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Çok girişli siklonlu yakicida türbülansli ön karişimli metan yanmasinin sayisal simülasyonu

Numerical simulation of premixed turbulent methane combustion in a multi-inlet cyclone combustor

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Numerical Simulation of Premixed Turbulent Methane Combustion in a Multi-Inlet Cyclone Combustor

Highlights

- *The residence time of the fuel in the combustion chamber has been extended*
- *Better mixing and proper combustion are achieved*
- *A uniform temperature range and low emissions are achieved*

Graphical Abstract

Simulation of combustion of a mixture of methane and air

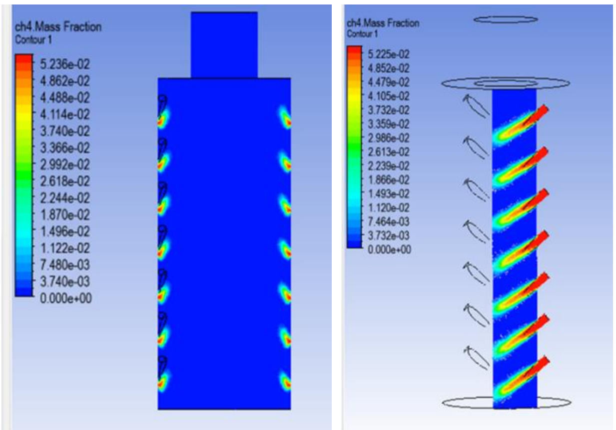

Figure. CH_4 mass fractions

Aim

Improve better combustion and reduce emissions

Design & Methodology

This study utilized the ANSYS Fluent CFD code to conduct numerical analysis. The simulation was carried out for an air:methan ratio (φ) of 1.0

Originality

Although there are studies on multi-inlet cyclone burners in the literature, there are no studies on gas fuel with low calorific value. In this study, low CO were achieved

Findings

The residence time of the fuel in the multi-inlet cyclone combustor was extended

Conclusion

Due to better fuel mixing, a uniform temperature field and low emissions are obtained

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

Çok Girişli Siklonlu Yakicida Türbülansli Ön Karişimli Metan Yanmasinin Sayisal Simülasyonu

Araştırma Makalesi / Research Article

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ÖZ

Bu çalışmada simüle edilen çok girişli siklon yakıcı, her biri 9.525 mm iç çapa sahip 14 teğet gaz/hava girişine sahiptir ve yedili 2 simetrik sıra halinde yanma odasının ön ucuna doğru 30° eğimlidir. Bu çalışmada metanla beslenen çok girişli siklonlu bir yakıcının sayısal simülasyonunu yapmak için CFD kodu kullanılmıştır. Türbülanslı akışı simüle etmek için standart k-Ɛ modeli seçilmiştir. Önceden karıştırılmış bir karışımın yanmasını simüle etmek için Eddy Dissipation kullanılmıştır. Simülasyon, 1,0 hava:yakıt oranı (φ) için gerçekleştirilmiştr. Yanma odasının girişindeki hız 20 m/s'dir. Tüm durumlarda giriş gazı sıcaklığının T=300 K olduğu varsayılmıştır. İterasyon sayısı 3000'dir. Diğer fiziksel sabitler ise literatürden alınmıştır. Çalışma basıncı için hesaplamalı varsayılan değer kullanılmıştır. Çalışmanın sonuçları, önerilen siklonik yakıcının daha iyi yakıt karışımı sağladığını, yakıtın yanma odasında kalma süresini arttırdığını, üniform bir sıcaklık alanı elde ettiğini ve emisyonları azalttığını göstermiştir

Anahtar Kelimeler: Çok girişli siklon yakıcı, CFD modelleme, metan yanması

Numerical Simulation of Premixed Turbulent Methane Combustion in a Multi-Inlet Cyclone Combustor

ABSTRACT

The multi-inlet cyclone combustion chamber simulated in this study has 14 tangential gas/air inlets, each with an internal diameter of 9.525 mm, and is inclined 30° towards the front end of the combustion chamber in 2 symmetrical rows of seven. This study used CFD code to numerically simulate a multi-inlet cyclone combustor fueled by methane. The standard k-Ɛ model was chosen to simulate turbulent flow. Eddy Dissipation was used to simulate the combustion of a premixed mixture. The simulation was carried out for an air:fuel ratio (φ) of 1.0. The design velocity at the entrance to the combustion chamber is 20 m/s. In all cases, the inlet gas temperature was assumed to be T=300 K. The number of iterations was 3000. The other physical constans were taken from the literature. The computational default value was used for the operating pressure. The results of the study showed that the proposed cyclonic combustor provides better fuel mixing, increases the residence time of the fuel in the combustor, achieves a uniform temperature field and reduces emissions.

Keywords: Multi-inlet cyclone combustor, CFD Modelling, methane combustion.

1. INTRODUCTION

Energy holds an extremely significant function in ensuring sustainable and safe development of society. The sufficiency and reliability of supplying electricity and heat to the growing needs of the economy and population are of decisive importance. Traditional energy provides about half of the world's man-made emissions of greenhouse gases and harmful substances into the environment [1].

However, achieving emission reduction targets requires the use of alternative, low-carbon or non-carbon fuels in the energy and industrial sectors using combustion systems [2].

Exploration of pristine, low-carbon alternative fuels alongside in-depth examination of combustion mechanisms stands as pivotal technological avenues toward enhancing energy efficiency and mitigating the discharge of pollutants into the environment [3-5].

Researchers are diligently engaged in investigating manufacturing and utilization of environmentally friendly energy sources, including CH_4 and H_2. A growing body of scholarly inquiry is dedicated to emission reduction strategies and carbon dioxide mitigation, alongside the promotion of safe energy practices.

Natural gas, primarily composed of methane (comprising 85 to 96 percent), represents an efficient and environmentally friendly fossil fuel source. Methane is high hydrogen-to-carbon ratio contributes to the mitigation of carbon emissions (CO and CO_2) during combustion.

Numerous scientists have undertaken experimental and computational investigations into the combustion properties of CH_4 and various gases across diverse conditions [6-8].

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Tunçer investigated the laminar flame velocities of hydrogen-rich methane fuel with chemical kinetic simulations based on the GRI 3.0 mechanism. It was determined that hydrogen enrichment increased the flame as expected. The investigation examined the influence of hydrogen ratio and pressure on flame velocities and emissions. He found that increasing pressure reduces flame velocities, but in turn increases emissions. Emissions and flame rates increase with increasing hydrogen content. He focused on one- and zero-dimensional simulations. The focus in zero-dimensional simulations is the effect of equivalence coefficient fluctuations resulting from thermo-acoustic instability on lean flame extinction and emissions. In this study, it was observed that hydrogen-rich mixtures were more resistant to equivalence ratio fluctuations [9].

V.V. Morozov, P.D. Shilin, A.A. Ravina, S.A. Shalynkov, in their work presented the results of numerical modeling of the combustion process of CH_4 and atmospheric air in an axisymmetric cylindrical burner. The simulation was carried out under the assumption of a staged combustion process with partial pre-mixing, where fuel was injected through the central annular channel and air through the outer annular channel. In their research, they used CFD modeling for the combustion process of a fuel mixture in an air flow using the ANSYS Fluent software package. The validity of the solved problem was confirmed through comparison of experimental data with numerical simulation results depicting the process of methane combustion in atmospheric air within an axisymmetric cylindrical burner. A mathematical model of chemical reactions of combustion of individual components of the sweep is proposed, taking into account their chemical kinetics depending on temperature and their concentration. The results obtained using it showed a high rate of reactions, while the time of their occurrence was several times greater than the time spent by the reagents in the burner, which allowed us to conclude that there is no influence of chemical kinetics on the working process, that is, the combustion process in the burner is determined by diffusion mixing high-speed air jets [10].

Mustafa Ilbas, İlker Yılmaz, in their work, conducted experiments using two different fuels (M70H30, M30H70) mixed from hydrogen and methane. The outcomes of this experiment demonstrated a positive correlation between the H_2 content in the blended fuel and both the elevation of temperature levels and the reduction of CO emissions. Burning fuel mixed with hydrogen and methane produces lower CO emissions because the C/H ratio decreases as the fuel is mixed. Reducing CO emissions results in a significant increase in combustion efficiency. It has been demonstrated that hydrogen-methane fuel blends can be effectively utilized without necessitating significant modifications to the gas burner [11].

A numerical investigation was undertaken by A. Krainov and K. Moiseeva to explore the combustion dynamics of an air-methane mixture within a slot burner featuring an internal insert and adiabatic external walls. The study delineated the domain of high-temperature stationary combustion mode for lean compositions, contingent upon the gas supply rate and volumetric CH_4 content in the mixture. The maximum extent of advancement of the combustion front within the slot burner channel was established, contingent upon the mixture composition. Furthermore, it was demonstrated that the presence of an inert internal insert within the slot burner expands the combustion limits of the methane-air mixture [12].

Jianfeng Pan, Hong Yu, and their colleagues conducted a comparative analysis of the combustion characteristics of premixed CH_4 and O_2 within 3 distinct types of mesocombustion chambers, each possessing an identical hydraulic diameter. Experimental measurements were performed to ascertain the upper limits of flammability of the premixed gas within combustion chambers of varying cross-sectional geometries. The experimental findings revealed a periodic reduction in the upper flammability limits of premixed gases when the CH_4 flow rate remained constant across combustion processes occurring within round, square, and rectangular combustion chambers. Additionally, under identical input parameters, the gas-phase reaction intensity within a combustion chamber with a round cross-section surpassed that within a square cross-section chamber, while the rectangular cross-section chamber exhibited the lowest intensity. Furthermore, at constant inlet velocities, the square cross-section combustion chamber demonstrated a higher average temperature compared to others, whereas the round cross-section combustion chamber exhibited less temperature variation and more uniform temperature distribution [13].

In their study, M. Ilbas, S. Karyeyen, and I. Ozdemir conducted a numerical investigation into pre-mixed hydrogen flame behavior within both closed and open combustion chambers. Utilizing computational fluid dynamics (CFD) methodology, the burning and discharge characteristics of pre-mixed hydrogen were extensively examined. The simulation encompassed variations in the excess air coefficient ranging from 0.8 to 1.7. The findings revealed a maximum temperature distribution of approximately 2000 K within the closed combustion chamber [14].

Li Guo and others conducted a comprehensive study, utilizing both experimental and computational methods, into the characteristics of CH_4/O_2 flames augmented with H_2 in a microclosed combustion space. Their findings revealed that the integration of hydrogen considerably extends the stable combustion range of CH_4/O_2 flames within microconfined spaces by approximately 20% when the hydrogen integration ratio reaches 50%. Moreover, they observed that the frequency and maximum flame propagation speed, denoted as FREI, experience augmentation. Additionally, they noted a nearly linear decrease in the extinguishing distance of $CH_4/H_2/O_2$ flames with increasing H_2 ratio. This phenomenon is attributed to the heightened critical rate of scalar dissipation, leading to local flame attenuation in flames enriched with higher H_2 content [15].

In this paper, Zhigang Liu and his colleagues examine the pollutant discharges, steady operational scope, and flame structure for the MILD jet combustor model. Variations in methane/hydrogen volume ratios span from 0:10 to 5:5. Notably, NOx emissions remain below 5 ppm at 15% O2 with hydrogen volume fractions below 50% under atmospheric conditions. Utilizing the chemical reactor network (CRN) model, calculations reveal an increasing influence of thermal losses on NOx emissions with rising adiabatic combustion temperatures. Concurrently, augmented turbulent combustion rates and heightened reaction intensities result in compressed reaction zones with escalating hydrogen content. Moreover, an increase in hydrogen content correlates with a narrowing of the stable operation range of the combustion chamber, with stable combustion becoming untenable beyond a hydrogen content exceeding 50% by volume [16].

Mustafa Ilbas and others performed an experimental investigation to explore the combustion instability characteristics of CH_4-NH_3 blended fuels for low-swirl and premixed burners. The study scrutinized the influence of NH_3 supplementation to CH_4 fuel gas on temperature and emissions. Pure CH_4 and three different CH_4-NH_3 mixtures at a concentration of 0.7 equivalents were utilized, along with three distinct acoustic parameters. An increase in ammonia addition led to elevated flame instability values, particularly evident at 95 Hz where the most significant distortion effect was observed. The addition of NH_3 to methane CH_4 fuel did not notably alter combustion characteristics; however, projected levels of NOx emissions notably increased due to the association of nitrogen with ammonia. Despite this, exhaust gas measurements did not reveal high levels of NOx emissions [17].

In their investigation, Mustafa Kemalettin Büyükakın and Semiha Öztuna employed computational fluid dynamics (CFD) techniques to conduct a numerical examination of CH_4 and O_2 combustion, devoid of a pre-mixture enriched with H_2. Both pure CH_4 and natural gas were utilized as fuel sources, with an excess air coefficient set at 1.2 across all considered combustion simulation scenarios. Varying H_2 addition ratios of 25%, 50%, and 75% by weight were applied. The resultant findings from the numerical studies demonstrated that methane enrichment with hydrogen led to a reduction in carbon emissions while significantly augmenting the formation of thermal NO emissions [18].

In their investigation, Meng Zhang, Zhenhua An, and their colleagues scrutinized the impact of CH_4 and H_2 regulation on emission characteristics within the air-ammonia flame in a gas turbine combustion chamber. Their findings revealed that NO_x and unburned ammonia (NH_3) emissions can be concurrently managed to desired levels with an equivalence factor (φ) of approximately 1.1. Analysis of NO and NO_2 variations with respect to φ for the $NH_3/H_2/O_2$ flame and $NH_3/CH_4/O_2$ flame at a mixing factor (Zf) of 0.1 demonstrated similarity to the NH_3/O_2 flame, with the peak shifting towards the enriched state. This suggests that the NH_3/O_2 flame can be regulated by incorporating a small quantity of active fuel without exacerbating NO_x emissions [19].

In their research, Mustafa Ilbas and Serhat Karyeyen conducted a computational modeling of a turbulent flame involving unmixed hydrogen (H2) within a model combustion chamber. Computational fluid dynamics (CFD) investigations were carried out utilizing the Fluent code, with variations in fuel composition ranging from pure hydrogen to natural gas (including 100% H_2, 70% H_2 + 30% CH_4, 10% H_2 + 90% CH_4, and 100% CH_4). The introduction of air at a rate of 25% through two tangential inlets was incorporated. The study outcomes revealed a general rise in flame temperature with the incorporation of H_2, while the introduction of methane led to temperature reduction and consequent emissions reduction. The implementation of staggered air supply led to the formation of rich and lean combustion zones, thereby mitigating NO_x emissions through the combustion chamber outlet [20].

Modern methods for modeling fuel combustion are designed to determine high combustion efficiency and minimal emissions of pollutants into the atmosphere. Mathematical and computer simulations are extensively employed in the development and optimization of practical combustion equipment due to their significantly lower costs compared to experimental testing and prototyping. To date, no real progress in development or optimization can occur without numerical or computer modeling. [21].

This research work proposes a cyclonic combustor designed with full premixing capability. This design ensures good pre-mixing of fuel and air, due to which more uniform combustion occurs inside the cyclone combustor and the flame completely occupies the body of the combustion chamber.

2. MATERIAL and METHOD

In this work, a multi-inlet cyclone combustor is investigated, which gives very good results with very low NOx emissions. This type of combustor is mainly used to burn fuels with low calorific value. The multi-inlet cyclone combustor modeled for this study is shown in Figure 1. The proposed combustor has 14 gas/air tangential inlets each of 9.525 mm ID and are inclined towards the front end of the combustion chamber by 300 in 2 symmetrical rows of seven. Characteristics are as follows [22];

Diameter of the combustor exit	: 76.20 mm
Diameter of the cyclone combustor	: 152.4 mm
Total length of the combustor	: 457.2 mm
Geometrical swirl number	: Sg=7.91

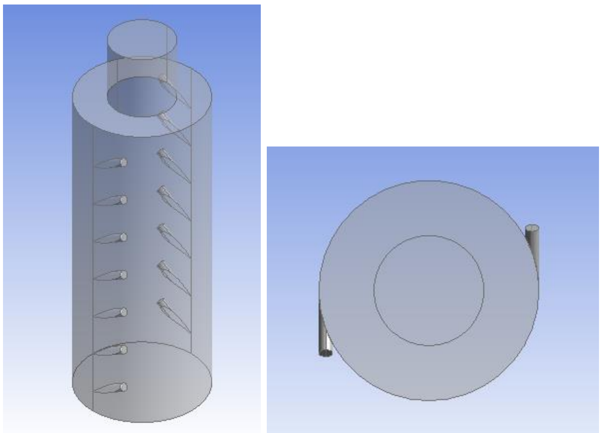

Figure 1. The multi-inlet cyclone combustor

Thus before simulation starts, there are many points to be considered; definition of the modelling aims, generation of the grid, definition of physical models, choice of turbulence model, choice of combustion models.

Prior to commencing the simulation, a computational mesh was generated for the model, exerting a substantial influence on the accuracy and stability of the numerical simulation solution.

Figure 2 shows the network structure of a multi-inlet cyclone combustor. Mesh details: nodes: 179 526 and elements: 933 738.

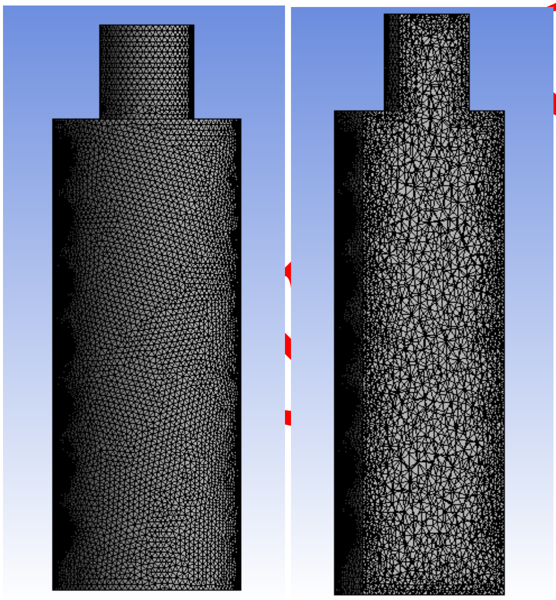

Figure 2. Mesh structure for multi-Inlet Cyclone Combustor

Considering that the flow is turbulent, the standard k-Ɛ model was chosen for the simulation. Premixed combustion modeling using the Eddy Dissipation. Boundary conditions for air intakes and walls are determined. For the input boundary conditions, the input velocity, composition and temperature of the flow are determined. The simulation was carried out for an air:fuel ratio (φ) of 1.0. Table 1 below shows the mass fractions of species at the combustor inlets. The calculated velocity at the entrance to the combustion chamber is 20 m/s. Turbulence intensity was taken as to be default value of 10 %. In all cases, the inlet gas temperature is assumed to be T=300 K. The number of iterations was 3000.

Table 1. Mass fractions of species at the combustor inlets

Mixture ratio	Mass fraction		
φ	CH_4	O_2	N_2
1.00	0.0540	0.2170	0.7290

3. RESULTS AND DISCUSSION

This study utilized the ANSYS Fluent CFD code to conduct numerical analysis of air-methane mixtures.

The results of modeling the combustion of a mixture of methane–air are shown in Figures 3 to 7

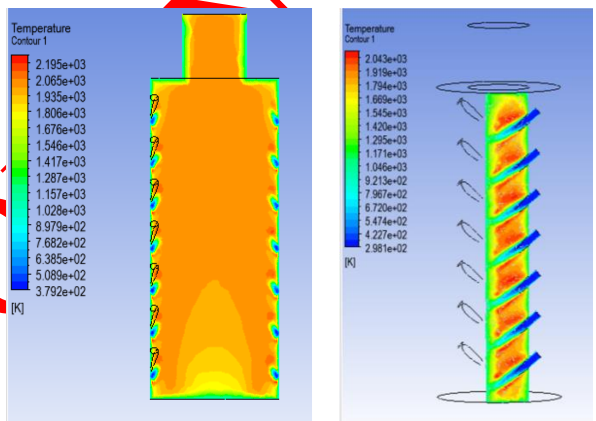

Figure 3. Temperature distributions (K)

Figure 3 shows the temperature distribution when simulating the combustion of air-methane mixture in the combustor. The peak temperature level is approximately 2195 K. In the figure you can see a constant temperature distribution along the entire length of the combustor, with the flame front located next to the chamber wall. This can be explained by the location of tangential air intakes along the chamber and stabilization of the flame at the wall. Temperature levels are reduced to 1800 K in the central vortex region of the core. This occurs due to the recirculation of somewhat cooler combustion products from the exhaust zone.

Velocity distributions are shown in Figure 4. In the combustion chamber, the velocity levels are 21 m/s near the wall, then the velocity gradually increases towards the axis of symmetry and reaches a maximum value and then gradually decreases to zero. Maximum velocity is in the exhaust exit region; 39 m/s. The maximum velocity level is doubled due to combustion.

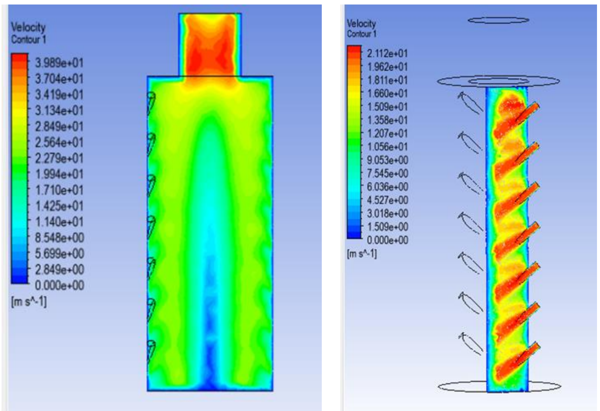

Figure 4. Velocity distributions

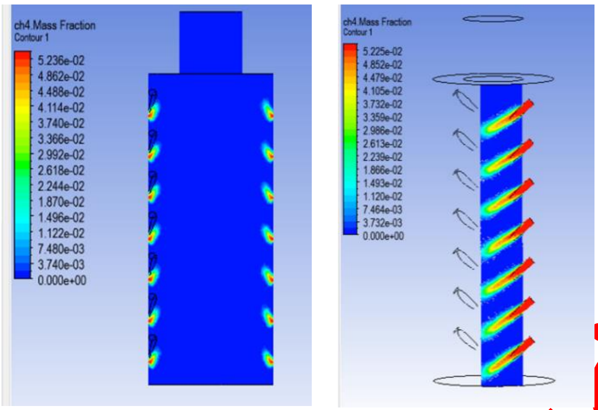

Figure 5. CH_4 mass fractions

Figure 5 shows the mass fractions of methane. It shows that methane is consumed in the area very close to the inlets. Additionally, methane was consumed as soon as it entered the combustion chamber. Methane is completely burned.

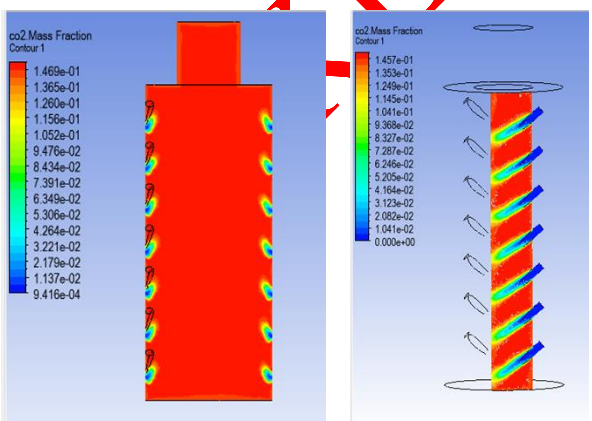

Figure 6. CO_2 mass fractions

Figure 6 shows the distribution of CO_2 fractions. The estimated maximum level of CO_2 produced from the conversion of CO to CO_2 in the second reaction is approximately - 14.7%.

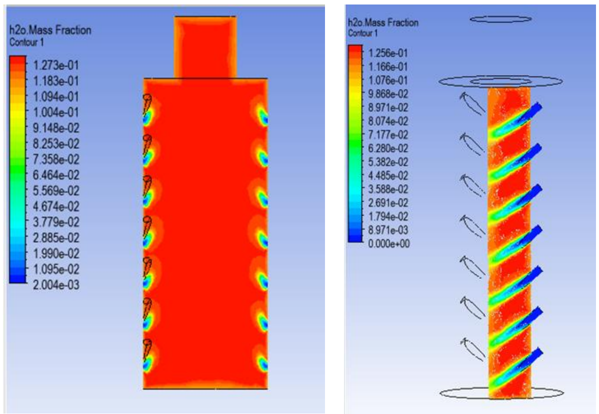

Figure 7. H_2O mass fractions

Figure 7 shows the distributions of H_2O mass fractions. The maximum H_2O level for these conditions is approximately - 12.7%.

4. CONCLUSION

A numerical study of premixed methane in a multi-inlet cyclone combustor was carried out. The results showed that the proposed cyclonic combustion chamber can be considered as the optimal design for complete combustion of methane. The residence time of the fuel in the combustion chamber is also increased. Due to the proposed design, better mixing of fuel is achieved, a uniform temperature field is achieved and emissions are reduced.

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 Ilbas: Supervision, methodology and analyse the results.

Assem Yerzhan: Conducted a literature review and a numerical experiment, writing.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

REFERENCES

[1] Porfiriev B.N., “Alternative energy as a factor of environmental and energy security”, ***Journal of Regional,*** 2:137-145, (2011).

[2] McAllister Sara, Jyh-Yuan Chen, Carlos Fernandez-Pello A., ***Fundamentals of Combustion Processes***, Springer, (2011).

[3] Geng P., Cao E., Tan Q., Wei L., "Effects of alternative fuels on the combustion characteristics and emission products from diesel engines: A review", ***Renewable and Sustainable Energy Reviews***, 71:523–534, (2017).

[4] Li M., Wu H., Zhang T, Shen B., Zhang Q., Li Z., "A comprehensive review of pilot ignited high pressure direct injection natural gas engines: factors affecting combustion, emissions and performance", ***Renewable and Sustainable Energy Reviews***, 119, (2020)

[5] Yanfei Li, Xin Zhang, Yue Wang, Jiuling Sun, "Effect of inhomogeneous methane-air mixtures on combustion characteristics in a constant volume combustion chamber", ***Fuel***, 331, (2023).

[6] Wang J., Fu R., Wen S., Ning P., Helal M.H., Salem M.A., Xu B.B., El-Bahy Z.M., Huang M., Guo Z., Huang L., Wang Q., "Progress and current challenges for CO_2 capture materials from ambient air", ***Advanced Composites and Hybrid Materials***, 5:2721–2759, (2022).

[7] Wang J., Wu Y., Zheng L., Yu M., Pan R., Shan W., "Study on the propagation characteristics of hydrogen/methane/air premixed flames in variable cross-section ducts", ***Process Safety and Environmental Protection,*** 135:135–143, (2020).

[8] Guilong Liu, Jian Wang, Ligang Zheng, Rongkun Pan, Chang Lu, Yan Wang, Jingyu Yu, Yuyu Dai, "Combustion characteristics of nonuniform methane-air mixtures in the duct", ***Fire Safety Journal,*** 137, (2023).

[9] Tuncer O., "Chemical kinetic analysis of flame rates and emission values of hydrogen-enriched methane fuel", ***Journal of Thermal Science and Technology***, 29(2):29-42, (2009).

[10] Morozov V.V., Shilin P.D, Ravina A.A., Shalynkov S.A., "Numerical simulation of the combustion of methane and air in a cylindrical chamber burning", ***News of Tula State University. Technical science***, 9:356-361, (2021).

[11] Ilbas M., Yılmaz I., "Experimental analysis of the effects of hydrogen addition on methane combustion", ***International Journal of Energy Research***, 36:643–647, (2012).

[12] Krainov A. Yu., Moiseeva K. M., "Combustion of lean methane-air mixtures in a slot burner with adiabatic outer walls", ***Physics of combustion and explosion***, 1:52-59, (2016).

[13]Jianfeng Pan, Hong Yu, Huimin Ren, Yi Zhang, Qingbo Lu , Evans Quaye, "Study on combustion characteristics of premixed methane/oxygen in meso-combustors with different cross-sections", ***Chemical Engineering and Processing - Process Intensification,*** 154, (2020).

[14] Ilbas M., Karyeyen S., Ozdemir I., "Investigation of premixed hydrogen flames in confined/unconfined combustors: A numerical study", ***International journal of hydrogen energy***, 40:11189 -11194, (2015).

[15]Li Guo, Ming Zhai, Shijie Xu, Qianhao Shen, Peng Dong, Xue-Song Bai, "Flame characteristics of methane/air with hydrogen addition in the micro confined combustion space", ***International Journal of Hydrogen Energy,*** 47:19319-19337, (2022).

[16] Zhigang Liu, Yan Xiong, Ziru Zhu, Zhedian Zhang, Yan Liu, "Effects of hydrogen addition on combustion characteristics of a methane fueled MILD model combustor", ***International Journal of Hydrogen Energy***, 47:16309-16320, (2022).

[17] Ilbas M., Kumuk O., Alabas B., "Experimental investigation of the combustion instability behaviors and NOx emissions in an ammonia/methane fueled low eddy premixed burner", ***Journal of the Energy Institute,***108, (2023).

[18] Büyükakın M.K., Öztuna S., "Numerical investigation on hydrogen-enriched methane combustion in a domestic back-pressure boiler and non-premixed burner system from flame structure and pollutants aspect", ***International Journal of Hydrogen Energy,*** 45:35246-35256, (2020).

[19] Meng Zhang, Zhenhua An, Liang Wang, Xutao Wei, Bieerlan Jianayihan, Jinhua Wang, Zuohua Huang, Houzhang Tan. "The regulation effect of methane and hydrogen on the emission characteristics of ammonia/air combustion in a model combustor", ***International Journal of Hydrogen Energy***, 46:21013-21025, (2021)

[20] Ilbas M., Karyeyen S., "An experimental and numerical study on turbulent combustion of hydrogen-rich coal gases in a generated non-premixed burner", ***Fuel,*** 194:274-290, (2017).

[21] Beisenbekova G.Zh., Urmashev B.A., Makashev E.P., "Modelling of the combustion process of methane (CH_4) in the software package PrIMe", ***Vestnik KazNU,*** 4(92):99-108, (2016).

[22] Ilbas M., "Studies of ultra low NO_x burners", PhD Thesis, School of Engineering, University of Wales, Cardiff, (1997).