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Effects of Steam Addition to the Oxidizer on the Combustion Performance and Emissions of Coke Oven Gas: A Numerical Study

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Anahtar Kelimeler

Yanma
Kok fırını gazı
Su buharı
HAD

Graphical/Tabular Abstract (Grafik Özet)

This study numerically investigates the effects of steam addition to the oxidizer on the combustion performance and emissions of coke oven gas. / Bu çalışmada, oksitleyiciye buhar ilavesinin kok fırını gazının yanma performansı ve emisyonları üzerindeki etkileri sayısal olarak araştırılmıştır.

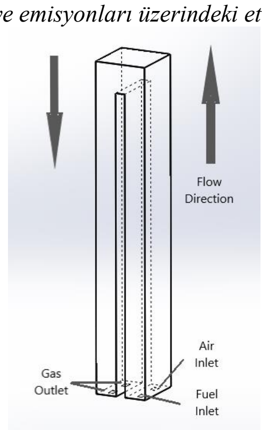

***Figure A**: Coke oven combustion chamber /**Şekil A:**.Kok fırını yanma odası*

Highlights (Önemli noktalar)

- *The utilization of coke oven gases has been thoroughly analyzed. / Kok fırını gazlarının kullanımı kapsamlı bir şekilde analiz edilmiştir.*
- *Comparative assessments were conducted under conventional operating conditions and with the addition of steam. / Karşılaştırmalı değerlendirmeler geleneksel çalışma koşulları altında ve buhar ilavesiyle yürütülmüştür.*
- *Remarkably, ultra-low NOx emissions were achieved, highlighting the environmental benefits of this approach. / Dikkat çekici bir şekilde, bu yaklaşımın çevresel faydalarını vurgulayan ultra düşük NOx emisyonları elde edilmiştir.*

Aim (Amaç): *The main aim of this study is to investigate the temperature, emissions, and performance of a coke oven gas combustion chamber under steam addition using non-premixed combustion. / Bu çalışmanın temel amacı, buhar ilavesi ve ön karışımsız yanma altında bir kok fırını gazı yanma odasının sıcaklığını, emisyonlarını ve performansını araştırmaktır.*

Originality (Özgünlük): *An examination of the existing literature reveals that no studies have investigated the effects of diluting the oxidizer with water vapor on the combustion and emission parameters of coke oven gas in the combustion chamber of a coke oven. / Mevcut literatür incelendiğinde, bir kok fırınının yanma odasında, oksitleyicinin su buharı ile seyreltilmesinin kok fırını gazının yanma ve emisyon parametreleri üzerindeki etkilerini inceleyen bir çalışmanın bulunmadığı görülmektedir.*

Results (Bulgular): *The flue gas temperature at the furnace outlet was measured at 1372 K. When 40% steam was added to the oxidizer, the temperature decreased to 1249 K. The NOX emission level was 6.9 ppm without adding steam, dropping to 1.2 ppm with the 40% steam addition. / Fırın çıkışındaki baca gazı sıcaklığı 1372 K olarak ölçülmüştür. Oksitleyiciye %40 buhar eklendiğinde sıcaklık 1249 K'e düşmüştür. NOX emisyon seviyesi buhar eklenmeden 6.9 ppm iken, %40 buhar eklenmesiyle 1.2 ppm'e düşmüştür.*

Conclusion (Sonuç): *It can be seen that adding steam to the oxidizer successfully reduces NOX emissions without significantly affecting performance. / Oksitleyiciye buhar eklenmesinin, performansı önemli ölçüde etkilemeden NOX emisyonlarını başarılı bir şekilde azalttığı görülebilir.*

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Abstract

This study investigates the effects of adding steam to the oxidizer on the combustion behavior of coke oven gas through numerical simulations. The analysis used the commercial computational fluid dynamics (CFD) software Ansys Fluent. The results obtained for the case where dry air was used as the oxidizer were compared with experimental data. The k-Ɛ standard turbulence model was employed for turbulence modeling, while the PDF/Mixture Fraction combustion model and the P-1 radiation model were used for the three-dimensional numerical simulations. According to the simulation results, adding steam to the oxidizer slightly reduced the Coke Oven Gas (COG) temperature. When assessing the emissions, it was observed that NO_X emissions significantly decreased, while CO_2 emissions showed a slight reduction. However, CO emissions were found to increase slightly. In conclusion, the study indicates that adding steam to the oxidizer significantly mitigates the high NO_X emissions typically associated with using coke oven gas as an alternative fuel. The flue gas temperature at the furnace outlet was measured at 1372 K. When 40% steam was added to the oxidizer, the temperature decreased to 1249 K. The NO_X emission level was 6.9 ppm without adding steam, dropping to 1.2 ppm with the 40% steam addition. Consequently, it can be observed that adding steam to the oxidizer successfully reduces NO_X emissions without significantly affecting the performance.

Oksitleyiciye Buhar Eklenmesinin Kok Fırını Gazının Yanma Performansı ve Emisyonları Üzerindeki Etkileri: Sayısal Bir Çalışma

Makale Bilgisi

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Öz

Bu çalışma, oksitleyiciye buhar eklenmesinin kok fırını gazının yanma davranışı üzerindeki etkilerini sayısal simülasyonlar yoluyla araştırmaktadır. Analizler, ticari bir hesaplamalı akışkanlar dinamiği (HAD) yazılımı olan Ansys Fluent kullanılarak gerçekleştirilmiştir. Kuru havanın oksitleyici olarak kullanıldığı durumdan elde edilen sonuçlar, deneysel verilerle karşılaştırılmıştır. Türbülans modellemesi için k-Ɛ standart türbülans modeli kullanılırken, üç boyutlu sayısal simülasyonlar için PDF/Karışım Kesri yanma modeli ve P-1 radyasyon modeli uygulanmıştır. Simülasyon sonuçlarına göre, oksitleyiciye buhar eklenmesi, kok fırını gazının (KFG) sıcaklığını hafifçe azaltmıştır. Emisyonlar değerlendirildiğinde, NO_X emisyonlarının önemli ölçüde azaldığı, CO_2 emisyonlarının ise hafif bir düşüş gösterdiği gözlemlenmiştir. Sonuç olarak, bu çalışma, oksitleyiciye buhar eklenmesinin, alternatif bir yakıt olarak kullanılan kok fırını gazına genellikle eşlik eden yüksek NO_X emisyonlarını önemli ölçüde azalttığını göstermektedir. Fırın çıkışında ölçülen baca gazı sıcaklığı 1372 K olarak belirlenmiş ve oksitleyiciye %40 buhar eklendiğinde sıcaklık 1249 K'e düşmüştür. Buhar eklenmeden önce 6.9 ppm olan NO_X emisyon seviyesi, %40 buhar eklenmesiyle 1.2 ppm'e düşmüştür. Dolayısıyla, oksitleyiciye buhar eklenmesinin, performansı önemli ölçüde etkilemeden NO_X emisyonlarını başarıyla azalttığı gözlemlenmiştir.

1. INTRODUCTION (GİRİŞ)

Energy remains one of the most critical topics in contemporary research, as it has been essential for humanity from its existence to the present day. With the advancement of technology and the increasing global population, the energy demand continues to rise. This growing demand has led to an intensified focus on using energy resources, contributing to the rapid depletion of fossil fuel reserves. The estimated depletion times for fossil energy sources such as

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natural gas and oil are projected to be less than a century.

Moreover, the global distribution of these resources has led to various socio-economic and political challenges. However, the situation with coal is slightly different, as coal is more evenly distributed worldwide. Furthermore, coal is expected to remain a viable energy source for at least the next 200 years. This makes coal a more critical energy source in the medium term. Fuels remain the dominant energy source, accounting for more than 85% of global energy consumption due to their high energy content. The heat energy produced by the combustion of fossil fuels is either used directly in specific applications or converted into electrical energy via a cycle for others. However, burning these fuels releases harmful emissions such as CO, CO_2, NO_X, SO_X, and others, negatively impacting both environmental and human health. In particular, coal combustion produces high CO, NO_X, and SO_X emissions. Many countries worldwide have implemented restrictions to reduce these pollutants, prompting researchers to develop cleaner, more efficient fuel production methods and improved combustion systems. One such method is the coking process, which removes impurities from coal and produces coke, a high-carbon fuel [1].

When analyzed in terms of its components, Coke oven gas is considered a high-quality gaseous fuel because combustible components such as hydrogen and methane constitute nearly 80% of its composition. Moreover, synthetic fuels derived from coal gasification contain five primary components (H_2, CH_4, CO, CO_2, and N_2), which are generally consistent across different types of synthetic fuels despite some variations in their content. The literature review conducted for this study encompasses all gaseous fuels, and some relevant works are summarized below [2].

Coke, produced from blends of coke and bituminous coal, is primarily used in iron production in blast furnaces, accounting for approximately 90% of its consumption. Regenerative coke ovens dominate global production and contribute over 90% of total output. Guo and Tang [3] developed a CFD model using the PHOENICS package to simulate fluid flow, combustion, and heat transfer in coke ovens, showing its effectiveness in optimizing thermal processes and operations. Their study identified vital factors such as temperature, moisture content, and coal density influencing production efficiency. Zhao et al. [4] conducted an energy balance analysis emphasizing the role of heat storage and exhaust gas temperature in selective non-catalytic reduction (SNCR) for flue gas desulfurization. They introduced the Total Thermal Storage Temperature (TTST) index to evaluate thermal storage. They validated their model with experimental data, demonstrating that optimized combustion and coke gas preheating could improve production efficiency while reducing exhaust emissions.

A study by Asai et al. [5] utilized a multi-injection burner to control the combustion oscillations of hydrogen-rich fuels and examined their combustion characteristics. The results showed that the convex burner used in the study reduced combustion instabilities while burning these fuels. Lee et al. [6] investigated the combustion characteristics of coal-derived synthetic fuels in an experimental setup. The study focused on reducing NO_X emissions by nitrogen dilution, achieving reductions of up to below five ppm. Another study by Lee et al. [7] explored synthetic fuels' combustion and emission characteristics with different compositions under gas turbine combustion conditions. In a subsequent study [8], they examined the effects of various diluents on emissions using the same gas turbine, concluding that the best results were achieved when steam was used as a diluent. A numerical study by Habib et al. [9] investigated synthetic fuels' combustion and emission characteristics with different compositions in a packaged boiler. The study found that fuels with a higher hydrogen content produced shorter flame lengths. Tian et al. [10] investigated the combustor characteristics of synthetic fuels composed of hydrogen, CO, and carbon dioxide in a non-premixed burner under humid air conditions. Their study revealed that increasing the moisture content of the air resulted in a reduction of NO_X emissions. Li et al. [11] numerically studied the effects of CO_2 and H_2O dilution on combustion and emission characteristics of synthetic fuels under partially premixed combustion conditions. The results, obtained using Large Eddy Simulation (LES) modeling, indicated that CO_2 significantly impacted flame structure more than H_2O.

The main aim of this study is to investigate the temperature, emissions, and performance of a coke oven gas combustion chamber under steam addition, using a swirl to achieve turbulent and non-premixed combustion. The studies above provide insights into various fuel combustion and emission control aspects. However, a gap in the literature is observed regarding investigating the effects of steam dilution on the combustion and emission parameters of coke oven gas. The coke oven gas mixture, whose composition will be presented in the following sections, was numerically investigated under dry air conditions. In their numerical study, the coke oven gas was diluted with an oxidizer containing 10%, 20%, and 30% steam by volume, and the effects of this dilution on the combustion characteristics were investigated numerically, with constant minimum O_2 levels for a thermal power of 8 kW and an equivalence ratio of 0.83.

2. MATERIALS AND METHODS (MATERYAL VE METOD)

2.1. Physical Model (Fiziksel Model)

Figure 1 depicts the structure of the coke oven combustion chamber, which has a total height of 5.1 meters [12]. The flow enters from a bridge passage, with the direction downward. The diagram also indicates the locations of the fuel inlet, air inlet, and gas outlet. The Coke Oven Gas (COG) and air are introduced through separate inlets, where they subsequently mix and undergo combustion within the chamber. This results in a non-premixed combustion process.

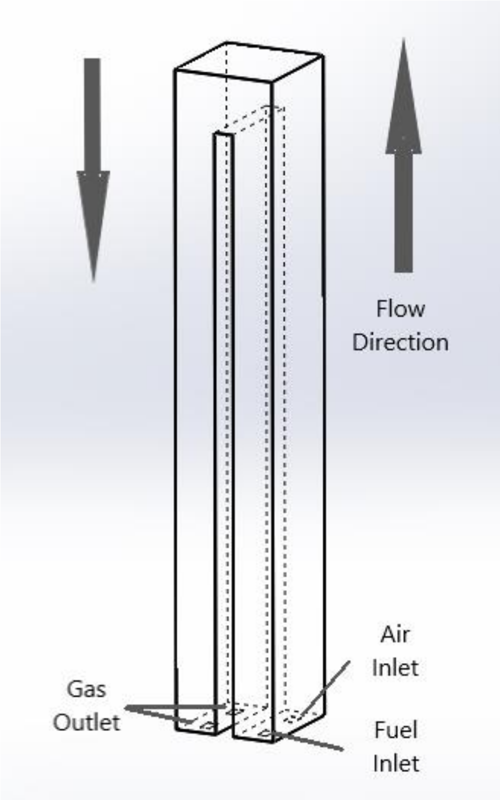

Figure 1. Coke oven combustion chamber (Kok fırını yanma odası)

2.2. Governing Equations (Temel Denklemler)

Mathematical models describing the combustion of gas mixtures are formulated under steady-state assumptions and rely on the three-dimensional forms of the continuity, momentum, energy, and species conservation equations. The general expression of the transport equation is presented as follows [13]:

$$\frac{\partial(\rho\Phi)}{\partial x} + \nabla \cdot \Phi(\rho\Phi \mathrm{u}) = \nabla \cdot \Phi(\Gamma\nabla\Phi) + S_{\Phi} \quad (1)$$

Here, Φ represents the dependent variables. Γ, Φ denotes the transport coefficient for the S_{Φ} represents the source term in the transport equation for Φ.

This study employs the Mixture Fraction / PDF Model as the combustion model. In this model, transport equations for each species are not solved directly. Instead, the concentration of each species is derived from the predicted mixture fraction fields [14].

The PDF model approach has been specifically developed to simulate turbulent diffusion flames. For the fuel/oxidizer system, the mixture fraction f can be expressed as the local fuel mass fraction as follows:

$$f = \frac{m_F}{m_F + m_O} \quad (2)$$

The mixture fraction f is a conserved quantity, and its value at each point in the flow field is calculated from the solution of the conservation equation for the time-averaged value of the turbulent flow field, as given below [13].

$$\frac{\partial(\rho \bar{f})}{\partial t} + \frac{\partial(\rho u_i \bar{f})}{\partial x_i} = \frac{\partial}{\partial t}\left(\frac{\mu_t}{\sigma_t}\frac{\partial \bar{f}}{\partial x_i}\right) + S_m \quad (3)$$

Here, S_m is a source term related solely to mass transfer from liquid fuel droplets to the gas phase. In addition to the solution for the mean mixture fraction, a conservation equation is also solved for the mixture fraction variable. $\overline{f'}^2$ is used in the closure model that defines the turbulence-chemistry interactions.

$$\frac{\partial\left(\rho \overline{f'}^2\right)}{\partial t} + \frac{\partial\left(\rho u_i \overline{f'}^2\right)}{\partial x_i} = \frac{\partial}{\partial t}\left(\frac{\mu_t}{\sigma_t}\frac{\partial \overline{f'}^2}{\partial x_i}\right) + C_g \mu_t \left(\frac{\partial \overline{f'}^2}{\partial x_i}\right)^2 - C_d \rho \frac{\varepsilon}{k} \overline{f'}^2 \quad (4)$$

Heat transfer by radiation occurs at high temperatures. In combustion chambers, the combustion temperature is typically high under stoichiometric combustion conditions, ranging from 1000 to 1600°C. Therefore, incorporating a radiation model in combustion processes allows for more accurate and better-predicted temperature distributions [14]. For instance, the P-1 model requires fewer computational steps to achieve efficient results. Additionally, it can be easily applied to complex geometries involving curvilinear coordinates. For these reasons, the P-1 radiation model has been chosen in this study to improve the accuracy of temperature and emission predictions in the numerical modeling of coke oven gas.

2.3. Boundary Conditions (Sınır Şartları)

The properties of the coke oven gas used in the study are presented in Table 1. The temperature of the coke oven gas has been set to 300 K, while the oxidizer temperature is adjusted to 300 K due to the addition of steam. The pressures of the COG and the oxidizer are assumed to be atmospheric.

3. RESULTS AND DISCUSSION (BULGULAR VE TARTIŞMA)

In computational studies, the flow volume is typically divided into cells. In this study, the flow volume within the combustion chamber has been subdivided into cells. However, to reduce computational time and achieve faster yet accurate results, decoupling the calculations from the number of cells is beneficial. Therefore, simulations with different cell numbers were conducted before the combustion modeling of the coke oven gas. The difference in the calculated emissions (NO_X) concentration between mesh sizes 1124441 and 3235475 was an average of 4.5%. For other parameters, deviations between mesh sizes of 3235475 and 5496942 were less than 3%. A grid system with 3235475 cells was chosen for the simulations to minimize computation time. The grid layout of the computational domain is illustrated in Figure 2.

Table 1. Coke oven gas content (Kok fırın gazı içeriği)

Coke Oven Gas	**Volumetric *(%)***
CH_4	27
H_2	57
N_2	8
CO_2	6
CO	2

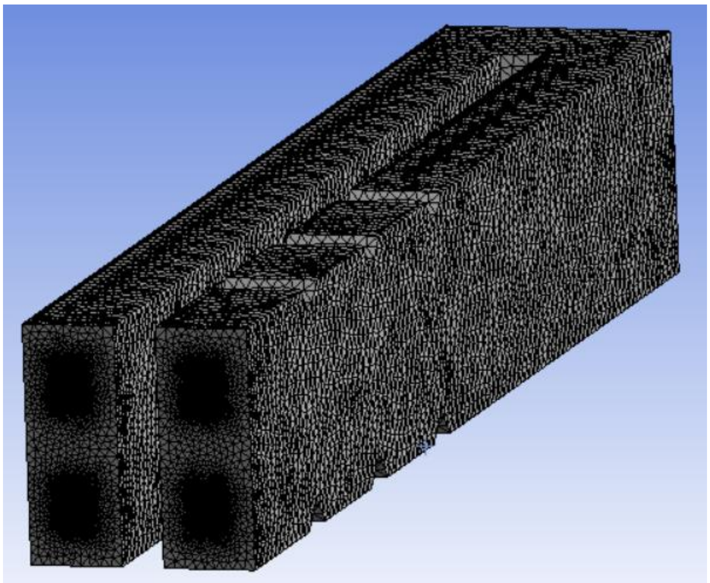

Figure 2. Mesh independence (Mesh bağımsızlığı)

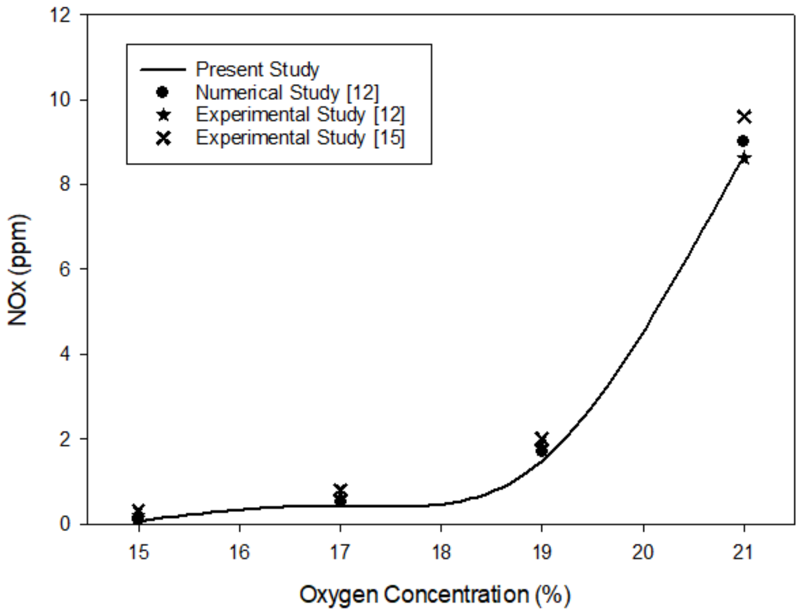

Figure 3. Comparison of measured and predicted gas outlet NO_X distributions [12,15] (Ölçülen ve tahmin edilen gaz çıkışı NO_X dağılımlarının karşılaştırılması)

The numerical model was validated to predict coke oven gas (COG) combustion under different oxidizer ratio conditions. Karyeyen et al. [15] noted that the composition of COG used in this study was similar to that used in their work, consisting of 10% N_2, 10% CO_2, 50% H_2, and 30% CH_4 by volume. The oxygen concentration was adjusted by varying the CO_2 flow rate. The coke oven gas and oxidizer mixture were combusted in a reactor with an internal diameter of 2 ⅜ inches and a height of 7 ⅞ inches. Figure 3 compares the NO_X emissions (ppm) from experimental data [12,15] with the model predictions. The numerical model results are in close agreement with the experimental measurements. The consistency between the simulation results and industrial and experimental data leads to the conclusion that the model is reliable and applicable to the given combustion conditions.

The temperature distribution predictions resulting from the dilution of the combustion air with steam in the coke oven gas combustion process are shown in Figure 4. Initially, it was observed that the highest temperature levels for all combustion conditions were reached in the flame zone. Under dry air conditions, the predicted flame temperature was approximately 1845 K. As the steam content in the oxidizer was increased, the expected flame temperatures decreased to approximately 1820 K, 1805 K, 1780 K, and 1760 K, respectively. Furthermore, for all combustion scenarios, a reduction in temperature was noted as the combustion chamber outlet was approached due to the effects of heat transfer through radiation and convection. Based on the predictions, the temperature at the combustion chamber outlet under dry air conditions was estimated to be around 1372 K. In contrast, the predicted outlet temperatures for the other combustion conditions were 1348 K, 1321 K, 1291 K, and 1249 K, respectively (Table 2). When evaluating the temperature predictions at various measurement points throughout the combustion chamber, it was observed that adding steam to the oxidizer slightly decreased the coke oven gas combustion performance. However, based on these findings, it can be concluded that using water-vapor-enriched oxidizer in coke oven gas combustion does not significantly reduce the combustion performance.

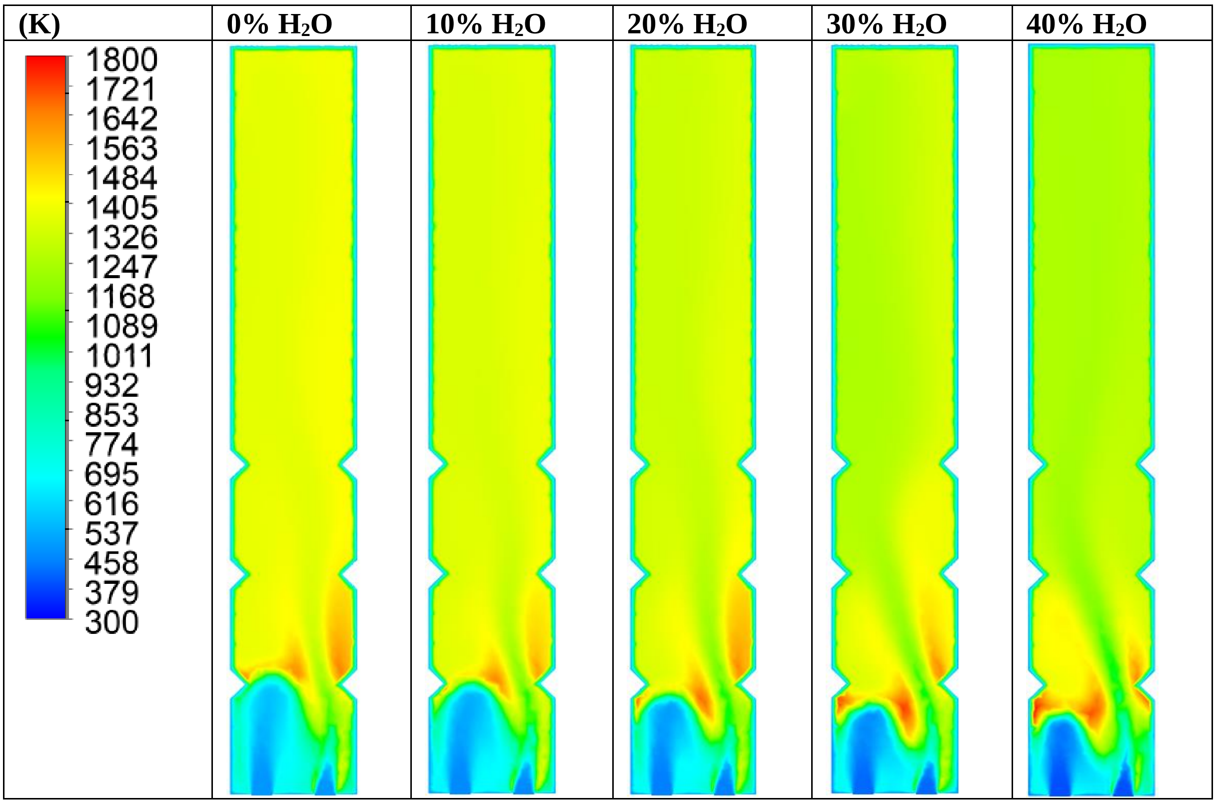

Figure 4. Temperature distribution in the combustion chamber at different H_2O concentrations (Farklı H_2O konsantrasyonlarında yanma odasındaki sıcaklık dağılımı)

Table 2. Temperature and NO_X emissions value at the outlet (Çıkıştaki sıcaklık ve NO_X emisyon değerleri)

	0% H_2O	**10% H_2O**	**20% H_2O**	**30% H_2O**	**40% H_2O**
Temperature Value (K)	1372	1348	1321	1291	1249
NO_X Value (ppm)	6,9	4,6	2,7	1,6	1,2

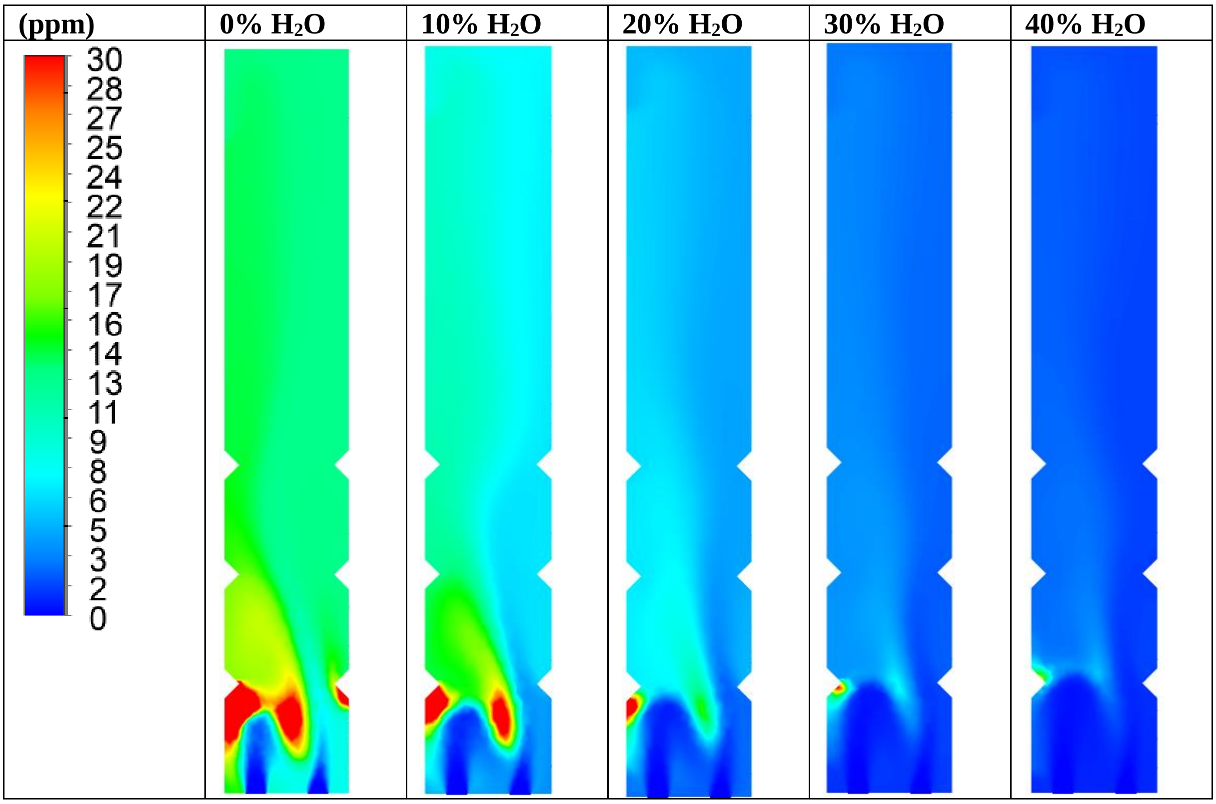

Figure 5. Emission distribution in the combustion chamber at different H_2O concentrations (Farklı H_2O konsantrasyonlarında yanma odasındaki emisyon dağılımı)

This study section examines the effects of diluting the oxidizer with steam on coke oven gas combustion post-combustion emissions. Initially, the radial NO_X distributions predicted using the Fluent program's NO_X-son processor are shown in Figure 5. According to the results, it can be quickly concluded that high NO_X formation occurs during the combustion process with dry air. At the combustion chamber outlet, the predicted NO_X level under dry air conditions was approximately 6.9 ppm. In this case, the contribution of free N_2 in the fuel, which behaves similarly to the N_2 in the air, to the formation of thermal NO_X plays a significant role. It is also evident from Figure 5 that substantial reductions in NO_X levels occur when the oxidizer is diluted with steam. With a 10% dilution, the NO_X level at the combustion chamber outlet drops to below 4.6 ppm, while at 20%, 30%, and 40% dilution, the levels further decrease to approximately 2.7 ppm, 1.6 ppm, and 1.2 ppm, respectively. In conclusion, when evaluated in terms of NO_X emissions, it can be determined that diluting the oxidizer with steam significantly reduces the NO_X emission levels during coke oven gas combustion.

4. CONCLUSIONS (SONUÇLAR)

- In this study, the effect of adding steam to the oxidizer used in coke oven gas combustion on the combustion characteristics of coke oven gas was numerically investigated. A commercial computational fluid dynamics (CFD) program, Ansys Fluent, was used for the numerical simulations. The models were developed in three dimensions, and post-combustion temperature and emission distributions were presented. Based on the predictions made through the simulations, it was concluded that adding steam to the oxidizer resulted in a slight reduction in temperature levels. However, it was also found that diluting the oxidizer with steam significantly reduced the NO_X emissions from the coke oven gas combustion. Considering all the results, it was concluded that coke oven gas could be used as an alternative fuel, and the high NO_X emissions associated with its combustion could be mitigated by adding steam to the oxidizer. The flue gas temperature at the furnace outlet was measured at 1372 K. When 40% steam was added to the oxidizer, the temperature decreased to 1249 K. The NO_X emission level was 6.9 ppm without adding steam, dropping to 1.2 ppm with the 40% steam addition. Consequently, it can be observed that adding steam to the oxidizer successfully reduces NO_X emissions without significantly affecting the performance.

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The author would like to express their gratitude to TÜBİTAK 2218 and Gazi University for using Ansys Fluent software.

DECLARATION OF ETHICAL STANDARDS (ETİK STANDARTLARIN BEYANI)

The author of this article declares that the materials and methods they use in their work do not require ethical committee approval and/or legal-specific permission.

Bu makalenin yazarı çalışmalarında kullandıkları materyal ve yöntemlerin etik kurul izni ve/veya yasal-özel bir izin gerektirmediğini beyan ederler.

AUTHORS' CONTRIBUTIONS (YAZARLARIN KATKILARI)

***Osman KÜMÜK*:** He developed the numerical model, conducted the analysis, and wrote the manuscript.

Sayısal modeli geliştirdi, analizleri yaptı ve makaleyi yazdı.

CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study.

Bu çalışmada herhangi bir çıkar çatışması yoktur.

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