POLİTEKNİK DERGİSİ

JOURNAL of POLYTECHNIC

ISSN: 1302-0900 (PRINT), ISSN: 2147-9429 (ONLINE)

URL: http://dergipark.org.tr/politeknik

Küçük bir girdaplı yakıcı ve fırında CO_2 seyreltmesinin alev stabilizasyonu ve nox emisyonu üzerindeki etkileri

Effects of CO_2 dilution on flame stabilization and NO_x emission in a small swirl burner and furnace

Yazar(lar) (Author(s)): Mustafa İLBAŞ[1], Göktürk CANDAN[2]

ORCID[1]: 0000-0001-6668-1484

ORCID[2]: 0000-0003-2369-1839

__To cite to this article__: İlbaş M., Candan G., “Küçük bir girdaplı yakıcı ve fırında CO2 seyreltmesinin alev stabilizasyonu ve nox emisyonu üzerinde”, ***Journal of Polytechnic***, 26(2): 603-608, (2023).

__Bu makaleye şu şekilde atıfta bulunabilirsiniz__: İlbaş M., Candan G., “Küçük bir girdaplı yakıcı ve fırında CO2 seyreltmesinin alev stabilizasyonu ve nox emisyonu üzerinde”, ***Politeknik Dergisi***, 26(2): 603-608, (2023).

__Erişim linki (To link to this article):__ http://dergipark.org.tr/politeknik/archive

__DOI:__ 10.2339/politeknik.1026159

Effects of CO_2 Dilution on Flame Stabilization and NO_X Emission in a Small Swirl Burner and Furnace

Highlights

- *Modelling and analysis of swirl burner.*
- *Using the CO_2 dilution technique.*
- *Comparison of methane burned with hydrogen, methane, and 10-50% CO_2 dilution.*

Graphical Abstract

Comparison was made of methane burning with hydrogen, methane, and CO_2 dilution technique in a modelled and analysed swirl burner/furnace for temperature, velocity, NO_X mass fraction, fuel mass fraction.

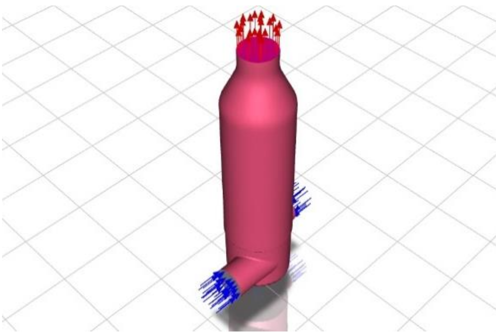

Figure. The model swirl burner and furnace

Aim

It was aimed to improve flame stabilization with modelled swirl burner and to reduce NO_X emission.

Design & Methodology

The design was carried out with Solidworks program, and the analysis with Ansys Fluent software.

Originality

The application of CO_2 dilution technique in swirl burner/furnace was carried out for the first time in this study.

Findings

Analyses were made, and data received were compared for methane burning with hydrogen, methane, and CO_2 by using observation technique in swirl burner for temperature, velocity, NO_X mass fraction, fuel mass fraction.

Conclusion

Decrease in the amount of NO_X was observed after the use of CO_2 dilution technique in swirl burner/furnace.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Küçük Bir Girdaplı Yakıcı ve Fırında CO_2 Seyreltmesinin Alev Stabilizasyonu ve NO_X Emisyonu Üzerindeki Etkileri

Araştırma Makalesi / Research Article

Mustafa İLBAŞ[1], Göktürk CANDAN[2*]
[1]Gazi Üniversitesi, Teknoloji Fakültesi, Enerji Sistemleri Mühendisliği Bölümü, Ankara, Türkiye
[2]Gazi Üniversitesi, Fen Bilimleri Enstitüsü, Ankara, Türkiye

(Geliş/Received : 19.11.2021 ; Kabul/Accepted : 30.11.2021 ; Erken Görünüm/Early View : 20.12.2021)

ÖZ

Son yıllarda düşük NO_X salınımına sahip hidrojen/metan yakma sistemlerine olan talepte hızlı bir artış olmuştur ve düşük NO_X salınımlı ve düşük emisyonlu brülörler ve fırınlar bu tür uygulamalar için umut verici platformlardır. Düşük NO_X salınımlı yakıcılarda ve homojen termal alanda en önemli dezavantaj yanma kararsızlığıdır. Bu çalışma, metan ve hidrojendeki CO_2'nin yanma kararsızlığı üzerindeki etkisini araştırmıştır. Küçük bir girdaplı brülör ve fırın sistemi kullanılarak sayısal yanma simülasyonları gerçekleştirilmiştir. Hidrojen ve metan yanmasında önemli bir etken olan yakıt türü ve CO_2 seyreltme hızının yanma özellikleri ve kararsızlığı üzerindeki etkileri araştırılmıştır. Daha yüksek CO_2 seyreltme oranları için yanma kararsızlığında azalma gözlemlenmiştir.

Anahtar Kelimeler: Girdaplı yakıcı, CO_2 ile seyreltme tekniği, alev stabilizasyonu, NOx salınımı.

Effects of CO_2 Dilution on Flame Stabilization and NOx Emission in a Small Swirl Burner and Furnace

ABSTRACT

There is a rapid increase in the demand for low NOx hydrogen/methane combustion systems in recent years, and low NOx and low emission burners and furnaces are promising platforms for such applications. Combustion instability is the most important drawback in low NOx burners and uniform thermal field. This paper investigates the influence of CO_2 in methane and hydrogen on combustion instability. Numerical simulations were conducted using a small swirl burner and furnace combustion system. The effects of fuel type and CO_2 dilution rate, which is a major contributor of hydrogen and methane combustion, on the combustion characteristics and instability are investigated. Combustion instability decreases for higher CO_2 dilution rates.

Keywords: Swirl burner, CO_2 dilution technique, flame stabilization, NOx emission.

1. INTRODUCTION

Today, the need for energy has increased rapidly together with the developing technology. A significant part of this energy need in parallel with these developments has been obtained through fossil fuels. This situation, nevertheless, brings together environmental problems. In order to prevent these problems restrictions have been imposed on gases that have polluting effects on the environment. Therefore, it is aimed to reduce NO_X gases that formed as a result of combustion in the World. Generally NO_X emissions consist of three different emissions. These are N_2O, NO, and NO_2. N_2O is an inert gas that demonstrates anesthetic characteristics. Independent from NO_X formation, it has a balanced structure in environmental circles. NO is an uncoloured gas and at concentrations of less than 0.50 ppm, its mephitic effect for human health is quite few. Besides, NO plays an active role in the formation of photochemical smoke. Additionally, when NO emissions are inhaled, they directly affect the nervous system and stick to hemoglobin in the blood. NO_2 emerges as a result of rapid transformation of NO to NO_2 in the atmosphere and causes eye and nose irritation. Also, if the level of NO_2 increases over 15 ppm, it may cause lung disorders [1]. Seventy-eight percent of the atmosphere consists of nitrogen. Major source of nitrous oxides is the nitrogen within the air. The conversion of the nitrogen within the air to its oxides (NO_X) occurs as a result of combustion processes. Most of the nitrogen oxides are generated in stable combustion plants with exhausts of motor vehicles in the traffic. Nitrogen oxides are formed from via nitrogenous substances within the fuel, as well as through the fusion of nitrogen that are used in high-temperature combustion plants with oxygen. Nitrogen oxides, which are existed in stable and unstable forms in the atmosphere, are known as the most important polluting emissions thrown into the air after combustion instances. In general, nitrogen oxides are NO, NO_2, NO_3. Among them, NO_2 and NO are the most important pollutants.

**Sorumlu Yazar (Corresponding Author)*
e-posta : gokturkcandan@gmail.com

Although there are many factors affecting nitrous oxide formation, after a quality combustion, the temperature rises and when it rises above 1800 ºC, and consequently, together with the separation of oxygen molecules, the velocity of NO_X formation increases [2]. Since the nitrogen dioxide exists as gaseous form, it has many effects on the health of living things through the respiratory. When the nitrogen dioxide in gaseous form is taken via the respiratory, it accumulates within the respiratory tracts of living things and creates harmful effects on the lower respiratory tract. In the places where there exists nitrogen dioxide, if there are other pollutants and especially ozone, negative interactions increase in human body due to the reactions occurring among these pollutants, and then, sensitivities of lungs towards bacterial infections scale up, and biochemical changes happen. [3-4]. İlbaş et al. designed a combustion chamber and in this combustion chamber, they investigated the burning performances and emission characteristics of H_2 and H_2 + CH_4 fuels. When the results of the conducted study were assessed, it was observed that as the amount of hydrogen in composite fuel increased, the flame temperature increased, and consequently, NO_X emissions increased as well [5]. In a study conducted by Normann et al. in oxy-fuel combustion, the probability of reduction of nitrous oxides in higher temperatures was examined [6]. In this study, pure oxygen was used and reduction of NO_X emission was achieved since the major source of post-combustion NO_X emission was not N_2 in the air. In another study by Hackler et al. it was experimentally and quantitatively examined the post-combustion NOx formation levels of weak pre-mixed CH_4, CO_2 and N_2 mixed fuel. In this study, CH_4 was diluted with CO_2 and N_2 at different levels. When experimental results were evaluated, it was indicated that fuel dilution could reduce NOx emissions [7]. In another research carried out by Lee et al. after dilution of combustion with N_2, CO_2 and steam, post-combustion emissions were investigated [8]. Li et al. experimentally and numerically investigated the effect of hydrogen addition on the characteristics of MILD combustion and the NO mechanism. The NO formation and reduction mechanisms under the MILD condition of CH_4/ H_2 mixtures are examined with detailed chemical kinetics model [9]. In the study carried out by Li et al., effects of CO_2 and the addition of Argon diluting on the combustion features were investigated. CHEMKIN simulation was performed in order to understand the effects of general combustion features, flame phenomenology, prediction of flame shape, pollutant emission, and dilution on the pollution emissions [10]. In this study, with a model referenced from a research conducted by D. Froud et al. the effects of methane burned in the combustion chamber with hydrogen, methane, and CO_2 dilution technique on temperature, velocity, NO_X mass fraction and fuel mass fraction were investigated by quantitative modelling [11].

2. MATERIAL and METHOD

In this study combustion chamber geometry that was used in a modelling carried out by D. Froud et al. was based as the reference geometry [11]. Limit conditions and geometry, together with the data of the experimental study conducted by D. Froud et al. were provided that model and analysis were confirmed. Details related to the created combustion chamber were shown in Fig. 1. (a) In the design, two-sided air intake duct opposite to each other provides the swirl flow. In the design, body structure carries swirl flow to the outlet part of the burner, and provides that swirl form continues along the combustion chamber.

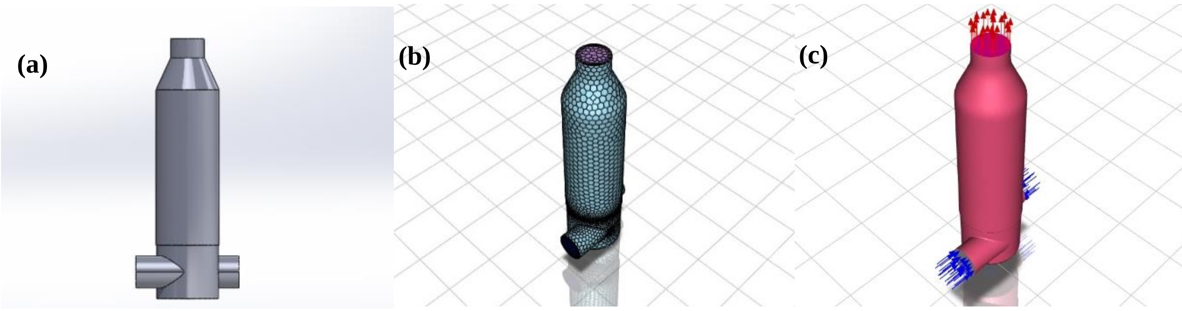

Figure 1. (a) Side view of the swirl burner and furnace [11], **(b)** The swirl burner and furnace mesh view, **(c)** Isometric view of limit conditions determined swirl burner

3. NUMERICAL MODELLING

The geometry formed with Solidworks program was transferred to Ansys Fluent program in order to conduct combustion analyses. Fluent is a CFD software using the finite volume method. Fluent, which is used in many industries around the world and has become one of the most used software in the CFD market all over the world, is able to offer easy and short solutions to its users' most difficult problems as advanced technology commercial CFD software [12]. Meshwork of transferred geometry was formed. Mesh count was increased in intake and the outlet ducts while forming the meshwork. Since swirl flow was designed, mesh measures in the external parts of the outlet duct were diminished and mesh density was obtained. At the point where a point independent from meshwork was found, there were 126,991 nodes, 1,315 edges, 162,531 faces and 29,228 cells. Meshwork formed swirl burner is shown in Fig. 1. (b).

Air intake 1, air intake 2, fuel intake and the outlet conditions of formed meshwork model was defined. From the parts shown with blue arrow in Fig. 1. (c) (0.075 m) air intake, from the parts shown with red arrow (0.081 m) the outlet of gases formed after combustion, and from the part below the model (0.026 m) fuel intake were provided. After limit conditions were formed in Ansys Program, model features were determined as the next step. From the part under "Models" tab, modules of "Energy", "Radiation", "NO_X", and "Species" were brought to "On" position. Turbulence (viscos) model used in the analysis was defined as k-epsilon (ε) (2 eqn.). After this stage, arrangements were made according to analysis in "Species" module under "Models" tab. "Species Transport" was selected and mixtures of Hydrogen-Air and Methane-Air were used as burning feature.

Employed model in this study was determined after the literature review, and confirmation process was completed before the analysis of determined model started. In Fig. 2. (a), (b) temperature data of D. Froud et al., and temperature data of this thesis study were compared. It was observed that temperature values in the study conducted by D. Forud et al. were measured between 405 °C and 1043 °C. In this study, analysis was made between the interval of 400 °C and 932 °C. The difference between quantitative values of data was thought to be due to different meshwork.

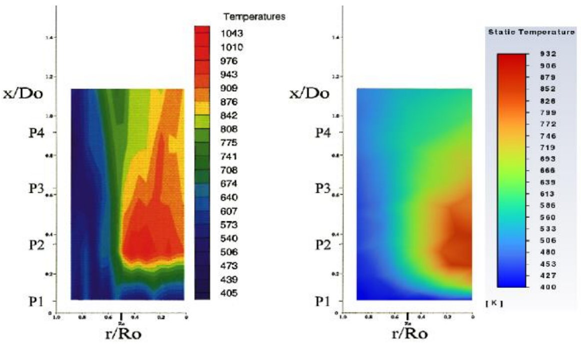

Figure 2. (a) Temperature contour of the referenced work, **(b)** Temperature contour of the present study

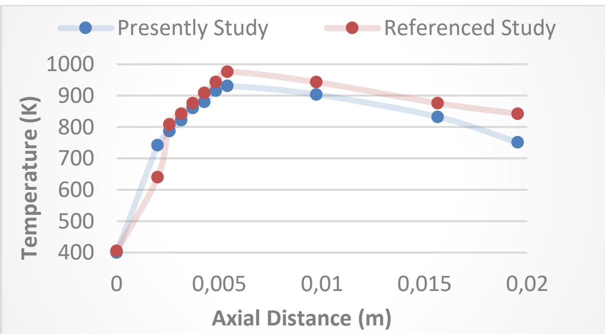

Figure 3. Graphical comparison of the referenced work and the present study

4. RESULTS AND DISCUSSIONS

4.1. Combustion in Swirl Burner

Input of values of formed limit conditions was made in this section. In the analysis of combustion of Hydrogen-Air mixture, "Magnitude, Normal to Boundary" as velocity determination method, "Absolute" as reference frame, 10% as turbulence density, and 0.075 m as hydraulic diameter in the intakes of "Inlet1" and "Inlet2" were defined as air intake. The temperature of the air entering the thermal section as 300 K, and mass proportion of O_2 were defined as 0.23 in order for Ansys software to recognize entering air. In the analysis of combustion of Hydrogen-Air mixture, "Inlet3" as air intake, "Magnitude, Normal to Boundary" as velocity determination method, "Absolute" as reference frame, 10% as turbulence density, and 0.02573 m as hydraulic diameter were defined. The temperature of the air entering the thermal section as 300 K, and mass proportion of H_2 entering from "Species" section were defined as 1.

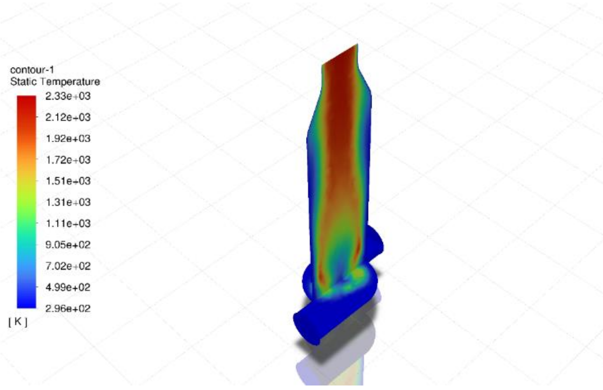

Figure 4. Temperature contour obtained by combustion of Hydrogen-Air mixture

4.2. Combustion of Methane in Swirl Burner

In the analysis of combustion of Methane-Air mixture, "Magnitude, Normal to Boundary" as velocity determination method, "Absolute" as reference frame, 10% as turbulence density, and 0.075 m as hydraulic diameter in the intakes of "Inlet1" and "Inlet2" were defined as air intake. The temperature of the air entering the thermal section as 300 K, and mass proportion of O2 were defined as 0.23 in order for Ansys software to recognize entering air. In the analysis of combustion of Methane-Air mixture, "Inlet3" defined as air intake, "Magnitude, Normal to Boundary" as velocity determination method, "Absolute" as reference frame, 10% as turbulence density, and 0.02573 m as hydraulic diameter were defined. The temperature of the air entering the thermal section as 300 K, and mass proportion of CH_4 entering from "Species" section were defined as 1.

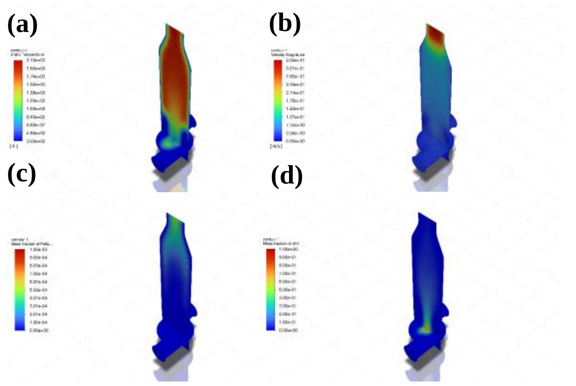

Figure 5. Obtained by combustion of methane-air mixture **(a)** Temperature contour, **(b)** Velocity contour, **(c)** NO_X mass fraction contour, **(d)** Methane mass fraction contour

4.3. Combustion of Methane by Using CO_2 Dilution Technique in Swirl Burner

In the analysis of combustion of Methane-Air mixture by using distributed air technique "Magnitude, Normal to Boundary" as velocity determination method, "Absolute" as reference frame, 10% as turbulence density, and 0.075 m as hydraulic diameter in the intakes of "Inlet1" and "Inlet2" were defined as air intake. The temperature of the air entering the thermal section as 300 K, and intake of 10-50% CO_2 was provided.

In the analysis of combustion of Methane-Air mixture by using distributed air technique, "Inlet3" defined as air intake, "Magnitude, Normal to Boundary" as velocity determination method, "Absolute" as reference frame, 10% as turbulence density, and 0.02573 m as hydraulic diameter were defined. The temperature of the air entering the thermal section as 300 K, and mass proportion of CH_4 entering from "Species" section were defined as 1.

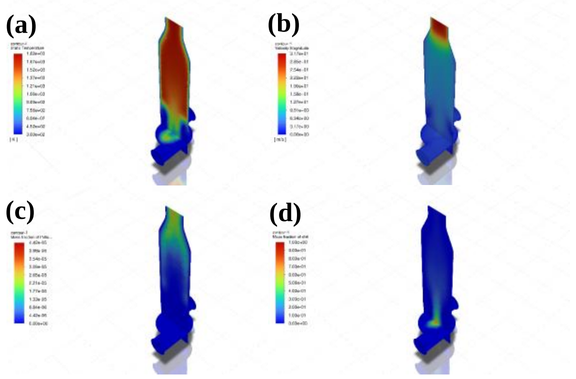

Figure 6. Obtained by the combustion of the methane-air mixture at a rate of 20% through the distributed combustion technique **(a)** Temperature contour, **(b)** Velocity contour, **(c)** NO_X mass fraction contour, **(d)** Methane mass fraction contour

4.4. Comparison between Methane Combustion and Methane Combustion Using CO_2 Dilution Technique (%10-%50)

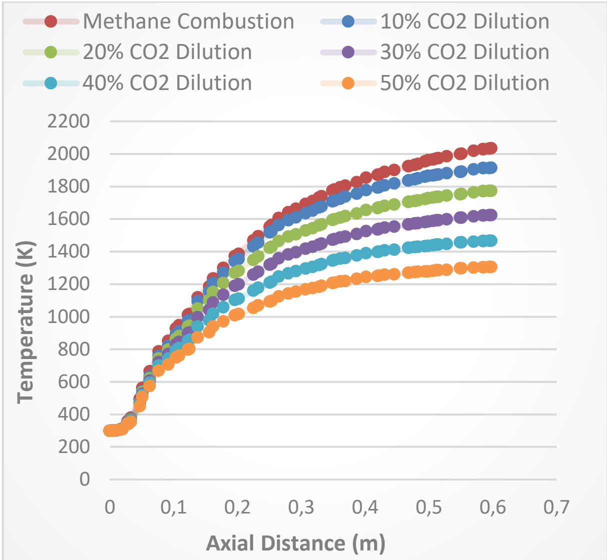

Figure 7. The axial temperature profiles in Methane-Air mixture

In Fig. 7, the temperature data received from the central point along the y axis of the methane combustion model diluted with methane and 10-50% CO_2 is shown. When the temperature contours shown in Fig. 7. were examined, as expected, the dilution technique with CO_2 made the combustion chamber temperature reduced and the temperature contour more homogenous. In addition, in all the applied methods, the temperature progressed as increasing from the inlet to the outlet section. Maximum temperature for the combustion of methane is 2035.67 K, the combustion of methane diluted with 10% CO_2 is 1915.74 K, the combustion of methane diluted with 20% CO_2 is 1772.58 K, the combustion of methane diluted with 30% CO_2 is 1624.42, the combustion of methane diluted with 40% CO_2 is 1467.46 K, and for the combustion of methane diluted with 50% CO_2 is 1305.87 K. When the combustion of methane diluted with CO_2 and methane were compared, 5.89%, 12.92%, 20.20%, 27.91% and 38.85% decreases in the rates of flame temperature were observed.

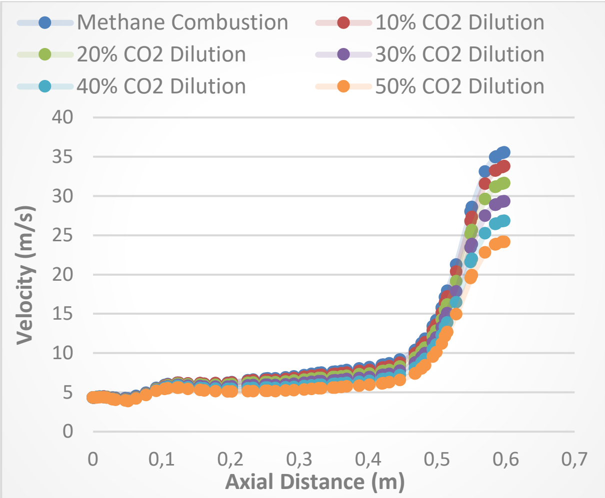

Figure 8. Axial velocity profiles in the Methane-Air mixture

In Fig. 8, the velocity data received from the central point along the y axis of the methane combustion model diluted with methane and 10-50% CO_2 is shown. When the velocity contours shown in Fig. 8. were examined, as expected, the dilution technique with CO_2 made the velocity in the combustion chamber reduced. In addition, in all the applied methods, it gave the first peak from the section where the velocity air inlet duct was located. Then, it was observed that the velocity progressed as increasing to the outlet section. Maximum velocity in the combustion of methane is 35.5456 m/s, in the combustion of methane diluted with 10% CO_2 is 33.784 m/s, in the combustion of methane diluted with 20% CO_2 is 31.6482, in the combustion of methane diluted with 30% CO_2 is 29.3249, in the combustion of methane diluted with 40% CO_2 is 26.8241, and in the combustion of methane diluted with 50% CO_2 is 24.1529. When the combustion of methane diluted with CO_2 and methane were compared, 4.96%, 10.96%, 17.50%, 24.53% and 32.05% reductions in the rates of the velocity in the combustion chamber were observed.

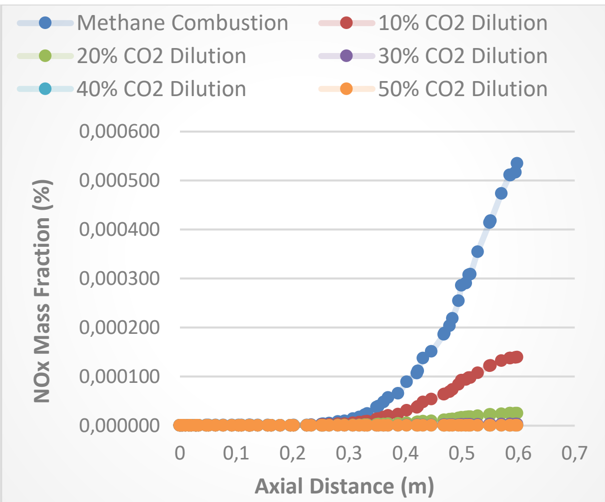

Figure 9. Axial methane mass fraction profile in the Methane-Air mixture

In Fig. 9, the NO_X mass fraction data received from the central point along the y axis of the methane combustion model diluted with methane and 10-50% CO_2 is shown. When the velocity contours shown in Fig. 9. were examined, the dilution technique with CO_2 made the NO_X emission in the combustion chamber reduced. In addition, in all the applied methods, NO_X emission was observed to the central sections of the combustion chamber. It was observed that the NO_X emission continued as increasing to the outlet section in the combustion chamber. Maximum NO_X emission in the combustion of methane is 0.0005346%, in the combustion of methane diluted with 10% CO_2 is 0.0001396%, in the combustion of methane diluted with 20% CO_2 is 0.0000251%, in the combustion of methane diluted with 30% CO_2 is 0.0000029%, in the combustion of methane diluted with 40% CO_2 is 0.0000002%, and in the combustion of methane diluted with 50% CO_2 is 0.0000000077%. When the combustion of methane diluted with CO_2 and methane were compared, 73.88%, 95.29%, 99.44%, 99.96% and 99.99% reductions in the rates of the NO_X emission in the combustion chamber were observed.

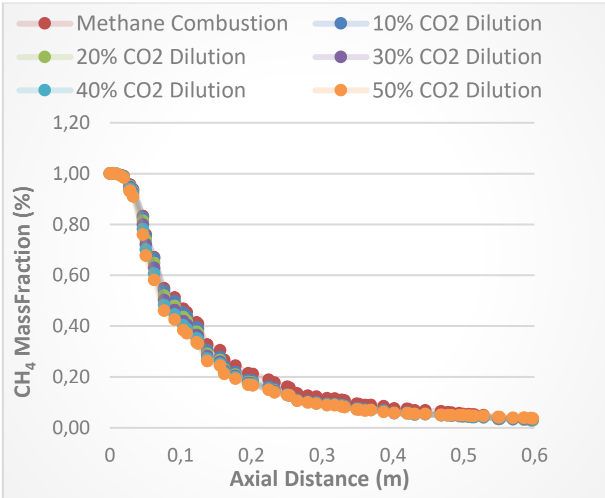

Figure 10. Axial methane mass fraction profile in the Methane-Air mixture

Fig. 10, the CH_4 mass fraction data received from the central point along the y axis of the methane combustion model diluted with methane and 10-50% CO_2 is shown. When the CH_4 mass fraction contours shown in Fig. 10. were examined methane was exhausted more rapidly in the dilution technique with CO_2. Finally, minimum CH_4 mass fraction for the combustion of methane is 0.0332652%, while for the combustion of methane diluted with 50% CO_2 is 0.0368814%. When the combustion of methane diluted with CO_2 and methane were compared, consecutively 11.47%, 7.85%, 2.16%, reductions in the amount of the methane in the combustion chamber, and 4.40% and 10.87% declines in the amount of the methane in the combustion chamber were observed.

5. CONCLUSION

In this study, quantitative analysis of a swirl burner in a combustion chamber was made. The effects of fuel type and CO_2 dilution rate, which is a major contributor of hydrogen and methane combustion, on the combustion characteristics and instability were investigated. In the study, contours of temperature, velocity, NO_X mass fraction, and CH_4 mass fraction were obtained and compared as a result of the combustion of methane and the combustion of methane diluted with 10%, 20%, 30%, 40%, and 50% CO_2 technique. When temperature distributions for methane and %10-%50 CO_2 dilutions were compared, the maximum temperature value (2035.67 K) was predicted for methane combustion, while the minimum temperature value (1305.87 K) was predicted for %50 CO_2 dilution. Moreover, lower NO_X emissions were predicted with increased CO_2 dilutions. It was concluded that the dilution with CO_2 technique reduced the flame temperature in the combustion chamber and made the temperature in the combustion chamber homogenously dispersed. At the same time, it was seen that the dilution technique made the NO_X amount that occurred after the combustion declined at significant proportions. As a solution to the stricter emission restrictions imposed day by day, it was concluded that the dilution technique with CO_2 could be employed.

DECLARATION OF ETHICAL STANDARDS

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS’ CONTRIBUTIONS

Mustafa İLBAŞ: Performed the experiments and analyse the results.

Göktürk CANDAN: Performed the experiments and analyse the results and wrote the manuscript.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

REFERENCES

[1] Ilbas M., “Studies of Ultra Low NO_X Burners”, ***PhD Thesis***, University of Cardiff, (1997).

[2] Heywood, J.B. Internal Combustion Engine Fundamental, ***Mc Graw-Hill Book Comp***., New York, (1988).

[3] Rigas, M. L., Ben-Jebria, A., and Ultman, J. S., Longitudinal distribution of ozone absorption in the lung: Effects of nitrogen dioxide, sulfur dioxide, and ozone exposures, ***Archive of Environmental Health***, 52, 173-178, (1997).

[4] Colvile, R. N. Hutchinson, E. J. Mindell, J. S., and Warren, R. F., The transport sector as a source of air pollution, ***Atmospheric Environ-ment***, 35, 1537-1565, (2001).

[5] Ilbas, M., Yilmaz, I. ve Kaplan, Y., ‘’Investigation of hydrogen and hydrogen-hydrocarbon composite composite fuel combustion and NO_X emission characteristics in a model combustor’’, ***International Journal of Hydrogen Energy***, 30, 1139-1147, (2005).

[6] Normann, F., Andersson. K., Leckner, B., Johnsson, F. “High-temperature reduction of nitrogen oxides in oxy-fuel combustion”, ***Fuel***, 87(17-18): 3579–3585, (2009).

[7] Fackler, K. B., Karalus, M. F., Novosselov, I. V., Kramlich, J. C. and Malte, P. C., “Experimental and numerical study of NO_x formation from the lean premixed combustion of CH_4 mixed with CO_2 and N_2”, ***Journal of Engineering for Gas Turbines and Power***, 133, 121502, 1-7 (2011).

[8] Lee, M., C., Seo, S., B., Yoon, J., Kim, M. ve Yoon, Y., ‘’Experimental Study on the Effect of N_2 , CO_2 and Steam Dilution on the Combustion Performance of H_2 and CO Synthetic Gas in an Industrial Gas Turbine’’, ***FUEL***, 102, 431-438, (2012).

[9] Li, P., Wang, F., Mi, J., Dally, B. B., Mei, Z., Zhang, J., & Parente, A. Mechanisms of NO formation in MILD combustion of CH_4/H2 fuel blends, ***International Journal of Hydrogen Energy***, 39(33), 19187–19203, (2014).

[10] Li YH, Chen CH, Ilbas M. Effect of Diluent Addition on Combustion Characteristics of Methane/Nitrous Oxide Inverse Tri-Coflow Diffusion Flames, ***Combustion science and technology***,(2020).

[11] Froud, Daniel, Beale, A., O'Doherty, Timothy and Syred, Nicholas . Studies of Helmholtz resonance in a swirl burner/furnace system. ***Proceedings of the Combustion Institute***,26 (2):3355-3362, (1996).

[12] Ansys, “ANSYS Fluent theory guide”, Canonsburg: ***ANSYS Inc***., (2017).