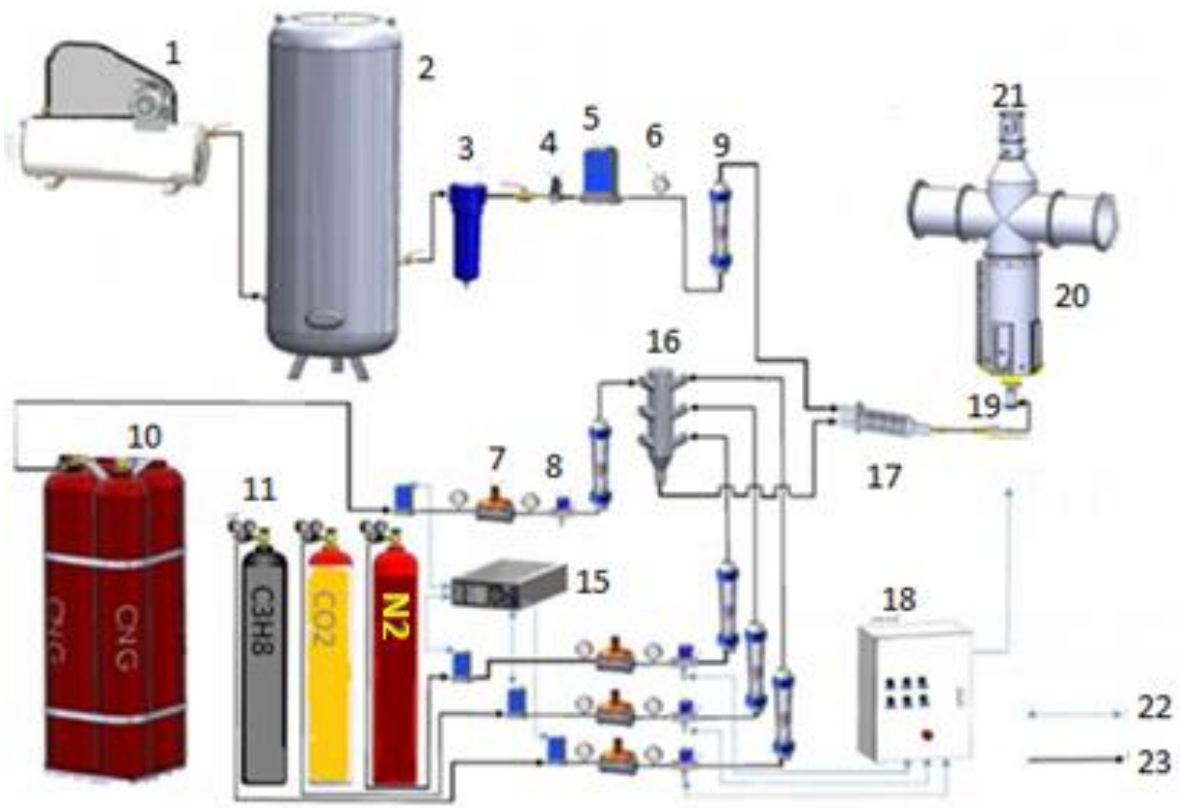

Figure 1. Schematic view of the experimental system, 1. Air Compressor, 2. External Air Tank, 3. Filter, 4. Pressure Regulator, 5. Electronic Flow Meter, 6. Manometer, 7. Pressure Regulator, 8. Solenoid Valve, 9. Floating Flow Meter, 10. CNG Tank (Methane), 11. Pressure Regulator, 12. C_3H_8 Tank, 13. CO_2 Tank, 14. N_2 Tank, 15. Control Station, 16. Gas Collector, 17. Air/Fuel Premixer, 18. Control Panel, 19. Burner, 20. Combustion Chamber, 21. Flue, 22. Electrical Connections, 23. Gas Supply Line

2.2. Combustion Chamber

The front view of the combustion chamber is shown in Figure 2. Combustion chamber is completely made of stainless steel. It is 175.5 cm in length, 32 cm in inner diameter and 210 cm in arm width. All parts are individually manufactured and combined with many fasteners. Thus, in case of any malfunction or deterioration, the sections can be disassembled very easily and convenience is provided. Quartz windows of 30 cm long and 10 cm wide were placed at two different places, providing easier visual monitoring during combustion. By these windows, it was possible to reach the combustion chamber and combustion chamber components easily. A fan is mounted behind the combustion chamber, which is used to cool parts of the combustion chamber. A cylindrical air flow channel is placed around the combustion chamber. The low temperature air collected by the cooling fan circulates in these parts, absorbing the high temperature of the combustion chamber.

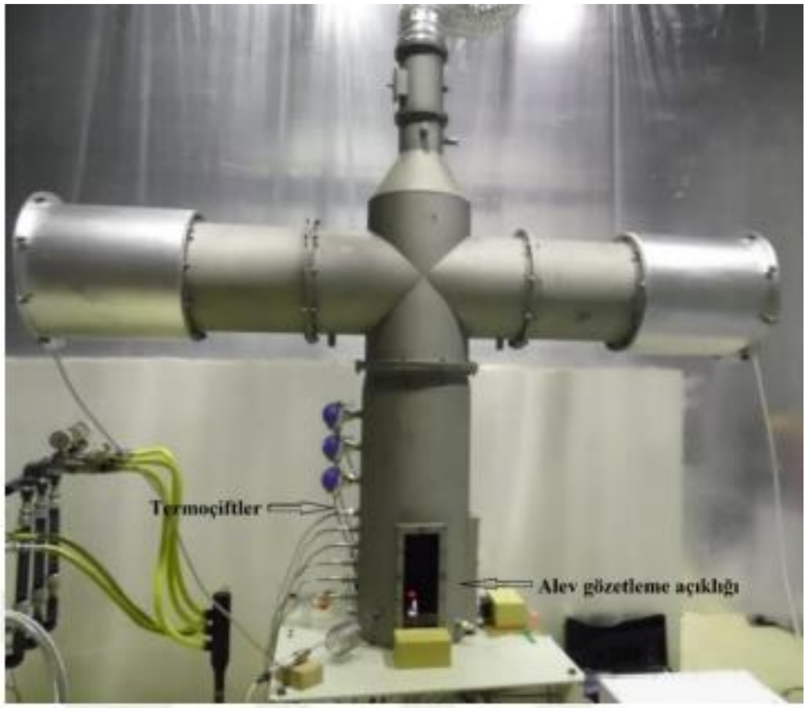

Figure 2. Front view of the combustion chamber

2.3. Burner Design

Burner type is very important in fuel efficiency and its compatibility with the fuel system is important. In addition, an ideal burner should reduce exhaust gas emissions by providing complete combustion with as little air as possible over its entire operating range. Finally, the flame diameter and size must be designed to provide an even distribution of heat within the burner. For these reasons, the burner and the burner system can produce up to 10 kW of thermal power, while in our experiment it is set to 4 kW.

2.4. Swirl Generator Design

In many burners, flow conditions are created that make the flow turbulent. Almost all mobile and stationary power sources operate in turbulent combustion conditions as it increases the mass consumption rates of the reactants, because as the mass consumption rates increase, the rate of chemical energy release increases and hence the power to be obtained from the respective combustor increases. It is preferred in many combustion applications due to its positive effects on performance (Yilmaz, 2018). Different swirl generators are shown in Figure 3.

Figure 3. Swirl generators

3. THE RESULTS AND DISCUSSION

In Figure 4, the comparison of the flue gas temperatures (at different swirl numbers) obtained as a result of the combustion of different shale gas mixtures with the flue gas temperature values obtained as a result of the combustion of methane gas is shown. It has been observed that the addition of C_3H_8 and CO_2 gases greatly affect the thermophysical capacity of the main fuel mixture. It is understood that for all shale gases, propane, CO_2 and N_2 contents cause flue gas temperature values to be higher than methane gas and generally show similar trends. The flue gas temperature values for swirl number 0.6 were measured as follows, from highest to lowest, respectively; shale gas 5 (K5), shale gas 6 (K6), shale gas 3 (K3), shale gas 4 (K4), shale gas 1 (K1), shale gas 2 (K2), and methane. Only at 0.2 swirl number, flame blows out. For this reason, it was not included in the respective graphic. The flue gas temperature generally decreased as the swirl number increased. However, it first showed a decreasing trend and then an increasing trend in the case of methane combustion. In shale gases with a swirl number of 0.6, the lowest flue gas temperature was measured in the mixtures of K1 and K2, and this lowest temperature value was 230 °C. Among the shale gases, the highest temperature values at 0.6, 1.0 and 1.4 swirl numbers were measured in the mixtures of K5 (252 C°), K1 (240 C°), K6 (231 C°), respectively. In general, it can be said that the best mixture in terms of efficiency and emission performance is the K1 mixture. It has been observed that NO_x emission is highly dependent on gas composition and swirl number.

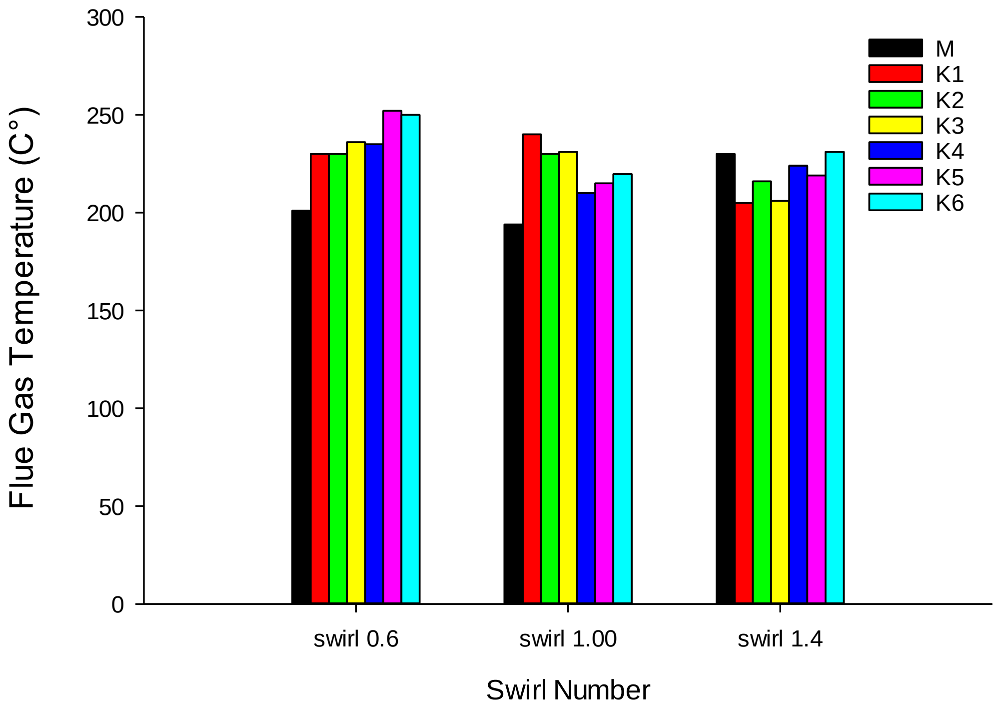

Figure 4. Variation of flue gas temperature with swirl number

The temperature values measured along the centerline of the combustion chamber are shown in figure 5. Axial temperature values in all mixtures formed very similar temperature profiles. The lowest temperature distribution from a distance of 100 mm was observed in the K2 mixture. The highest peak temperature value was 1173K (K4 mixture). The highest temperature distributions generally occurred in the mixture of K5 and K6.

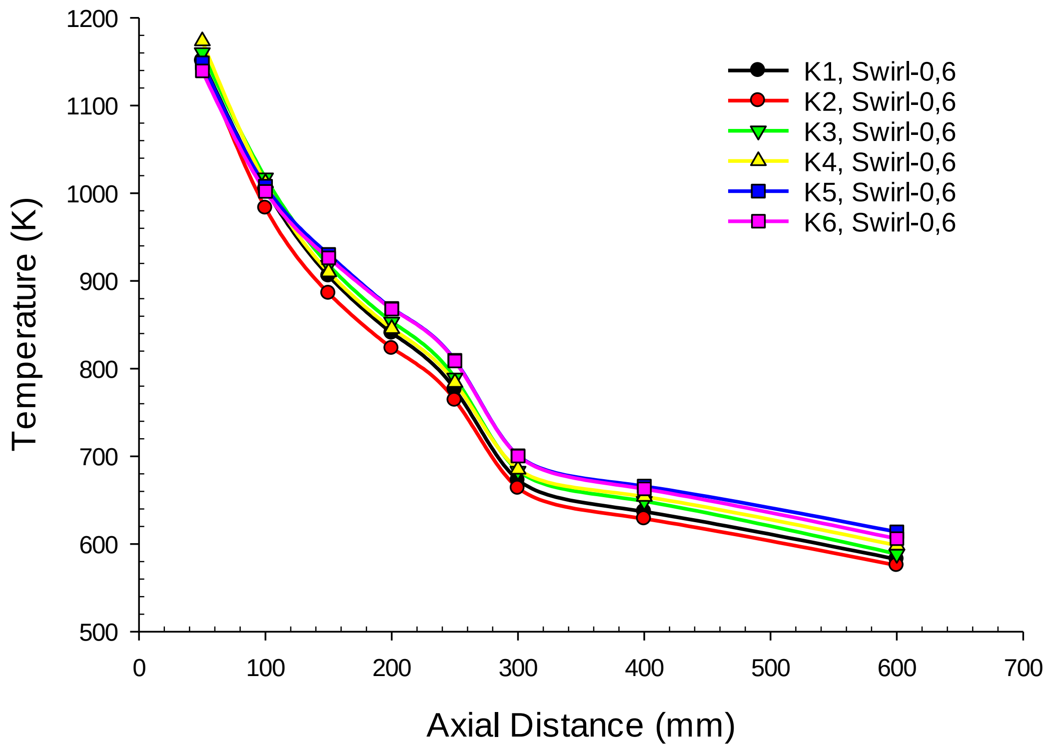

Figure 5. Variation of axial temperature with swirl number 0.6

Axial temperature distributions at 1.0 swirl number are shown in Figure 6. It created a non-linear profile compared to the other two swirl values. At 100 mm of axial distance, the temperature difference of the mixtures took the greatest value. The highest temperature distribution at 1.0 swirl number was generally seen in the K4 mixture. The main reason for this is the high propane ratio and low N_2 ratio in the K4 mixture. Towards the combustion chamber exit, the measured values of all mixtures approached each other and the temperature differences decreased.

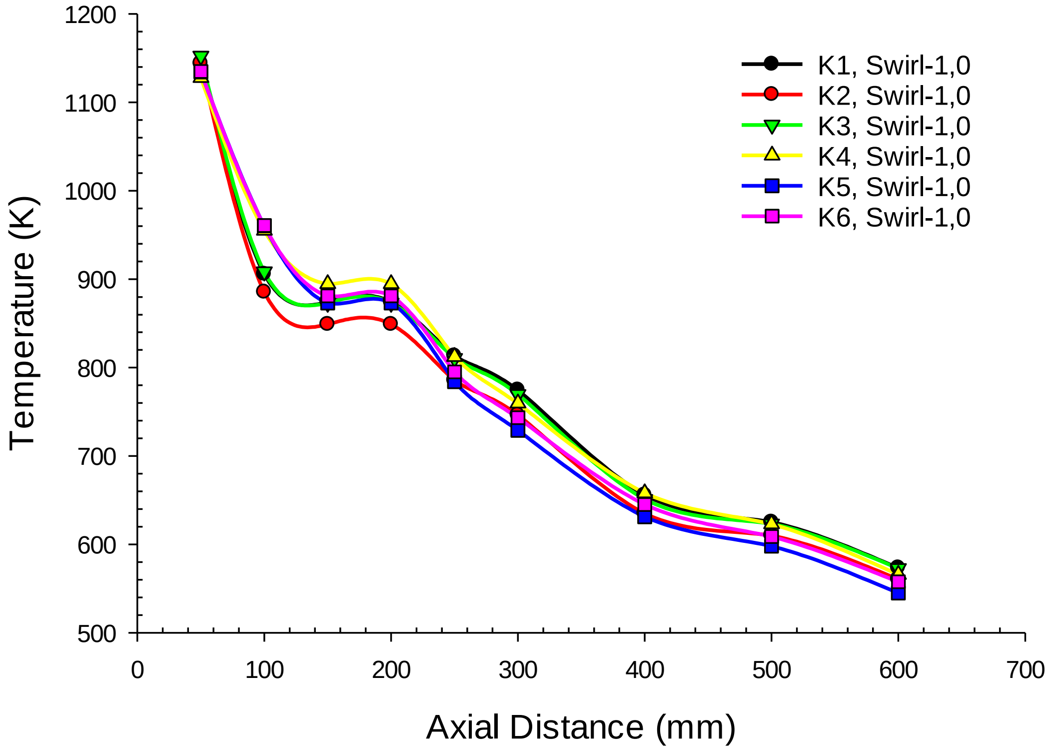

Figure 6. Variation of axial temperature with swirl number 1.0

Axial temperature values measured at 1.4 swirl number are shown in Figure 7. As the swirl value increased from 0.6 to 1.4, the combustion efficiency of the K2 mixture increased and the temperature values formed the highest values compared to the other mixtures. After 100 mm axial distance, the lowest temperature was observed in the K1 mixture. K6 mixture at three different swirl values generally had the highest temperature distribution due to the high propane content. (Seo et al., 2019).

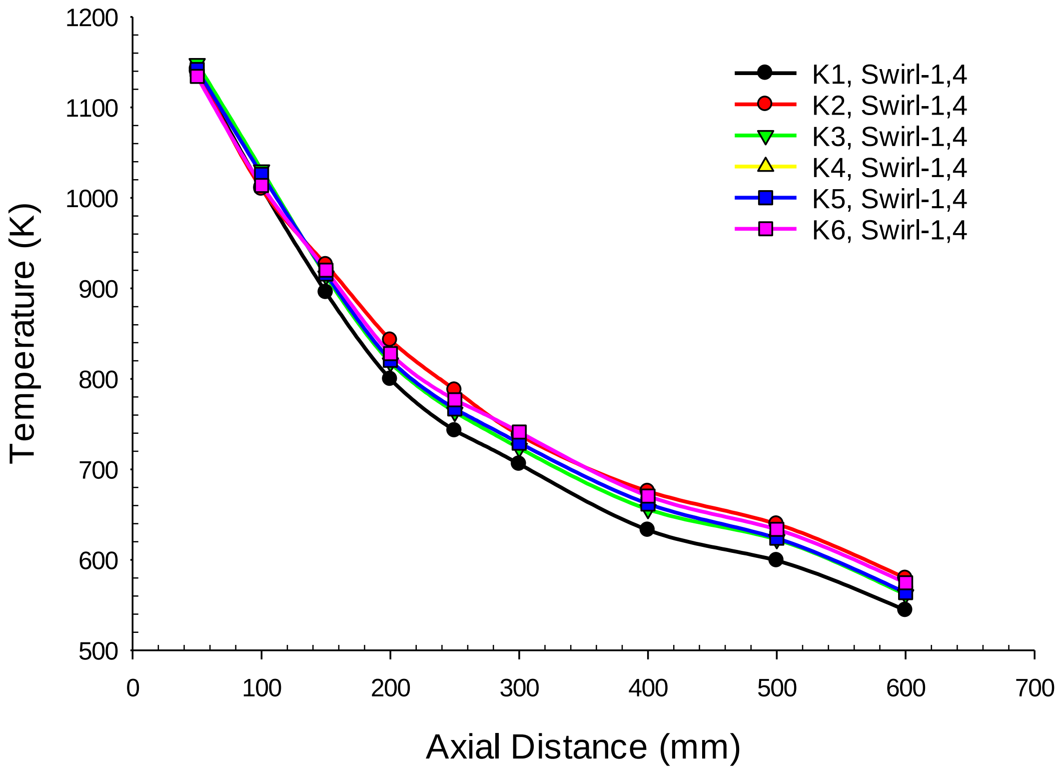

Figure 7. Variation of axial temperature with swirl number 1.4

The NO emission values obtained as a result of the combustion of methane and shale gas mixtures and how these results change at different swirl numbers are shown in Figure 8. In general, the highest NO emission values among all mixtures were observed in the K2 mixture. For the swirl value of 0.6, the NO emission values are in descending order: K6 (22 ppm), K2 (17 ppm), K4 (17 ppm), K5 (16 ppm), K3 (15 ppm), K1 (13 ppm), Methane (11 ppm). The highest NO emission value for the swirl number 0.6 was 22 ppm in K6 mixture and the lowest value was 11 ppm at methane combustion. The lowest and the highest NO emission values in all swirl numbers occurred in K1 fuel. It was observed that the most sensitive fuel to all swirl values was K1. In general, it can be said that NO emission values tend to decrease with increasing swirl value (Shao et al., 2010).

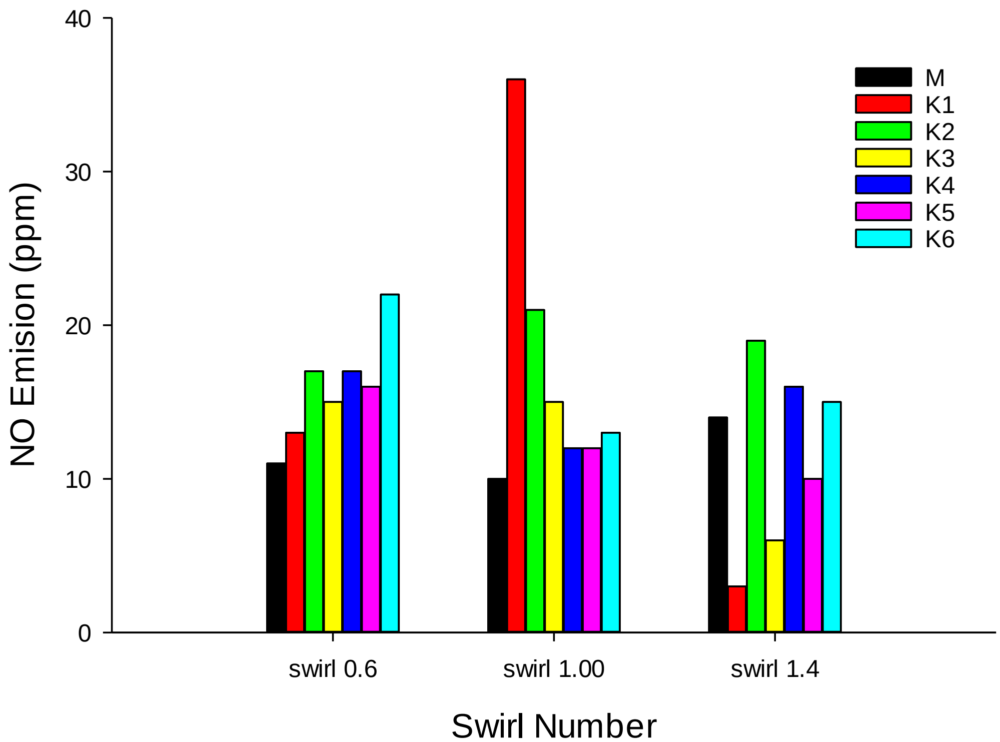

Figure 8. Variation of NO emission with swirl number

The CO emission values of the tested mixtures are shown in Figure 9. In general, the CO concentration increases in the combustion chamber due to the inhomogeneous distribution of the fuel, lack of oxygen, and low reaction temperature. As swirl number increased, the CO emission values tended to decrease, and combustion was positively affected (Ozturk, 2020). The highest CO emission value was measured as 7300 ppm at 1.0 swirl for K1 mixture. Overall, K6 mixture had the highest CO emission values at all swirl values, with 3409 ppm, 2703 ppm, 2671 ppm. The lowest CO emission value among the shale gases occurred for K4 fuel at 1.0 swirl number. It is the K4 fuel that emits the lowest CO emission value in all swirl values tested. In general, the values were very close to each other.

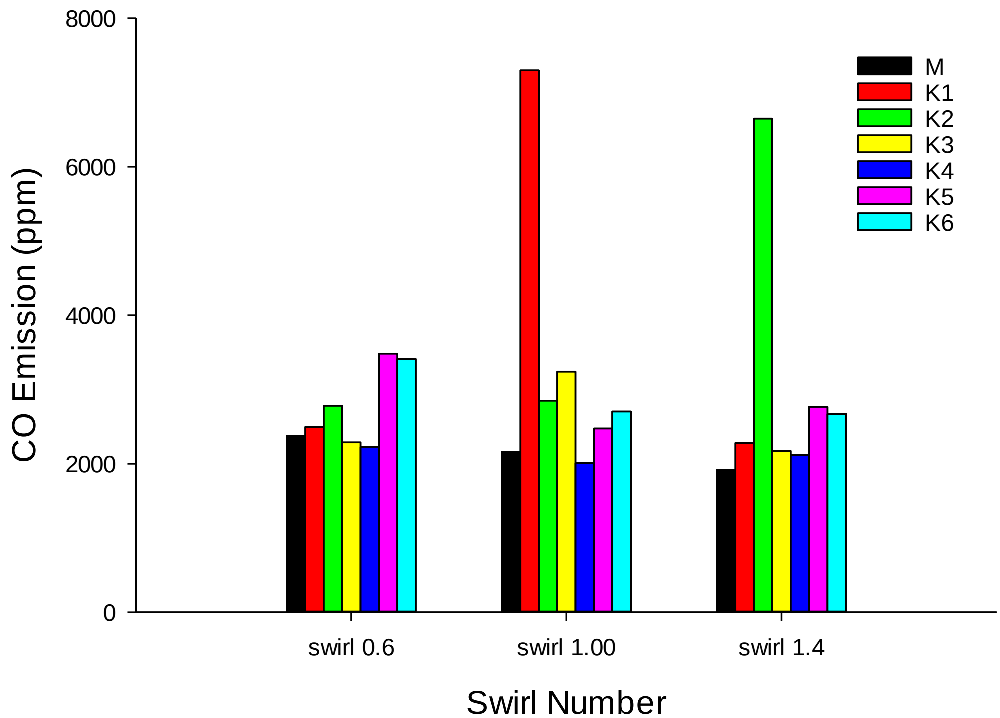

Figure 9. Variation of CO emission with swirl number

Figure 10. shows the CO_2 emission values of the tested mixtures. The CO_2 value generally decreased while the swirl value increased. While the mixture of K1 and K3 had the same amount of methane and propane, the mixture of K3 with a higher CO_2 ratio created more CO_2 emissions. CO_2 emission tended to increase when the amount of methane was increased by decreasing the propane content in the shale gas mixture.

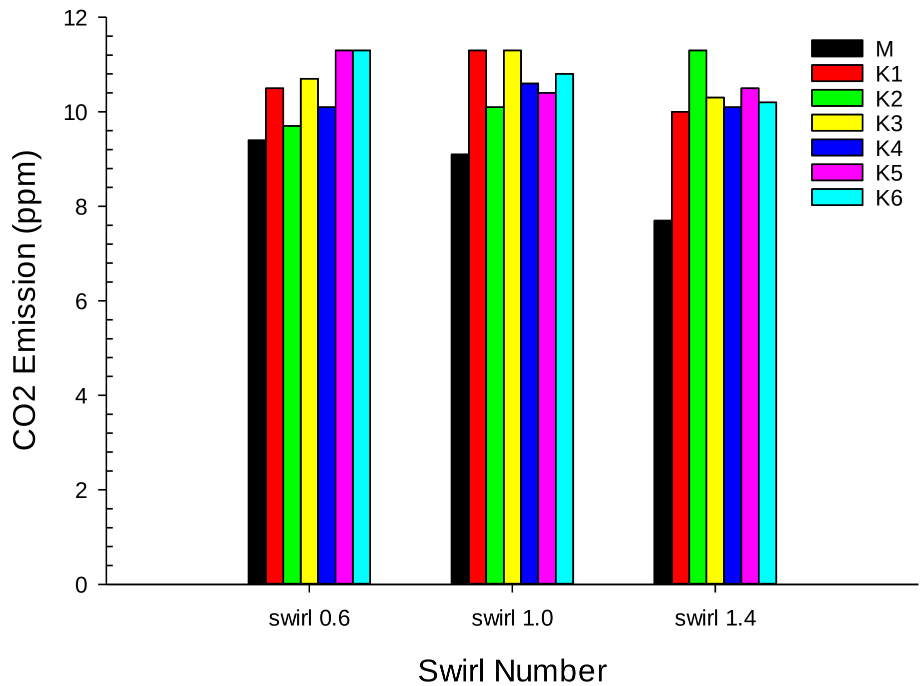

Figure 9. Variation of CO_2 emission with swirl number

K1 and K3 shale gas mixtures were compared to determine the effect of CO_2 and N_2 content on emissions. The ratios of the components of these two mixtures are shown in Table 2. There is no CO_2 component in the K1 mixture, instead the N_2 ratio has been increased by 5%. Due to this content difference, the focus is on the temperature change of K1 and K3 mixtures. Flue gas temperature and axial temperature values of K3 mixture are higher than K1. Inert components in the shale gas mixtures did not affect the adiabatic flame temperature much, but the nitrogen in the mixture decreased the combustion temperature. (Vargas et al., 2016). The low temperature values of the K1 mixture are based on this situation. It has been observed that the temperature distribution of shale gases is higher than that of methane gas. As the ethane and propane content increase, the local temperature increases (Yilmaz, 2019; Seo et al., 2019). This situation can be explained by this.

When Figure 8 is examined, it is seen that the highest NO emission values compared to the K1 mixture in general belong to the K3 mixture. The NO_x emission distribution in all combustions followed the temperature distribution. NO_x is also high where the temperature is high (Hraiech et al., 2015). N_2 dilution causes a decrease in NO as it lowers the temperature by changing the temperature-based kinetic pathways (Sabia et al., 2015). This was the reason why the K1 mixture produced lower emissions.

When Figure 9 is examined, the CO emission values of K1 gas were generally higher than that of K3 gas. It has been observed that the N_2 gas in the K3 mixture reduces the thermal value more than the CO_2 gas (Vargas et al., 2016). The K1 mixture achieved very high CO emissions at 1.0 swirl.

Table 2. K1 and K3 mixing ratios

Shale Gas	CH_4	C_3H_8	CO_2	N_2
K1	85	5	0	10
K3	85	5	5	5

In order to see the effect of propane ratio in the mixture more clearly, K3 and K6 mixtures were examined. In Table 3, the content ratios of these two mixtures are shown in the table. When the temperature graphs are examined, it is seen that the K6 gas generally has higher temperatures than the K3 mixture. This is because the K6 blend contains a higher proportion of propane (C_3H_8). In support of this, they stated that while the ethane and propane content increased, the local temperature increased (Yilmaz, 2019; Seo et al., 2019; Park et al., 2011). It is known that propane has a higher thermal value compared to methane gas. It is related to this that it creates the lowest axial temperature profiles as a result of methane combustion.

When K3 and K6 shale gases are examined, it is seen that NO emission values generally reach higher values in high temperature combustions, as seen in Figure 8. It is known that the mount of NO_x highly depends on reaction temperature because thermal NO_x is faster and more effective than fuel NO_x, especially at reaction temperatures above 1300°C. (Ozturk, 2020). As K6 mixture have N_2 content, this mixture generally created high emission values due to the high temperature values. Higher NO_x values occurred due to the high C_2H_6 and C_3H_8 content (Flores, et al., 2003). The highest and lowest NO emission difference for both mixtures was %60 at swirl number =1.4.

When Figure 9 is examined, it is seen that the CO emission values of K6 gas generally take higher values. The reason for this is the increase in propane content and C ratio (Tastan, 2018).

Table 2. K3 and K6 mixing ratios

Shale Gas	CH_4	C_3H_8	CO_2	N_2

K3	85	5	5	5
K6	80	10	5	5

4. Conclusions

In order to better understand the shale gas combustion and emission characteristics, shale gas mixtures with different contents were analyzed at different swirl numbers in a laboratory scale premixed burner. It was observed that all shale gas mixtures produced higher temperature, NO, CO, CO_2 emission values than methane. While the swirl value increased, the axial temperature values tended to increase, while the NO, CO emission values decreased in general. The CO_2 value first increased and then decreased. Temperature values and NO emission increased with the increase of propane content. As a result of the increase in the N_2 content, the temperature values decreased more than the CO_2 content. The increase in N_2 content caused more pollutant emissions. When the emission values of the mixtures were examined, it was seen that the best mixture was the K1 mixture.

Ethics in Publishing

There are no ethical issues regarding the publication of this study

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