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Distributed regime and swirler effects on methane and coke oven gas combustion characteristics

Girdap üreticinin dağıtılmış rejimde metan ve kok fırını gazı yanma özelliklerine olan etkileri

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Distributed Regime and Swirler Effects on Methane and Coke Oven Gas Combustion Characteristics

Highlights

- *In the study, the combustion of the swirl generator in the distributed regime for two different fuels was investigated.*
- *It is observed that the reduction in oxygen concentration favors low NOx formation under all conditions.*
- *For fuels with high hydrogen content, it is concluded that increasing the swirl number does not reduce NOx formation.*
- *Ultra-low NOx emission values could be obtained by decreasing oxygen concentration and changing the swirl number.*

Graphical Abstract

Combustion chamber geometry, oxygen concentration, and swirl numbers were determined. As a result of the analysis, the flow velocity distribution, temperature distribution, and NOx formation distribution in the combustion chamber were analyzed.

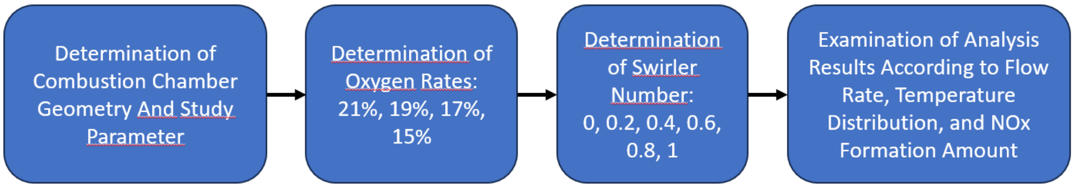

Figure. Flow chart of the study

Aim

The aim of this study is to examine the variations in the oxygen concentration and swirl number values for different types of fuels and to determine the optimum combustion criteria.

Design & Methodology

Based on a specified combustion chamber, the burning of methane and coke oven gas was analyzed numerically by altering the swirl number and oxygen concentration.

Originality

The originality of this study is to examine the effect of swirl number and oxygen concentration changes on methane and high-hydrogen coke oven gas combustion characteristics.

Findings

A decrease in the oxygen concentration causes the combustion to be slowed down and carried out throughout the combustion chamber, reducing the formation of NOx by lowering the maximum temperature attained in this case. By increasing the swirl number, the flame is generally spread throughout the combustion chamber.

Conclusion

According to the findings, it was concluded that the hydrogen content in the fuel, oxygen concentration in the oxidizer, and the swirl number optimized combustion at different rates.

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.

Distributed Regime and Swirler Effects on Methane and Coke Oven Gas Combustion Characteristics

Research Article

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ABSTRACT

The present study deals with combustion characteristics of methane and coke oven gas for various swirl numbers in a highly internal recirculative combustor under colorless distributed combustion conditions. In order to achieve that, the fuels have been consumed numerically in the combustor at various oxygen concentrations by using a N2 diluent to reduce oxygen concentration in the air. During the modelings, swirl number has been changed from s=0 to s=1 in an interval of 0.2. In this way, swirler effects on its combustion characteristics have been studied. In order to perform all modelings, the k-ε realizable turbulence model, the PDF/Mixture Fraction combustion model, and P-1 radiation model have been used. The results showed that decrease in oxygen concentration caused a more uniform temperature field in the combustor along with ultra-low NOx emissions. When the oxygen rate was reduced from 21% to 15%, a 9% decrease in the highest temperature reached in the combustion chamber was observed. In addition, a 99% decrease in nitrogen oxide formation was observed. This has been achieved with internal and external (colorless distributed regime) entrainments. In addition to these, it is concluded that the swirler has affected that combustion took place faster mostly because of better air-fuel mixture in the combustor. It has been observed that the air and fuel mixture occurs faster in the swirler effect, which has effects on the flow characteristics in the combustion chamber and has positive effects on recirculation, which can help to obtain conditions close to distributed combustion conditions in general. For 21% oxygen ratio, nitrogen oxide formation could be reduced by approximately 50% by increasing the swirl number from 0 to 1.

Keywords: Distributed Regime, Swirler, Combustion, Ultra-low NO_x

Girdap Üreticinin Dağıtılmış Rejimde Metan ve Kok Fırını Gazı Yanma Özelliklerine Olan Etkileri

ÖZ

Bu çalışma, renksiz dağıtılmış yanma koşulları altında yüksek düzeyde iç resirkülasyonlu bir yanma odasında çeşitli girdap sayıları için metan ve kok fırını gazının yanma özelliklerini ele almaktadır. Bunu başarmak için, havadaki oksijen konsantrasyonunu azaltmak amacıyla N2 seyrelticisi kullanılarak yakıtlar yanma odasında çeşitli oksijen konsantrasyonlarında sayısal olarak tüketilmiştir. Modellemeler sırasında girdap sayısı 0.2 aralıklarla s=0'dan s=1'e kadar değiştirilmiştir. Bu şekilde yanma özellikleri üzerindeki girdap etkileri incelenmiştir. Tüm modellemelerin gerçekleştirilebilmesi için k-ε Realizable türbülans modeli, PDF/Mixture Fraction yanma modeli ve P-1 radyasyon modeli kullanılmıştır. Sonuçlar, oksijen konsantrasyonundaki azalmanın, ultra düşük NOx emisyonlarıyla birlikte yanma odasında daha düzgün bir sıcaklık alanına neden olduğunu ortaya koymuştur. Oksijen oranının %21'den %15'e düşürülmesi ile birlikte yanma odasını içerisinde ulaşılan en yüksek sıcaklıkta %9 oranında düşüş gözlemlenmiştir. Bununla birlikte azot oksit oluşumunda %99 oranında düşüş gözlemlenmiştir. Bu durum, iç ve dış (renksiz dağıtılmış rejim) resirkülasyonun birlikte olmasıyla başarılmıştır. Bunlara ek olarak, yanma odasındaki hava-yakıt karışımının daha iyi olması nedeniyle, girdap üretici kullanımının yanmanın daha hızlı gerçekleşmesini etkilediği sonucuna varılmıştır. Girdap oluşturucu etkisinde hava ve yakıt karışımının daha hızlı gerçekleştiği, bunun yanma odası içerisinde akış karakteristiği üzerine etkileri olduğu ve genel olarak dağıtılmış yanma şartlarına yakın koşulların elde edilmesine yardımcı olabilecek şekilde resirkülasyona olumlu etkileri olduğu gözlemlenmiştir. %21 oksijen oranı için, girdap sayısının 0'dan 1'e çıkarılması ile azot oksit oluşumu yaklaşık %50 oranında düşürülebilmiştir.

Anahtar Kelimeler: Dağıtılmış Rejim, Girdap Üretici, Yanma, Ultra-düşük NO_x

1. INTRODUCTION

Less use of fossil fuels is on the agenda today. But, increase in usage of fossil fuel capacity shows that the use of carbon-based fuels for energy generation will continue to increase for many years (U.S. Energy Information, 2016). Improving the efficiency of fossil fuel use today can serve as a bridge towards a more sustainable energy future. It provides an opportunity to transition gradually to renewable energy sources that are cleaner while still meeting energy demands and supporting economic growth. Less pollutant emission aim emerges here because environmental issues continue being problem. Colorless distributed combustion (CDC) is one of the most efficient and ultra-low pollutant

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emission combustion methods that can serve this aim. CDC is a unique combustion process characterized by the absence of visible flames. It offers advantages such as ultra-low pollutant emissions, improved flame stability, and enhanced heat transfer efficiency. By optimizing the fuel-air mixture and utilizing specialized combustion devices and chambers, this combustion technique contributes to cleaner and more efficient energy utilization in various industrial applications.

Colorless Distributed Combustion (CDC) regime is such a condition that enables ultra-low pollutant emissions without reducing combustion performance (Arghode and Gupta, 2010). It also provides reduced combustion noise and high combustion efficiency along with less flashback tendency, especially in high hydrogen content fuel combustion (Karyeyen et al., 2019). CDC is a result of internal and/or external combustion products entrainment. The most important step to achieve internal entrainment is to design an internal recirculative combustor (Lammel et al., 2010; Khalil and Gupta, 2015; Khalil and Gupta, 2011). In the study reported in (Arghode et al., 2012), Arghode et al. designed better internal recirculative combustor, and they examined high intensity colorless distributed combustion inside it. In addition to internal entrainment, external entrainment can be implemented to achieve CDC. CDC is here achieved via combustion product recirculation into the fresh air-fuel mixture before ignition. As a result of this, oxygen concentration in the oxidizer is reduced, the reaction rate is slowed down, and finally, the flame starts to be an invisible one (Khalil and and Gupta, 2016; Ilbas et al., 2022).

Studies have reported that ultra-low NOx and CO levels are observed in combustion conditions where CDC conditions are achieved. Arghode and Gupta (Arghode and Gupta, 2010), for instance, investigated entrainment effects to achieve CDC, and they concluded that less pollutant emissions. Arghode et al. (Arghode et al., 2012) conducted a study on combustion performance improvement and emission level reduction under CDC conditions in a high thermal density combustion chamber. As a result of the reported study, ultra-low NOx emission values were reached for both premixed conditions and non-premixed conditions. With the CDC conditions fulfilled, the CO level decreased below 30 ppm with a 5% loss in combustion chamber pressure. Karyeyen and Ilbas (Karyeyen and Ilbas, 2020) examined some high hydrogen containing fuels combustion characteristics under colorless distributed regime. They concluded that ultra-low pollutant emissions were achieved without reducing combustion performances considerably. Arghode and Gupta (Arghode and Gupta, 2011) investigated colorless distributed combustion effects on methane combustion at various equivalence ratios in a internal recirculative combustor. It has been determined that almost colorless or invisible flames could be achieved in the study. Khalil and Gupta (Khalil and Gupta, 2011) focused on examination of high heat release applications such as gas turbine conditions with highly swirling under distributed regime. The results showed that low pollutant emissions were achieved through transition to CDC regime. The authors who studied the previous work (Khalil and Gupta, 2011) performed another study in which thermal field under conventional and CDC conditions was examined in a swirl-stabilized burner (Khalil and Gupta, 2015). They concluded that there were some temperature decrements under CDC in the combustor. It has been, however, observed that there is just a slight difference between the temperature profiles at 21% O2 and 13.8% O2 concentrations at the combustor outlet. Roy and Gupta (Roy and Gupta, 2022) examined the flame and pollutant emissions characteristics of the methane fuel using data-driven artificial neural network (ANN) approach under CDC conditions. The air inlet flowrates and oxygen concentrations were used as the input, and the pollutant emissions and adiabatic flame temperatures were used as the output. Other studies which contribute to the CDC field can also be reported here (Roy and Gupta, 2023; Karyeyen et al., 2020; Karyeyen et al., 2019; Wang et al., 2020; Roy and Gupta, 2020; Khalil and Gupta, 2017).

In the light of the studies reported above, it is concluded that colorless distributed combustion method enables ultra-low pollutant emissions without reducing combustion performance substantially. Internal and/or external entrainment is the basis process to achieve CDC here. Most studies reported do not focus on conjuction effects on CDC achievement. This study herein contributes to the CDC field in terms of conjuction effects to achieve CDC. For this purpose, a highly internal recirculative combustor has been used to examine combustion and emission characteristics of methane which is the major part of natural gas and coke oven gas including high hydrogen concentration fuel. With the recirculative combustor, residence time can be more, with reducing oxygen concentration in the oxidizer, external entrainment can be achieved. In addition to external/internal entrainment effects, swirler effects on CDC regime is within the scope of this study to generate more turbulence in the flow inside the combustor to rapidly mix the air with fuel.

2. MATERIAL and METHOD

The combustion chamber used in this study to achieve internal entrainment is the combustor reported in the study (Arghode et al., 2012) because this study includes numerical simulations, and there have been experimental results in that study to validate the present modeling results. The modeling validation results details can be found elsewhere (Ilbas et al., 2022). The combustor details are presented in Figure 1. The combustor is such a rectangular and small type. The main aim to generate a smaller combustor is to simulate a gas turbine combustor having higher heat release intensity. In Figure 2, it is also seen that some lines being actually virtual to examine results in the next chapters. Those can be termed the inletline which shows from the air inlet line to the bottom of the combustor, the bottomline, and the outletline that illustrates from the combustor bottom to the combustor outlet. Finally, in the drawn figures which those are included in the next chapters, temperature, velocity, and NOx results predicted are presented.

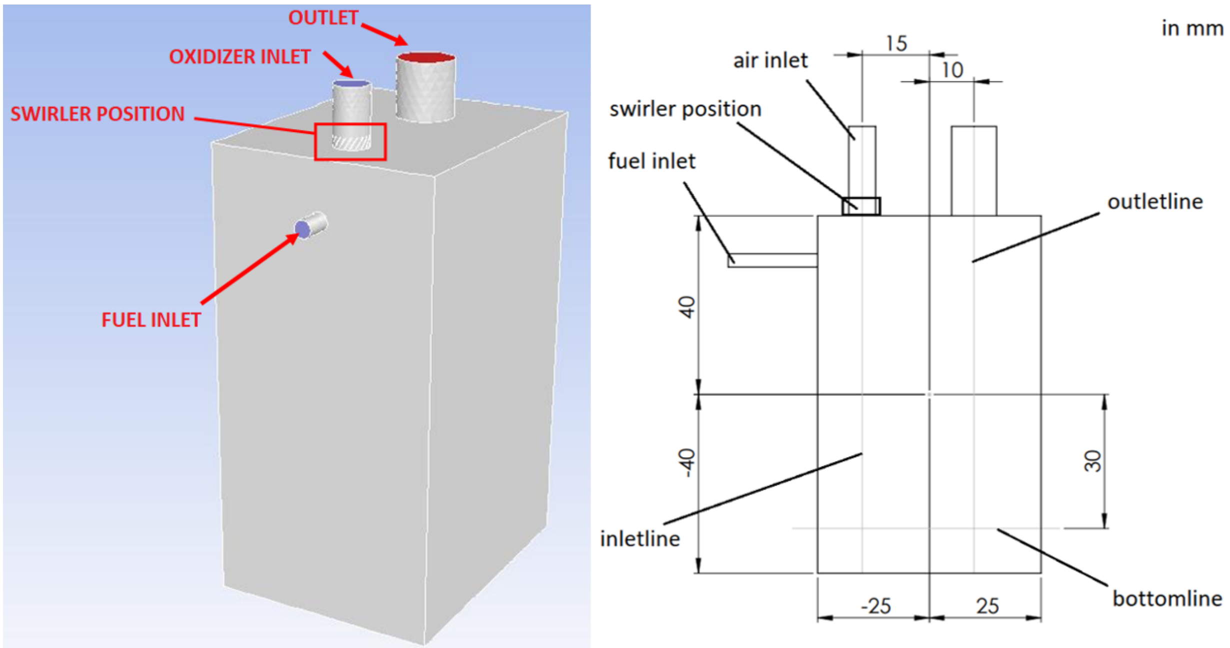

Figure 1. The combustor and its details

A thermal power of 10 kW and an equivalence ratio of 0.83 for methane (100% CH_4), and coke oven gas (55% H_2, 27% CH_4, 10% N_2, 6% CO and 2% CO_2) are studied at 21%, 19%, 17%, and 15% oxygen concentrations to seek colorless distributed combustion regime. Within the scope of the present study, various swirl numbers (0, 0.2, 0.4, 0.6, 0.8, 1) are sought to investigate swirler effects on CDC. In this way, tangential momentum jets are generated inside the combustor to achieve better fuel-air mixtures just as in a gas turbine combustor. Swirl number is calculated through the equation 1:

$$S = \frac{2}{3}\left(\frac{1-\left(\frac{d_h}{d}\right)^3}{1-\left(\frac{d_h}{d}\right)^2}\right)\tan\beta \qquad (1)$$

where S is swirl number, d is the outer swirl generator diameter, d_h is generator hub diameter, and β is exit angle of the swirl vanes.

Modeling details can be discussed here. For turbulence modeling, k-ε realizable turbulence model was used. Besides, the PDF/Mixture Fraction combustion model has been selected to model reaction details as it is better to present all combustion characteristics results for especially blending fuels such as coke oven gas. Finally, P-1 radiation model has been used to determine temperature distributions inside the combustor because after combustion process, probable temperature levels are higher than 1000°C. After combustion modeling, NOX post-processing for thermal and prompt NOX mechanisms has been performed to predict NOX distributions inside the combustor. A study flow chart can be shown in Figure .

3. RESULTS and DISCUSSION

The modeling results are presented and discussed here. Contours and profiles of velocity, temperature, and NOX results inside the combustor are subsequently illustrated in the next sub-sections. In order to validate the present study results, the experimental results reported in Arghode et al. (Arghode et al., 2012) are needed, and those were compared with the present non-reacting predictions. According to validation result, it can be said that the velocity profile predicted is satisfactory good agreement with the experimental data in terms of value and trends. Even though there are slight differences, inlet line velocity values very close to experimental PIV results and comparison graph is given Figure 2. Other results and detailed explanation to the non-reacting modeling results can be found elsewhere (Ilbas et al., 2022).

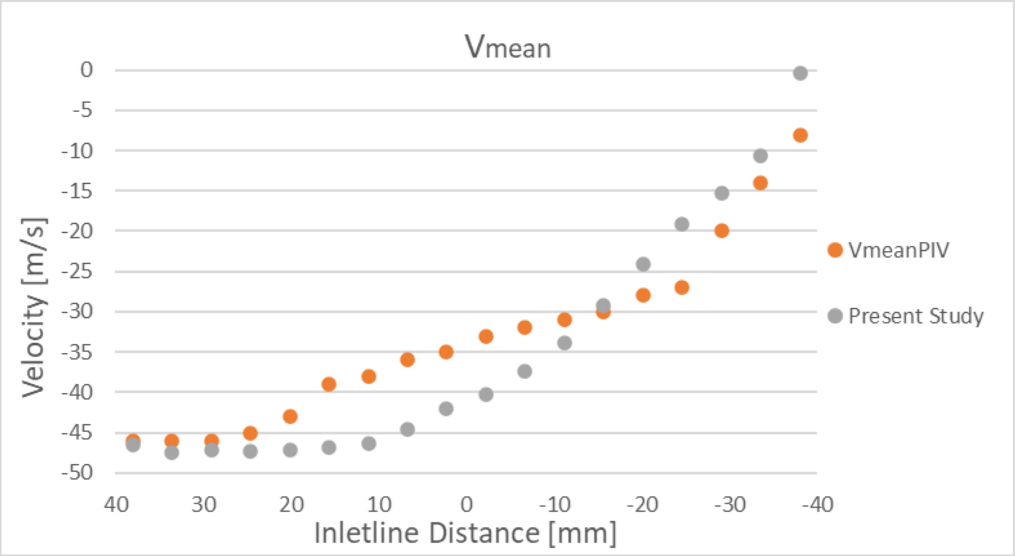

Figure 2. Validation results of inletline velocity

3.1. Velocıty

When the velocity graphs are examined, the flow velocity from the air inlet to the bottom of the combustion chamber decreases with the increase in the number of swirls for both methane and coke oven gas. Especially for s=0.8 and 1 conditions, the velocity values decrease and appear distributed in the regions close to the bottom of the combustion chamber for all cases. The reason for this is that the air entering the combustion chamber has lower axial momentum with the increase in the swirl number, and is separated in the radial and tangential directions, and much more distributed into the combustion chamber.

In order to keep the thermal power and equivalence ratio constant, the air flow rate introduced was increased with increase of the nitrogen concentration or decrease of oxygen concentration in the air to seek distributed regime. When these cases are examined, it is seen that the axial velocity decreases with increase in the number of swirls in all cases, although the distribution in the velocity graph is preserved a little more towards the bottom of the combustion chamber with the increase in flow rate. Especially in cases of s=0.8 and 1, the flow in the combustion chamber is distributed along the combustion chamber with the eddies formed.

It is evaluated that the created vortices increase the residence time in the combustion chamber through the fuel and air mixture throughout the combustion chamber, and this reduces the formation of harmful emissions. In this way, the distribution of combustion throughout the combustion chamber reduces the hot spot zones resulting in less thermal NOx formation. When the velocity results (Figure 4, Figure 5, Figure 6, Figure 7 and Figure 8) are evaluated together with the temperature results (Figure 9, Figure 10, Figure 11, Figure 12 and Figure 13), it is seen that increase in swirl number changes the air flow regime in the combustion chamber and as a result, the regions with high temperature are displaced. In conditions with higher oxygen concentrations, the effect of the increase in the number of swirls on the temperature levels was less, while the effect of the number of swirls increased with decrease in the oxygen concentration in the air. The reason for that may be considered that the instantaneous mixture of air and fuel increases at higher swirl numbers, and in this case, combustion takes place faster. In cases where the oxygen concentration is lower, since the instantaneous combustion situation is reduced, the well-distributed fuel throughout the combustion chamber burns relatively slowly, causing a homogeneous distribution combustion. When all prediction results for both fuels were examined, it was evaluated that the highest temperature values were approached under the conditions where s = 0.4 and the temperature distribution was more homogeneous.

When the velocity changes on the inletline are examined, the velocity values for both fuels gradually increase with the effect of the decrease in the oxygen concentration because of higher flow rates. However, in the same graphs, it was observed that as the swirl value increased, the increase in the velocity value gradually decreased, even if the inlet air flow rate increased with the decrease in the oxygen amount. This situation gains importance due to the increase in the residence time in the combustion chamber.

On the bottomline, the flow rate varied diffusely in all cases. Although the complexity of the graphs increases under conditions where the amount of oxygen gradually decreases along the bottomline, it is difficult to make a clear determination of the effect of the change. For this reason, it is better to understand swirler and distributed combustion regime effects on the profiles along with the outletline.

In addition to the fact that all graphs obtained on the outletline line have close values with each other, it is possible to say that the velocity at the bottom of the combustion chamber is low for the value of s=1 and that there is a proportionally higher velocity increase towards the combustion chamber outlet compared to other conditions. The reason for this is that the air-fuel mixture, which is divided into dense eddies under the effect of swirls, collects less on the bottom of the combustion chamber than in other cases, and this air-fuel mixture collects and accelerates towards exit of the combustion chamber.

3.2. Temperature

Cross-sectional temperature contours and profiles obtained on the inletline, bottomline, and the outletline for methane and coke oven gas are presented and discussed in this sub-section. For both fuels; decrease in oxygen concentration in the air introduced to the combustion chamber decreased the temperature values throughout the combustor. This is because of the reaction rate is slowed down. This resulted in a more homogeneous temperature distribution resulting in achievement of colorless distributed combustion conditions. When combustion conditions are examined with air at the same oxygen concentration, the regions reaching high temperature values are displaced throughout the combustion chamber. This can be explained that the air that gains momentum under the effect of the swirler is repositioned by creating vortices throughout the combustor by dragging the fuel as well. It is observed in the temperature contours under the effect of the formed eddies. It can be evaluated that this situation occurs with the formation of flame unstability for some swirl numbers.

Especially in the combustion conditions at lower oxygen concentrations, the air movements caused by the swirler led to the formation of high temperature zones. This is because lower oxygen concentration in the air has a higher flow rate and higher momentum, thereby creating local high-temperature zones by entraining the fuel to different locations in the combustor. For both fuels, it can be said that the temperature is evenly distributed throughout the combustion chamber at s=0.4.

Even if the temperature distribution regions change under various swirl numbers in combustion conditions at higher oxygen concentrations, the locations of the high temperature regions are generally close. It has been evaluated that the effect of swirls on the general characteristics of combustion is low in these conditions, where combustion takes place. When the temperature graphs for methane and coke oven gas combustion are examined, along the inletline, decrease in oxygen concentration caused a decrease in the temperature curves towards the bottom of the combustor. In addition, it can be said that the distribution of temperature values in the combustor is improved under the swirling conditions along the line. For all oxygen concentration, the most stable temperature reduction and improved distribution is when the swirl number is 0.4. When the bottomline profiles are examined, although the maximum temperature value reached noticeably decreases with decrease in oxygen concentration, it is seen that the flow and temperature distribution are complicated towards the bottom of the combustion chamber and no meaningful results can be obtained about the swirl effect just as in the velocity profiles. The complex structure in the air flow continues in all conditions along the outletline, and it is seen that the temperature values are lower in the parts close to the bottom of the combustion chamber with decrease in oxygen concentration. Due to high hydrogen level in coke oven gas, it reacts earlier than methane, and reaches higher temperature values due to the rapid reaction of air and fuel, which mixes quickly under the swirling conditions. Increase in the swirl number decreases the flow momentum in the axial direction, and causes the reaction to take place more intensely in the combustor inlet sections.

3.3. Nox Emission

The formation of high temperature zones, which is the most important factor that leads to form NOx, was also observed in the study. When the temperature graphs and NOx graphs are examined, it is seen that NOx formations occurred in the high temperature zones due to the thermal NOx formation along with prompt NOx. When it is evaluated the methane combustion in terms of NOx emission, along the inletline, for all oxygen concentration, increasing the swirl number resulted in a decrease in NOx formation. In addition to the swirler number, it has been observed that the local NOx formation regions are considerably reduced for the cases when oxygen concentration in the air is reduced. It is considered that two reasons have caused this situation. Firstly, with the increase of the swirl number, the mixing of the fuel with the air over a larger area supported the internal recirculation, and reduced the NOx formation. Secondly, with the air dilution, the air flow rate introduced to the combustor increases, which both supports the first case and causes transition to CDC condition. Under these effects, less thermal NOx and prompt NOx was achieved.

For the same reasons, stable values have observed in the bottomline and outletline profiles. The NOx formation along the bottomline showed little variation along a horizontal line. When the outletline graph is examined, there is a slight increase in NOx formation in the region whose value of 40 mm represents at the exit of the combustor. But it can be said that NOx formation has been stable in general.

As for evaluation of the coke oven gas combustion figures, similar to methane combustion along the inletline, although there was a general downward trend in NOx formation with increasing swirl numbers for all oxygen concentrations, a stable correlation was not observed up to the lowest oxygen level. It is thought that the reason for this is the combination of fast mixing and high hydrogen concentration, which contributes prompt NOx formation due to hot spot zones. When all figures are considered, it has been observed that the swirler effect provides optimum benefit to reduce NOx formation under CDC condition when the swirler number is of 0.4.

In general, it is concluded that transition to CDC can contribute to reduce NOx formation.

4. CONCLUSIONS

The aim of this study is to observe the changes in combustion condition for methane and coke oven gas fuels for various swirl numbers in a highly internal recirculative combustor under distributed regime. In order to achieve swirler effects on colorless distributed regime, nitrogen as a diluent was introduced into the combustion air, and in this way, oxygen concentration in the oxidizer was reduced. Thereby, the reaction rate was slowed down, and as a result of that, distributed regime was achieved, resulting in a more uniform thermal field and ultra-low NOx emission levels. With all modeling results, the following conclusions have been obtained.

When the temperature results have been examined, it was observed that increase in the swirl number at the same oxygen concentration contributed to achieve a more uniform combustion field in the combustor. In this way, the hot spot zones were repositioned inside the combustor, and the temperature differences between all zones decreased. This effect has been especially emerged at lower oxygen concentrations. With introduction of the diluent and entrainment of the fuel by swirling, the normal and tangential momentums have been increased, helping to distribute the fuel throughout the combustor. It is concluded that well-distributed air-fuel mixture throughout the combustor helped to sustain combustion.

Increase in the swirl number led to a decrease in the introduced air momentum in the axial direction, and as a result of that, an increase in the tangential momentum was achieved. For this reason, when the combustion conditions at the same oxygen concentration are examined, it is possible to interpret that the high temperature regions in the combustor moved towards to the center of the combustor gradually. When all results are examined, it is determined that the temperature distributions and NOx formations are better than those of other results for both fuels when $s = 0.4$ was studied in the combustor. Besides, increase in the swirl number contributed to achieve the distributed regime through which a more uniform thermal field existed in the combustor. In particular, for cases in which oxygen concentration in the oxidizer was lower, increase in the swirl number reduced local hot zones formations, and it was effective to reduce the thermal NOx formation as the reaction rate was slowed down.

In this study, numerical results were obtained on how to obtain lower combustion maximum temperature values. With future studies, the study can be detailed to establish empirical mathematical models with the basic principles set out here. In future studies, the number of analyzes can be increased for values close to 17% oxygen content in order to examine the effect of the oxygen content in the air in more detail. Additionally, swirler geometries can be studied to ensure that the flow through the combustion chamber is slower and more homogeneous.

In conclusion, combustion characteristics of different fuels have been examined for various swirl numbers in a highly internal recirculative combustor under colorless distributed combustion conditions. The results obtained from the present study can provide an insight usability of methane and coke oven gas in various applications such as gas turbines, furnaces etc. for different swirl numbers under distributed regime, resulting in ultra-low NOx emissions without reducing its combustion performances.

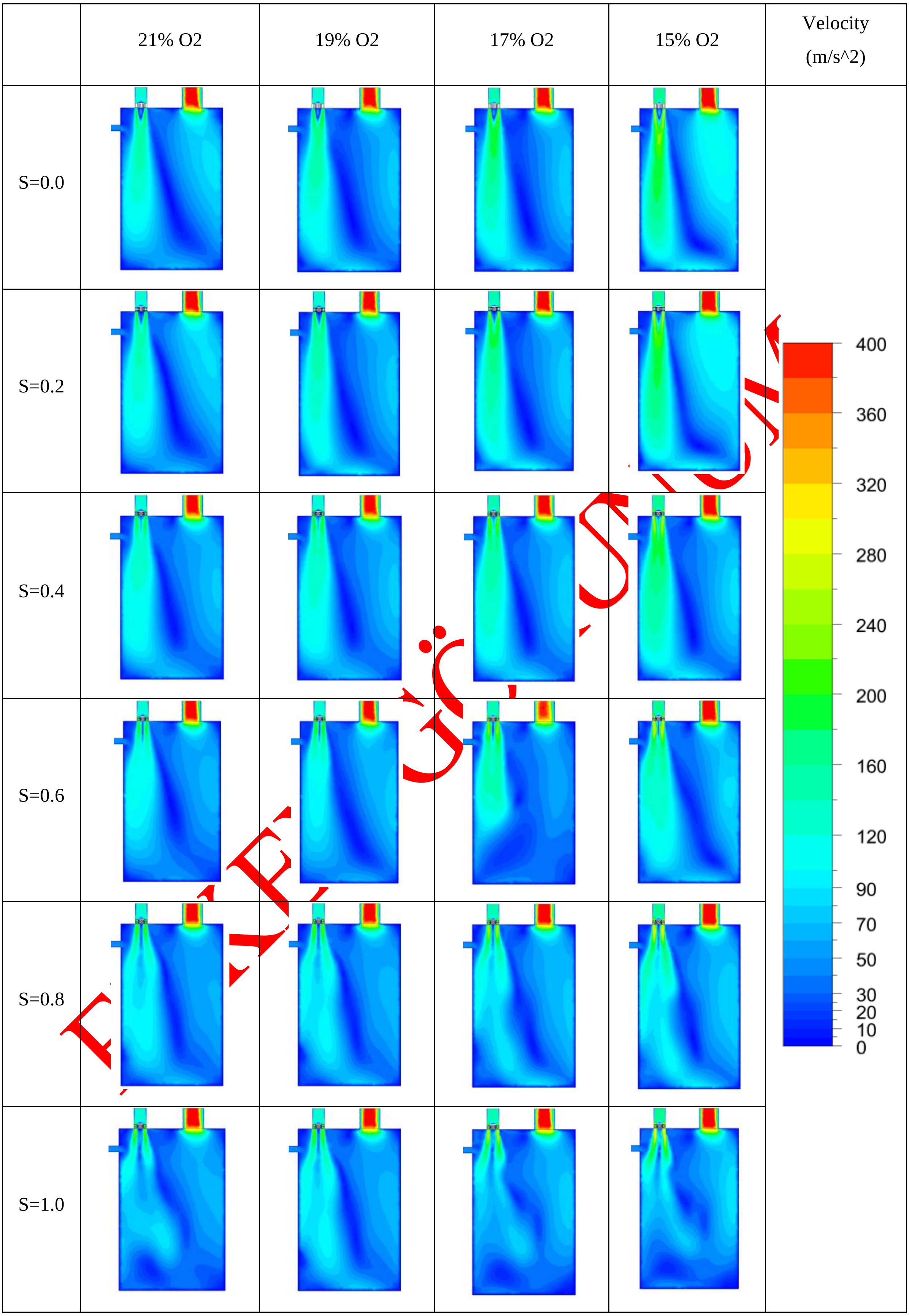

Figure 3. Velocity contours of methane combustion

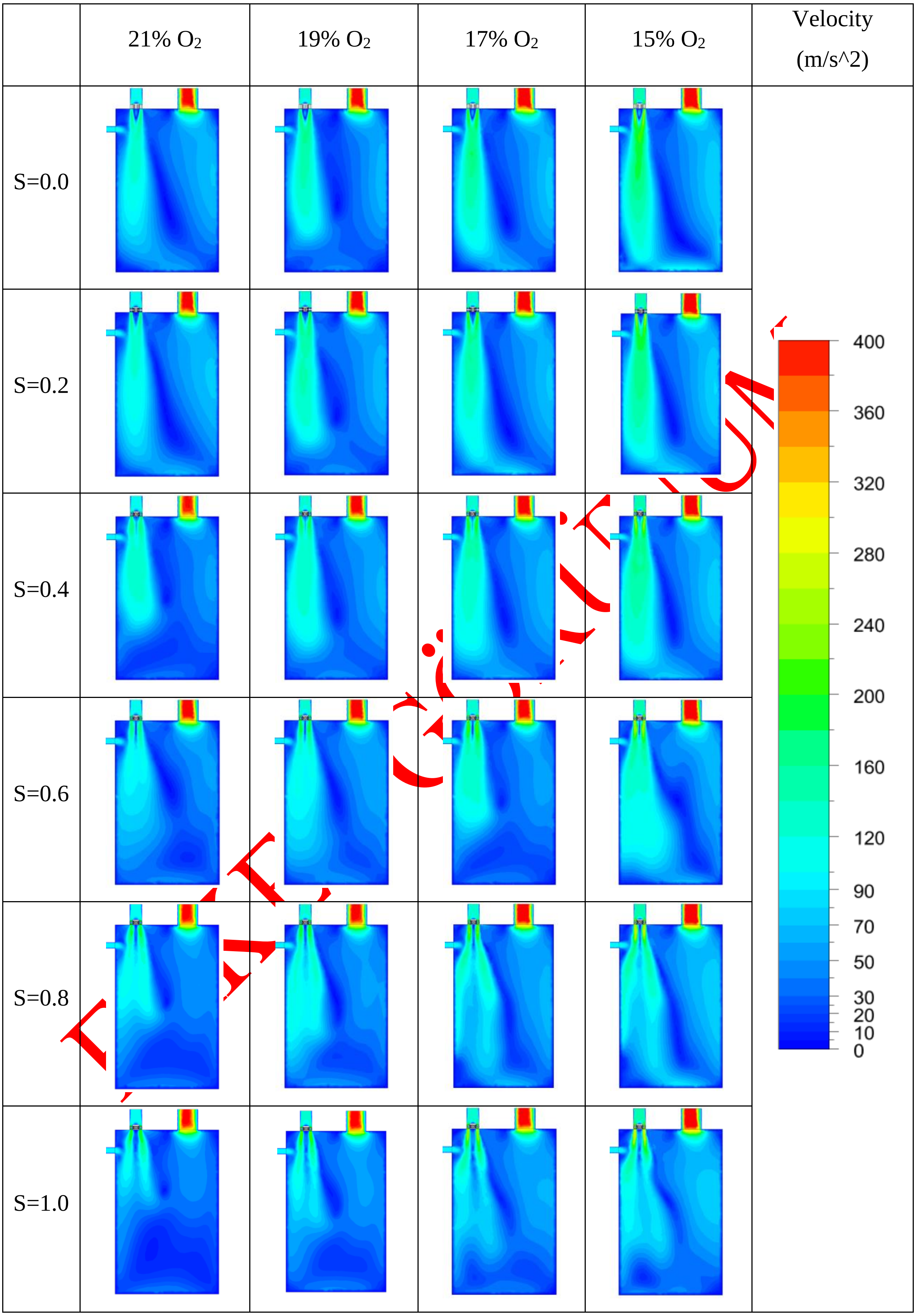

Figure 4. Velocity contours of coke oven gas combustion

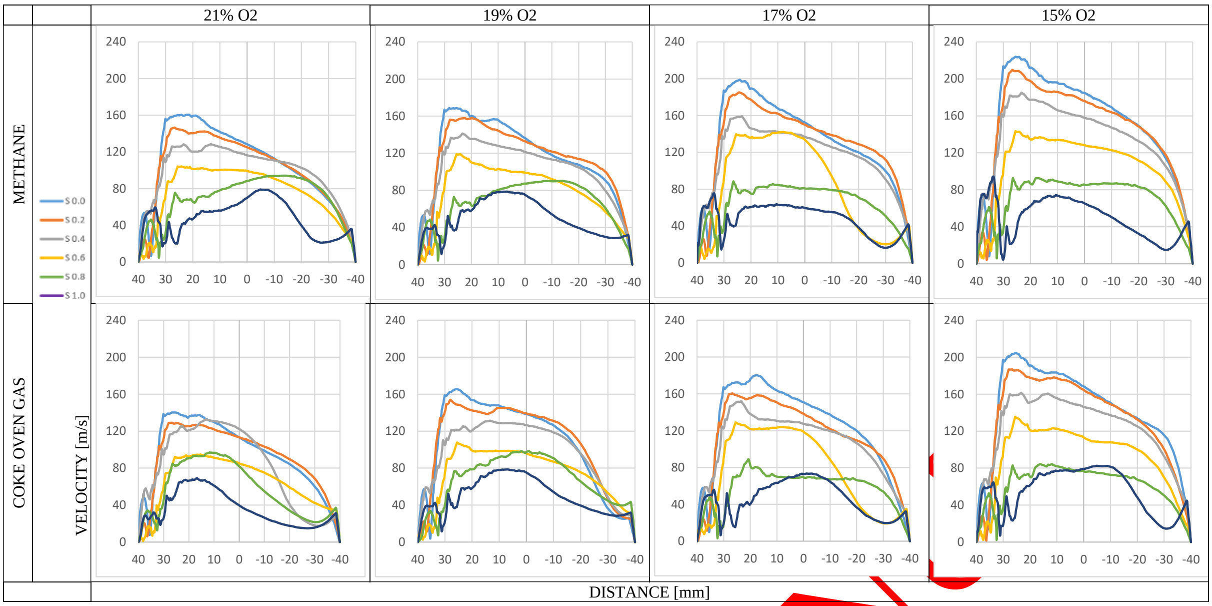

Figure 5. Velocity profiles on the inletline

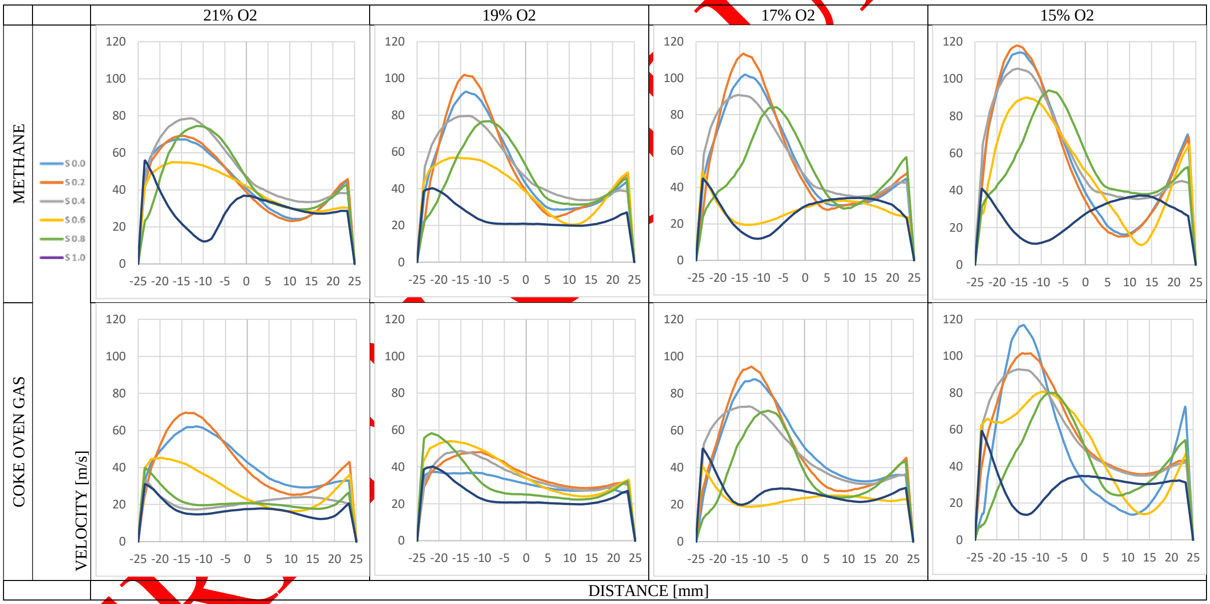

Figure 6. Velocity profiles on the bottomline

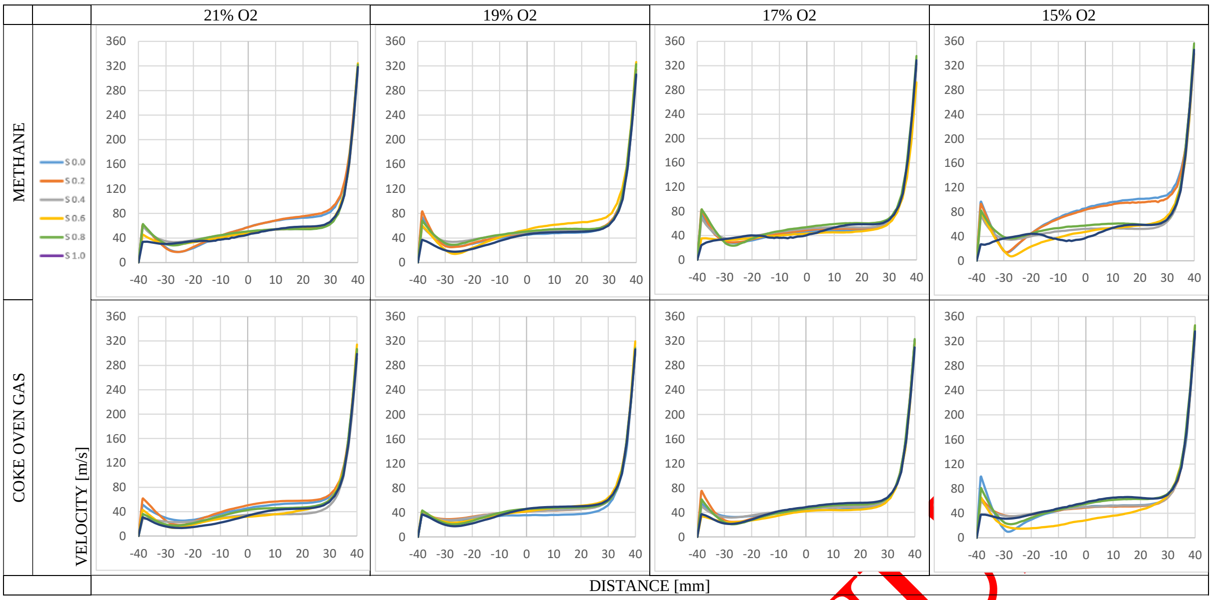

Figure 7. Velocity profiles on the outletline

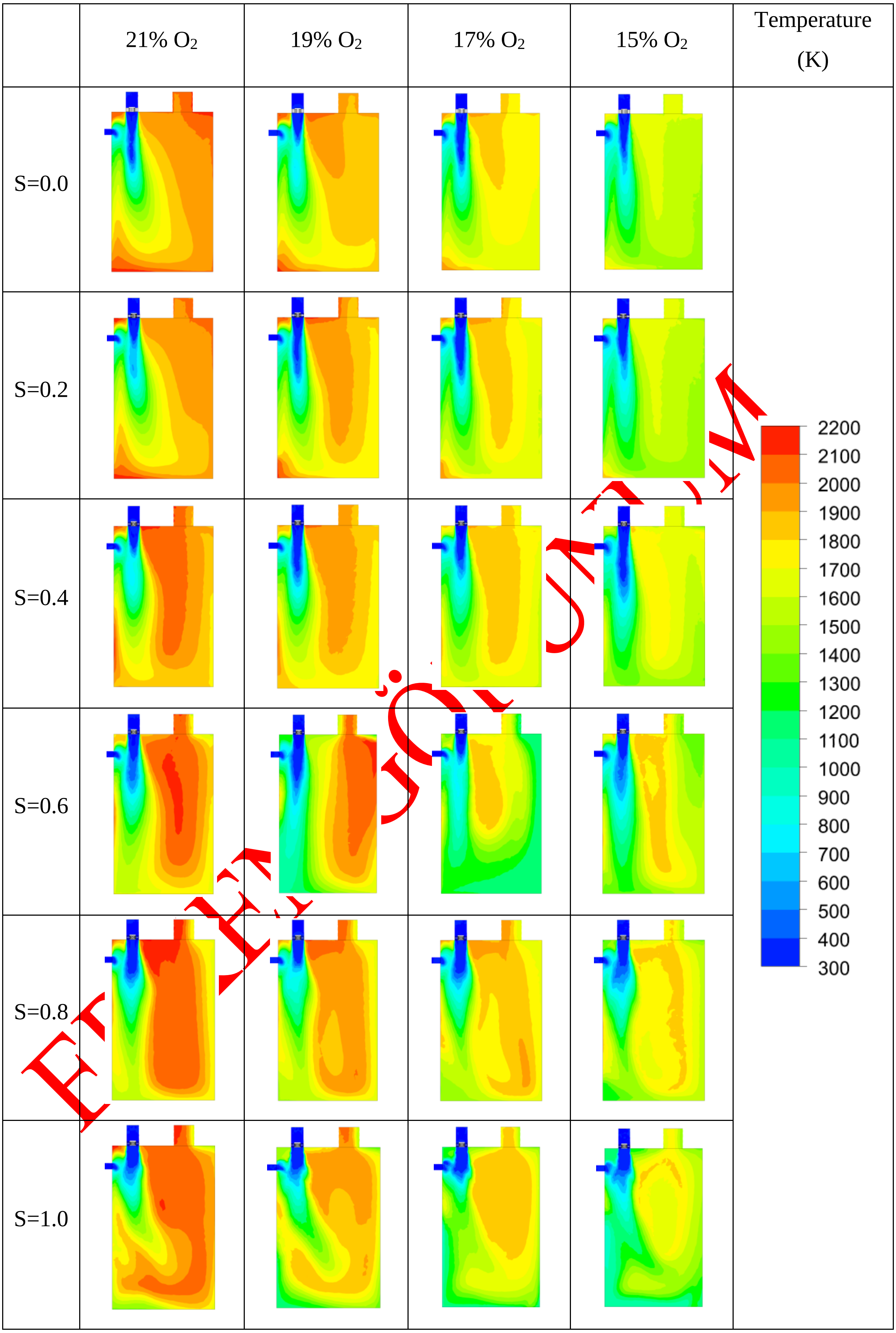

Figure 8. Temperature contours of methane combustion

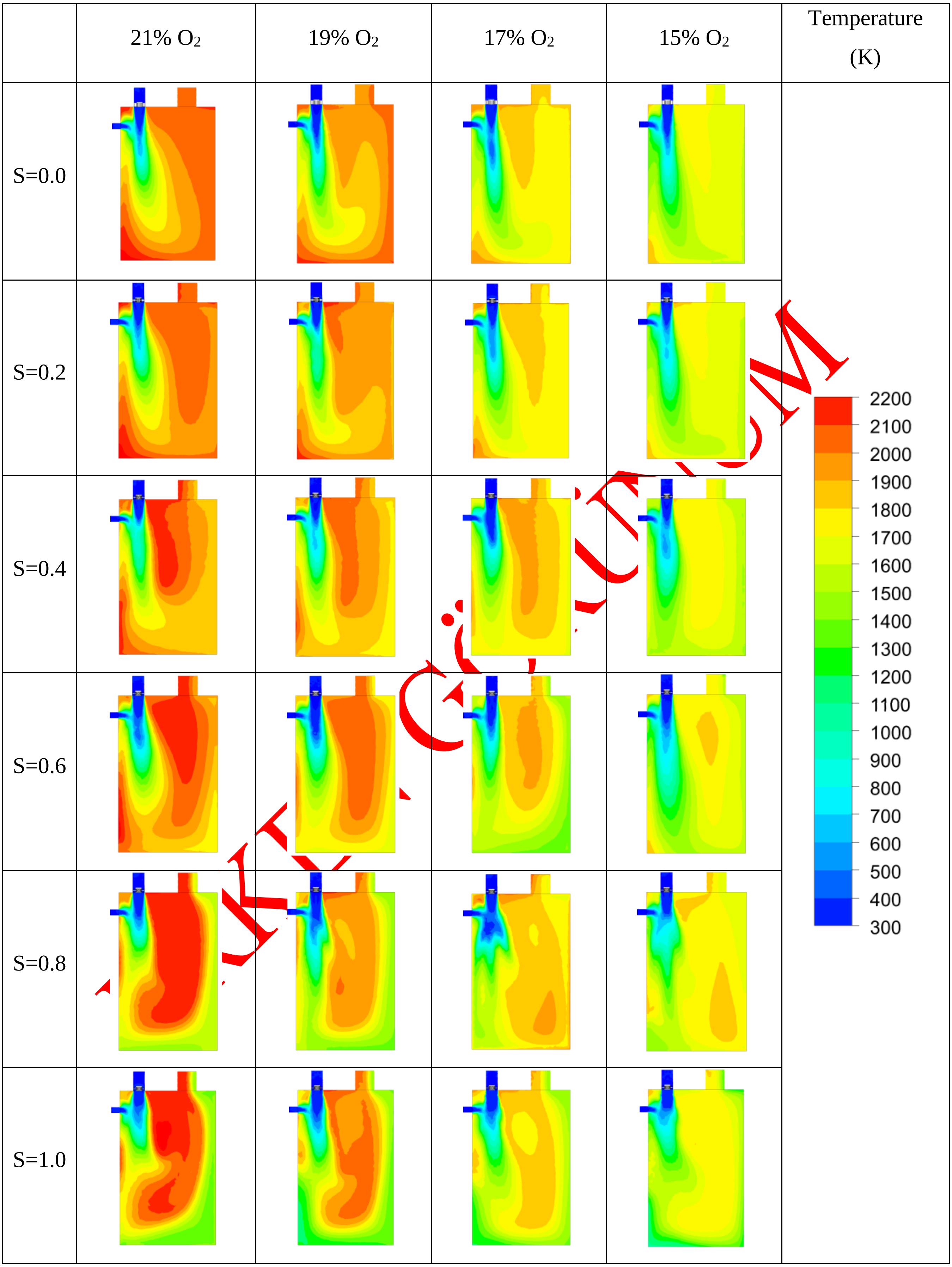

Figure 9. Temperature contours of coke oven gas combustion

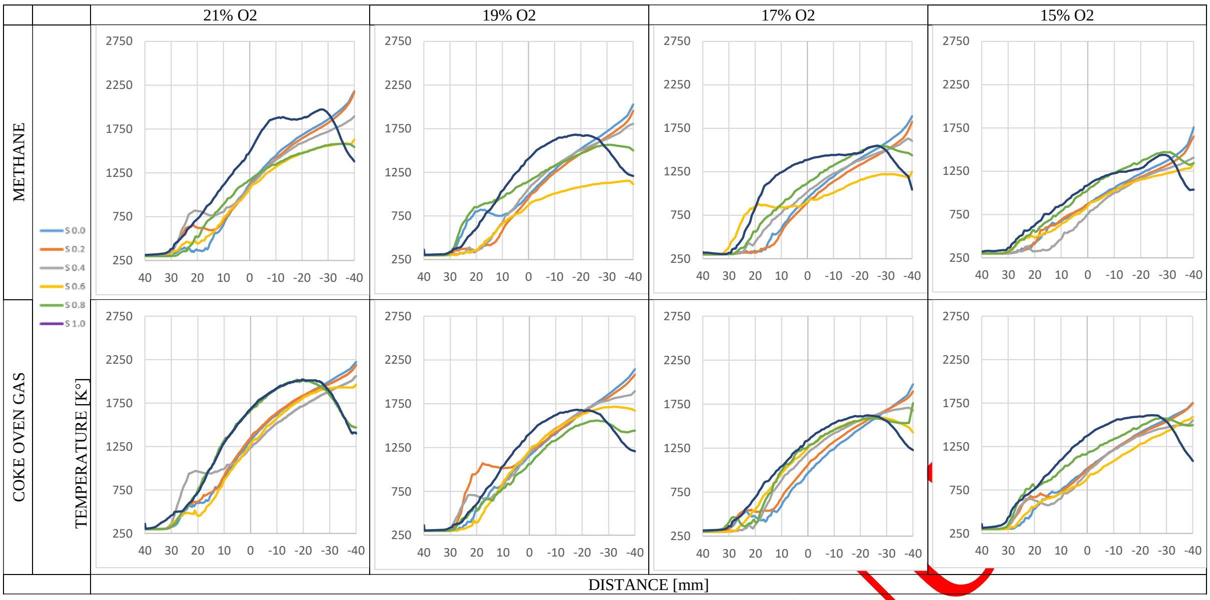

Figure 10. Temperature profiles on the inletline

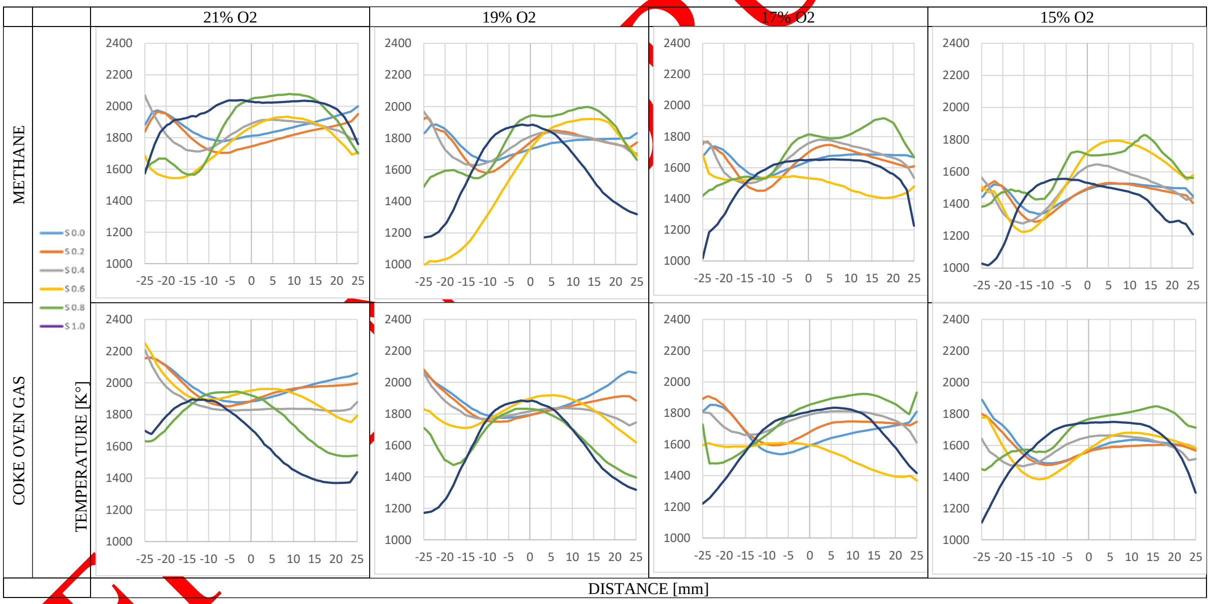

Figure 11. Temperature profiles on the bottomline

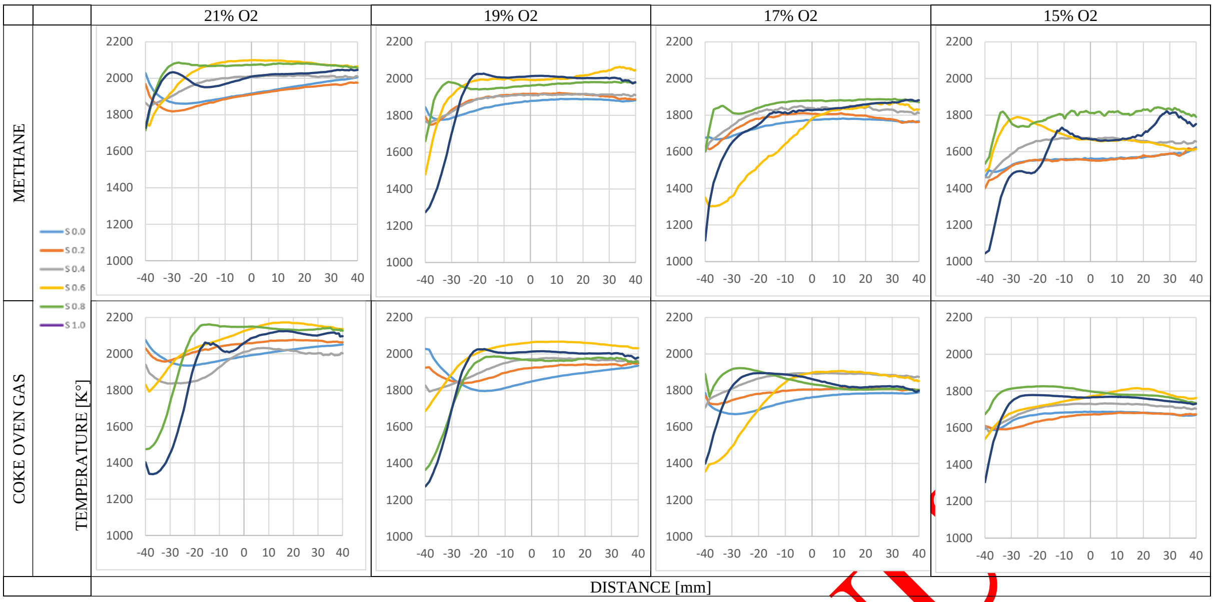

Figure 12. Temperature profiles on the outletline

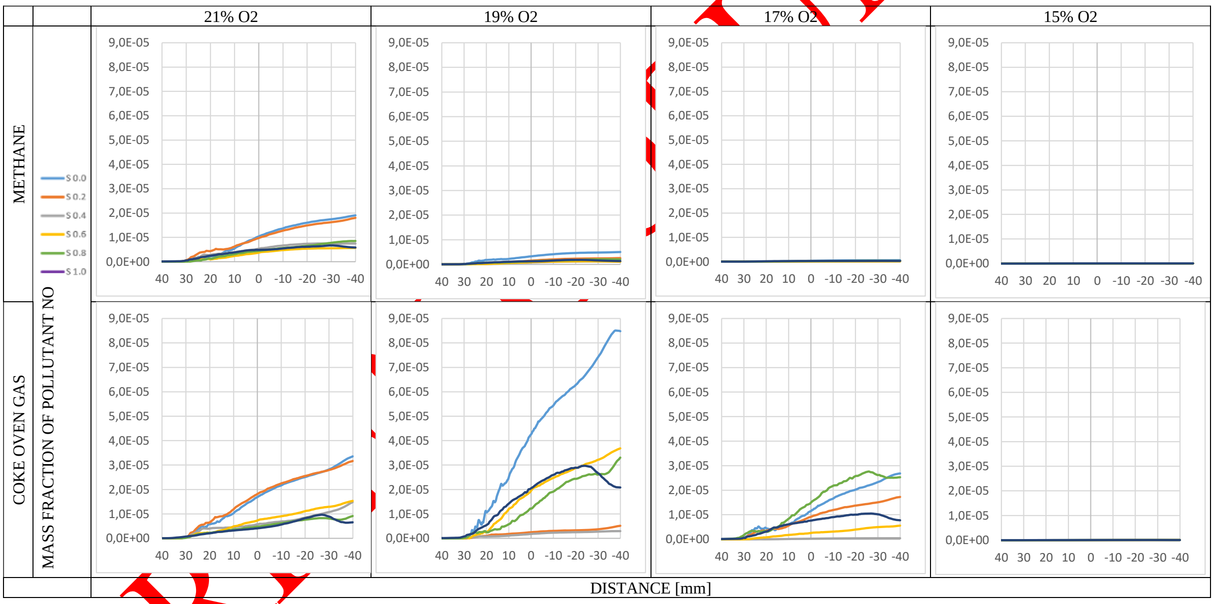

Figure 13. NOx mass fraction profiles on the inletline

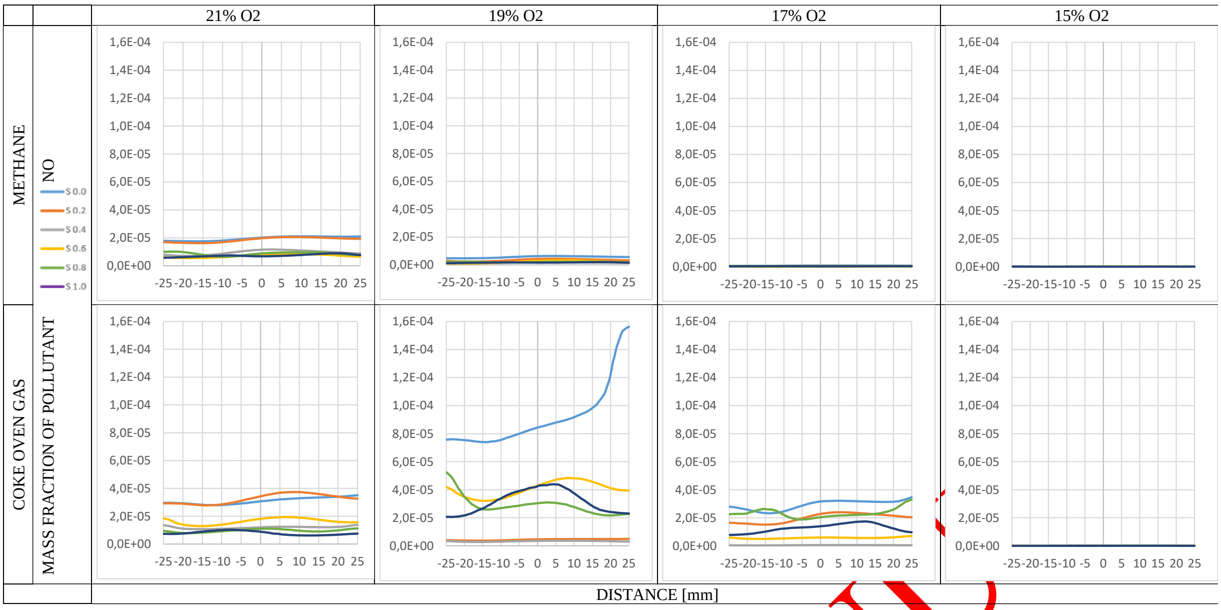

Figure 14. NOx mass fraction profiles on the bottomline

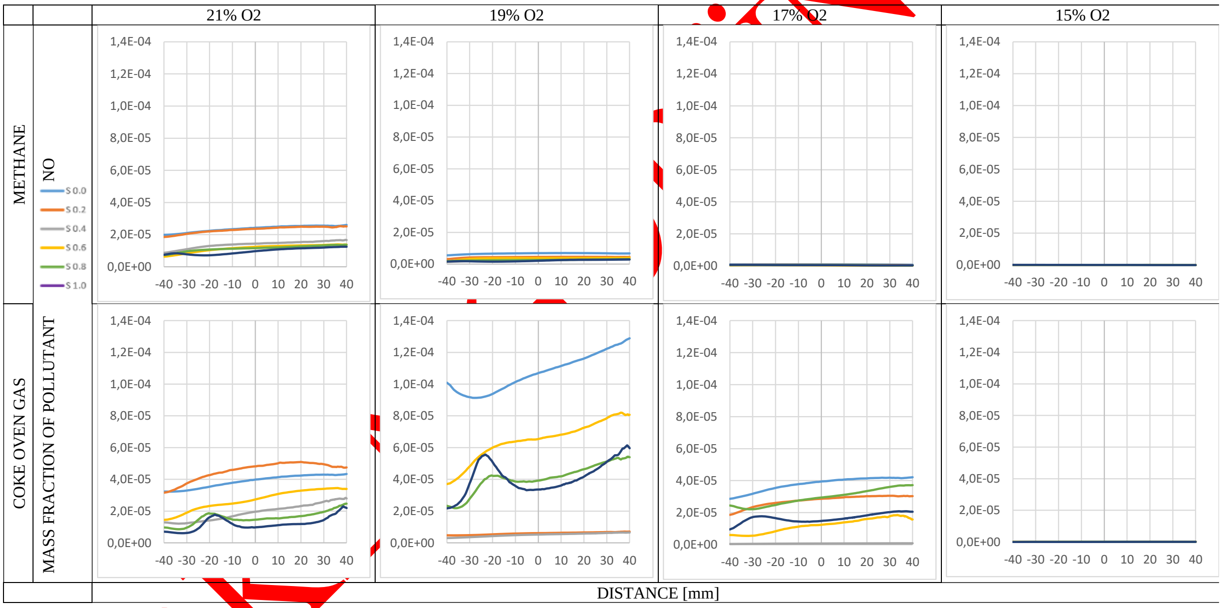

Figure 15. NOx mass fraction profiles on the outletline

DECLARATION OF ETHICAL STANDARDS

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

AUTHORS' CONTRIBUTIONS

Alparslan İLBAŞ: Performed design, simulation, implementation and CFD analysis, prepared graphs and reported results.

Mustafa Bahadır ÖZDEMİR: Performed the theoretical studies, literature research, implementation, prepared graphs and reported results. Managed the writing process of the article.

Serhat KARYEYEN: Performed the theoretical studies, literature research, implementation, prepared graphs and reported results. Managed the writing process of the article.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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