Marmara Fen Bilimleri Dergisi 2018, 3: 218-226
DOI: 10.7240/marufbd.423142

RESEARCH ARTICLE / ARAŞTIRMA MAKALESİ

Farklı Uygulama ve Tasarımların Bir Gaz Yakıcıdakı Emisyonların Düşürülmesine Etkileri

Effects of Different Applications and Designs on Emission Reduction in a Gas Burner

Murat Umut YANGAZ [1], **Gökçen Alev ÇİFTÇİOĞLU** [2], **Mehmet Arif Neşet KADIRGAN** [2]

[1] *Marmara Üniversitesi, Mühendislik Fakültesi Makine Mühendisliği Bölümü, 34722, İstanbul, Türkiye*

[2] *Marmara Üniversitesi, Mühendislik Fakültesi Kimya Mühendisliği Bölümü, 34722, İstanbul, Türkiye*

Öz

Verimsiz enerji kullanımı, kaynakların hızla tükenmesinin ve aynı zamanda tam yanmanın gerçekleşmediğine işaret edebilecek, yüksek orandaki emisyonlara bağlı küresel ısınmanın ana nedenlerinden biridir. Genel olarak, toplu sistemler ya da büyük ölçekli sistemler yukarda belirtilen problemlerin en büyük pay sahibidirler.

Endüstriyel yakıcılar metal şekillendirme sanayisinde ve büyük ölçekli elektrik üretim süreçlerinde yaygın bir şekilde kullanılmaktadır. Bu alanlarda, hem karbon hem de azot bazlı emisyonlar için katı kurallar vardır. Buradan yola çıkarak, bu çalışma, çevresel kirleticilerin minimize edilmesi için oksi-yakıt yanması, yanmış gazların iç devirdaimi ya da ön karışımlama gibi konsept ve tasarımları içeren farklı teknikler kullanarak, yanma verimi ve emisyon düşüşü açısından iyileştirme sağlamayı amaçlamaktadır. Bütün sonuçlar birbiriyle karşılaştırılmış ve birçok parametreyi içeren tablolar ile sıcaklık konturları şeklinde verilmiştir. Bazı konseptlerin diğerlerinden performans ve emisyonlar açısından daha etkin olduğu gösterilmiştir.

Anahtar Kelimeler: Yanma, Hesaplamalı Akışkanlar Dinamiği (HAD), Endüstriyel Yakıcı, Yakıt, Emisyonlar

Abstract

Inefficient energy usage is one of the main reasons of depletion of resources at a faster rate and global warming due to the higher-level emissions, which may be also an indicator of incomplete combustion. Bulk systems or large-scale systems generally are the biggest contributors to the problems stated above.

Industrial burners are widely used in metal forming industry and the process of large-scale production of electricity. There are strict rules for both carbon and nitrogen based emissions in these sectors. Therefore, this study aims to provide an enhancement in combustion efficiency and reduction in emissions using different techniques for minimization of environmentally hazardous pollutants, which includes concepts and designs such as oxy-fuel combustion, internal flue gas recirculation (IFGR) or premixing. All the results has been compared with each other and they have given in the form of tables of various outputs and temperature contours. It has been shown that some of the concepts have greater effect than the other ones in terms of performance and emissions.

Keywords: Combustion, Computational Fluid Dynamics, Industrial Burner, Fuel, Emissions

I. INTRODUCTION

Population of the world is increasing day by day which leads to a raise in the energy demand. Recent projections reveal that energy demand will increase another 30% until 2040 despite the slowing rise in it **[1]**. Considering the excessive usage of the resources, there have to be many precautions and strict rules to ensure the sustainability of the situation. It is an obvious fact that in order to provide the necessary amount of energy, which increases depending on population growth and advancing technology, the systems in use must be efficient.

Sorumlu Yazar/Corresponding Author: Murat Umut Yangaz, **Tel:** 05312268618**, e-posta:** murat.yangaz@marmara.edu.tr
Gönderilme/Submitted: 13.05.2018, **Düzenleme/Revised:** 25.09.2018, **Kabul/Accepted:** 26.09.2018

Energy generation sector mainly depends on the fossil fuels. And the main process is through the combustion of the fuels with an oxidizer (generally air). This process can only be sustainable if it is supported by the technological developments in certain areas related to the combustion industry. Efficiency is the key component where only limited amount of resources are available or where the regeneration of the resources is slower than the consumption **[2]**. Emission is the other topic which has to be considered when the sustainability is taken as an important aspect **[3]**. Hazardous emissions affect the environment in a bad way. All the living creatures need oxygen to stay alive and carry out the vital processes in cellular level. In order to preserve the life forms in the earth, the atmosphere and the water must be protected from the hazardous effects of the emissions emanating from the systems or devices which are the sources of pollution. Bulk systems are generally preferred by the energy production sector due to their comparably higher efficiencies such as gas turbines, industrial burners and large scale burners.

In this study, which is part of a thesis, the emission reduction techniques have been investigated in a certain scale of industrial burners, numerically. The common, well known techniques have been applied to the conventional design and the results have been compared accordingly in this study. The fuel has been chosen as a mixture of 90% methane and 10% hydrogen in molar basis. Aforementioned methods are:

- Oxy-fuel combustion
- Flue gas recirculation
- Premixing

There are many publications on combustion systems involving the efficiencies and emissions. Where some of the studies were carried out using detailed chemical mechanisms, in some others, they used reduced mechanisms or tabulated data depending on statistical calculations.

It is clearly stated in the literature that hydrogen addition enhances the combustion efficiency due to the molecule's fast burning rate and the smaller amount of oxygen for its complete combustion. It is also preferred for its cleaner nature since it is only producing H_2O as the products ideally. Moreover, the products do not contain any carbon-based compounds. On the other hand, hydrogen flame is much hotter than the fossil fuel flames. Lower heating value (LHV) of hydrogen is larger than twice of the LHV of methane. This situation creates a significant effect on thermal NO rates, which leads to higher NO emissions.

Cellek et al. **[4]** experimented on natural gas combustion in a low swirl burner and investigated the effects of different gas compositions which consist hydrogen and natural gas at various ratios using a CFD software. They used 2-step mechanism Eddy-Dissipation Model for the reactions. They observed a significant drop in carbon-based emissions (CO and CO_2) with hydrogen enrichment. On the other hand, NO emissions were higher due to high temperatures which leads Thermal NO mechanism to become dominant in the combustion process.

Due to high NOx output of hydrogen combustion systems, hydrogen is not a preferred energy source in burners. However, Cappelletti et al. **[5]** published a paper on a gas turbine burner using hydrogen as fuel. According to the results, they confirmed the possibility to use hydrogen in such systems. Their solution is a lean premixed combustion with use of a new axial swirler and a co-flow injection. The best result they reached was 17 ppm as the lowest value of NOx emission.

Ilbas et al. **[6]** investigated the non-premixed hydrogen (H_2) and hydrogen–hydrocarbon blends in a low capacity burner numerically. They examined the effects of gas composition from pure hydrogen to methane (pure H_2, 70%H_2+30% CH_4, 10%H_2+90% CH_4, and pure CH_4) and explained that according to the results over-all NO reduction was about 20% with 25% air staging.

Yapıcı et al. **[7]** studied numerical simulation of the combustion of hydrogen with air, investigating the effects of equivalence ratio (ϕ) and oxygen percentage in combustion air (γ) on both combustion characteristics and production of entropy. Results had showed that the increase in ϕ reduced the level of reaction rates significantly. Moreover, the average temperature increased around 23% and 70% with the increase in ϕ (from 0.5 to 1.0) and γ (from 10 to 30%) in the chamber respectively.

Since, flashback is a serious issue when considering combustion of hydrogen, there are many studies and investigations on this topic. Among them, Syred et al. **[8]** published an article about flashback tendency due to the effects of hydrogen involvement in swirl burners. According to their results, the peaks of the flashback curves had the tendency to occur at lower equivalence ratios contrary to the expected just on the rich side of the stoichiometric value.

When hydrogen involved, another problem arises such as the NO_x formation due to higher flame temperatures. Bell et al. **[9]** carried out numerical simulations of a lean premixed hydrogen flame in a low-swirl burner with detailed chemical kinetics which also includes NO_x chemistry. Compared to both laminar flame and simulations at lower

turbulent intensities, they found out a steep increase in NO formation. They also stated that NNH pathway is the dominant for NO production, whereas the Zeldovich mechanism has a significantly smaller role, at around 20% of the total NO output.

As it comes to lean combustion, there are serious issues to take care of, such as extinction of the flame. Riahi et al. **[10]** published an article on the subject, which investigates the effects of the change in fuel richness (from 0.7 to 1.0), hydrogen enrichment in the fuel and oxygen enrichment of the oxidizer on the flame structure and its stability and emissions. Particle Image Velocimetry was used to observe the flame form and the dynamic changes on it as well. They stated that the enrichment in both hydrogen and oxygen have led to a stable flame. Their results also showed that the drop in the fuel richness has caused a decrease in CO and CO_2 as NO_x levels got higher.

In another study, the significance of hydrogen addition was shown in an internal combustion engine. They used diesel fuel with 10% hydrogen in its content. They stated that they achieved 5.3% increase in the peak pressure and 5.7% increase in maximum temperature. Moreover, with this application, they reduced CO, HC and CO_2 emissions. NO_x emissions on the other hand increased by 18.3%. They tried ammonia injections to decrease the NO_x rates. Since thermal NO_x mechanisms are active around 1200 K, the injection timing is critical. Another outcome of their study reveals that the increase in flow rates of ammonia causes a significant amount of excess ammonia discharge at the outlet of the system where NO_x reduction levels reach higher values **[11]**.

II. MATERIAL AND METHOD

2.1. General Information About The Study

In this study, hydrogen combustion has been simulated using the commercial software ANSYS Fluent (version 17.2), which is based on finite volume method. CAD geometry of the original burner, which was the starting point, has been created by making some alterations in a commercial burner-furnace combinations which are already in use of many branches of the industry. Then, the other geometries have been created over the conventional geometry. Meshes have been created using the meshing tool of the same software.

Oxidation of methane with hydrogen addition (combustion of the mixture) in air ideally can be given by below equation:

$$CH_4 + 2.5(O_2 + 3.76N_2) + H_2 \rightarrow CO_2 + 3H_2O + 9.4N_2 \quad (1)$$

Table 1. Properties of methane and hydrogen as fuel **[12]**

Chemical structure	Methane – CH_4	Hydrogen – H_2
Fuel material (feedstocks)	Underground reserves	Methanol, electrolysis of water and natural gas
Lower heating value (LHV) [kj/kg]	47,573	119,987
Higher heating value (HHV) [kj/kg]	52,225	141,916
Physical state	Compressed Gas	Liquid / compressed gas
Autoignition temperature [^oC]	540	565.6 – 582.2

2.2. NO*x* Mechanisms

Thermal NO_x, which is also called as Zeldovich Mechanism, is highly dominant in combustion where the temperatures are high. It is relatively effective over a wide range of equivalence ratios. The mechanism can be given in below chain reactions:

$$O + N_2 \leftrightarrow NO + N \quad (2)$$

$$N + O_2 \leftrightarrow NO + O \quad (3)$$

$$N + OH \leftrightarrow NO + H \quad (4)$$

Thermal mechanism is strongly dependent on temperature due to the large value of activation energy in Eqn. 1. Therefore, it is negligible under 1800 K **[13]**.

Prompt NO_x mechanism on the other hand, is directly relevant to hydrocarbon combustion chemistry. In the first studies of Fenimore **[14]** with laminar premixed flames, he observed that some portion of NO was created around flame core in rapid manner distinctively before the thermal mechanism steps in to create thermal NO. Due to its fast-paced formation, it has been named as prompt NO_x mechanism. The mechanism revolves around the reaction of the radicals of hydrocarbons with nitrogen molecule to create cyano compounds or amines. These cyano compounds and amines form into intermediate compounds, which leads to the formation of NO through series of reactions. After the formation CH radicals which is the initiation step of the mechanism. Prompt mechanism continues with **[13]**:

$$CH + N_2 \leftrightarrow HCN + N \quad (5)$$

$$C + N_2 \leftrightarrow CN + N \quad (6)$$

Here, Eqn. 4 is the rate limiting reaction and primary path in the process. Hydrogen cyanide (HCN) takes part in a chain reaction for the formation of NO following the sequence below:

$$HCN + O \leftrightarrow NCO + H \quad (7)$$

$$NCO + H \leftrightarrow NH + CO \quad (8)$$

$$NH + H \leftrightarrow N + H_2 \quad (9)$$

$$N + OH \leftrightarrow NO + H \quad (10)$$

The chemistry is more complex for the equivalence ratios higher than 1.2, which leads to other pathways and the above sequence is not rapid any longer. Moreover, the studies of Miller et al. **[15]** the thermal mechanism interacts with the Fenimore mechanism and inhibits the NO formation. Figure 1 shows the progress of prompt NO_x mechanism **[16,17]**.

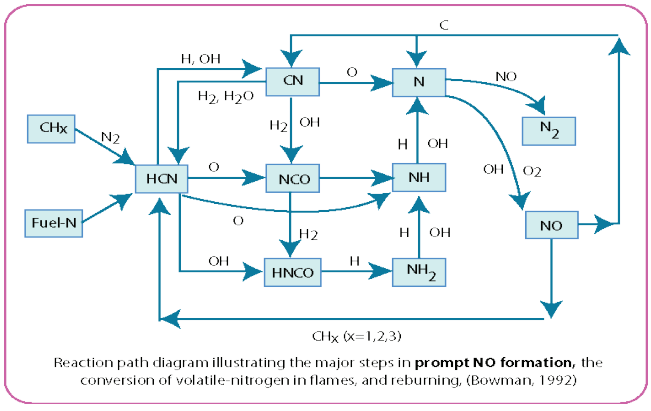

Figure 1. Prompt (Fenimore) Mechanism (NO Production)

N_2O-intermediate mechanism becomes significant in lean-fuel, where equivalence ratios are below 0.8. And it is rather important at low temperature states. The steps of N_2O-intermediate mechanism are given below:

$$O + N_2 + M \leftrightarrow N_2O + M \quad (11)$$

$$H + N_2O \leftrightarrow NO + NH \quad (12)$$

$$O + N_2O \leftrightarrow NO + NO \quad (13)$$

This mechanism is dominant where lean premixed combustion concept is valid. This concept is generally used in gas turbine sector **[18]**.

2.3. Governing Equations

Governing equations that are solved in the simulations are given below **[13,19]**:

- Conservation of Mass:

$$\frac{\partial \rho}{\partial t} + \nabla * (\rho \vec{v}) = 0 \quad (14)$$

Conservation of mass corresponds to the summation of the change in density over time and the net mass flow across the boundaries of the control volume by convection.

- Conservation of Momentum:

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla * (\rho \vec{v}\vec{v}) = -\nabla p + \nabla * (\bar{\bar{\tau}}) + \rho \vec{g} + \vec{F} \quad (15)$$

Conservation of momentum can be identified as the summation of the change of velocity with time and convective term on one side. It is equal to the summation of pressure gradient, diffusion term, body force term and the other source terms on the other side of the equation.

$$\frac{\partial}{\partial t}(\rho e) - \nabla * (\rho e \vec{v}) = \frac{\partial p}{\partial t} + \nabla * (k \nabla T) + S_e + S_{rad} \quad (16)$$

Energy equation represents the summation of local change in the internal energy with time and convection term on the left hand side (LHS) of the equation. They equal to the summation of pressure work, diffusion (heat flux) term and irreversible mechanical energy transfer into heat on the right hand side (RHS).

- Reynolds Stress turbulence model and its transport equation is given below **[20-23]**:

$$\frac{\partial}{\partial t}\left(\rho \overline{u_i' u_j'}\right) + \frac{\partial}{\partial x_k}\left(\rho u_k \overline{u_i' u_j'}\right) = -\frac{\partial}{\partial x_k}\left[\rho u_k \overline{u_i' u_j' u_k'} + \overline{p'\left(\delta_{kj} u_i' + \delta_{ik} u_j'\right)}\right] + \frac{\partial}{\partial x_k}\left[\mu \frac{\partial}{\partial x_k}\left(\overline{u_i' u_j'}\right)\right] -$$
$$\rho\left(\overline{u_i' u_k'}\frac{\partial u_j}{\partial x_k} + \overline{u_j' u_k'}\frac{\partial u_i}{\partial x_k}\right) + \overline{p'\left(\frac{\partial u_i'}{\partial x_j} + \frac{\partial u_j'}{\partial x_i}\right)} - 2\mu \overline{\frac{\partial u_i'}{\partial x_k}\frac{\partial u_j'}{\partial x_k}} - 2\rho\Omega_k\left(\overline{u_j' u_m'}\epsilon_{ikm} + \overline{u_i' u_m'}\epsilon_{jkm}\right) \quad (17)$$

, or in a simplified and more explanatory way:

$$Local\ Time\ Derivate + C_{ij} = D_{T,ij} + D_{L,ij} + P_{ij} + \varphi_{ij} - \epsilon_{ij} + F_{ij} \quad (18)$$

where C_{ij} symbolize the convection term, $D_{T,ij}$ is the turbulent diffusion term, $D_{L,ij}$ equals the molecular diffusion, P_{ij} stands for production of stress, φ_{ij} is the term for pressure strain, ϵ_{ij} is for the dissipation term and F_{ij} stands for production by system rotation. Among the terms above, only $D_{T,ij}$, φ_{ij}, ϵ_{ij} must be modelled for the closure of equation system.

According to preliminary results, Reynolds number at the outlet boundary is around 11230 for the conventional case which makes the flow to remain in turbulent region. And, because of the significant drawbacks of linear eddy viscosity models (i.e. k-ε, k-ω etc.) in modelling flows with high anisotropy, RSM, which is a non-linear eddy viscosity turbulence model has been preferred.

2.4. Burner Geometries And Information About Grid Structures

The geometries in the current study consists of 45-degree slices due to their symmetricity. The conventional design is given in Figure 2. Mid-section, where the flame was assumed to be located, have been separated in order to increase the grid density on that piece. Grid structure mainly consists of hexahedral cells. In some regions where it is not possible to create hexahedral type grids, tetrahedral cells have been utilized.

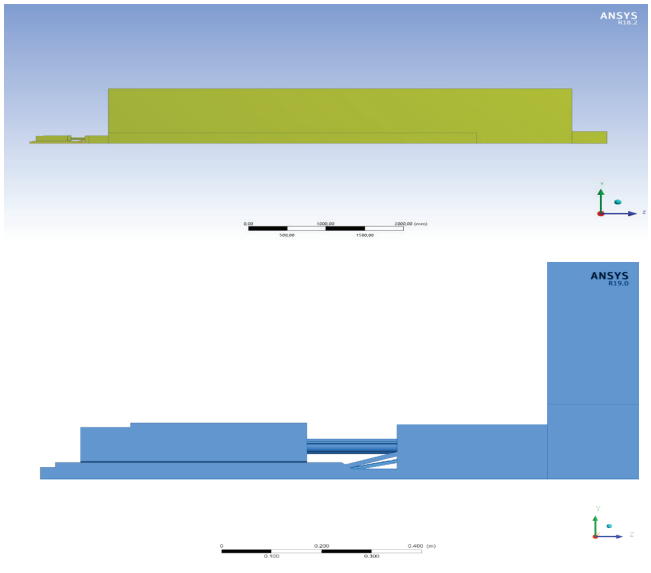

Figure 2. Conventional burner-furnace design

Grid types of all designs are the same. Therefore, only the mesh view of conventional design is given below (Figure 3).

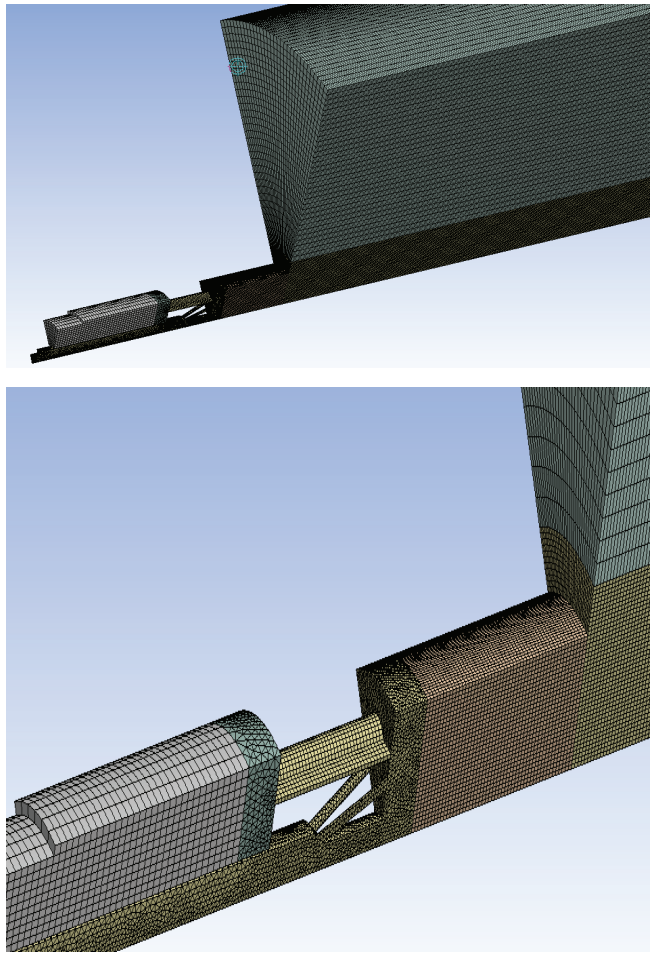

Figure 3. Grid structure of the burner body

In the second design, internal flue gas recirculation (IFGR) concept has been applied onto the existing design (conventional). With this change, the burnt mixture cannot pass directly to the chimney, instead it turns back towards the burner head then it enters the flue gas channel which is connected to the chimney. The motion of flue gases can be seen from Figure 4.

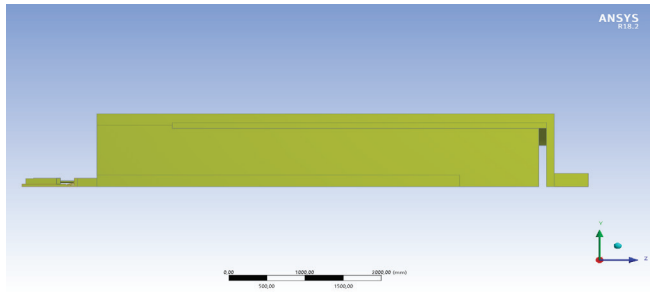

Figure 4. Design with IFGR application

Third design has been made for the investigation of effects of premixing on emissions. In Figure 5, it can be seen that there are relatively small channels which connects the passages of air and fuel.

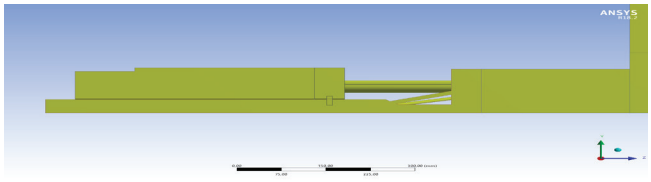

Figure 5. Closed look-up at the partially-premixed design

There is no need for a geometric adjustment for oxy-fuel concept for the observation of reduction in emissions.

Simulations have been carried out using coupled algorithm. Green-Gauss-Node-Based technique has been used for the calculation of gradients. Throughout the whole process, all parameters were solved with second order upwind and central-difference schemes for the discretization except for the radiation equation Simulation parameters and boundary conditions are given in Table 2.

Table 2. Parameters of simulation and boundary conditions

Ambient temperature [K]	300 K
Atmospheric pressure [Pa]	101,325
Flow rate of fuel [kg/s]	0.004802
Fuel inlet temperature [K]	300 K
Flow rate of air [kg/s]	0.077791 for oxy-fuel application, 0.091885 for the remaining cases
Air inlet temperature [K]	300 K
Furnace wall temperature [K]	1273
Furnace walls internal emissivity	0.8
Furnace front wall temperature [K]	1173
Equivalence Ratio	0.909091

Apart from the above information about the simulation parameters, 20% of pure oxygen has been supplied for oxy-fuel application. Therefore, air flow rate drops from 0.091885 to 0.077791 kg/s. The reason is that instead of 100% of air as oxidizer, 20% of pure oxygen and 80% of air have been used in the simulation for oxy-fuel application.

III. RESULTS AND DISCUSSION

At the beginning of the current study, mesh independency simulations for all different geometries have been carried out on five different grid densities. Table 3, Table 4 and Table 5 shows the outcome of the applications or designs.

Table 3. Some Results of the mesh independency simulations (conventional case)

Cell Count	Outlet Temperature	Outlet Velocity	Mass Frac. of NO_x
1160552	1947.3	28.9	2.35e-4
1546874	2015.1	30.1	2.97e-4
1806055	1835.0	27.8	1.44e-4
2180848	1811.9	26.3	1.54e-4
2389806	1808.7	26.0	1.47e-4

Table 4. Some Results of the mesh independency simulations (IFGR application)

Cell Count	Outlet Temperature	Outlet Velocity	Mass Frac. of NO_x
998153	1870.2	32.7	1.26e-4
1254668	1616.9	28.5	9.59e-5
1603544	1339.6	23.9	6.99e-5
1803371	1365.8	24.5	7.01e-5
2255640	1359.1	24.3	7.01e-5

Table 5. Some Results of the mesh independency simulations (Partially-premixed combustion)

Cell Count	Outlet Temperature	Outlet Velocity	Mass Frac. of NO_x
1002916	1803.2	23.8	8.30e-5
1421561	1810.2	24.0	8.30e-5
1761777	1856.3	24.4	8.51e-5
1948595	1866.8	24.5	8.64e-5
2101559	1879.5	24.7	8.66e-5

Mesh independency has been achieved for all the designs/applications as they can be seen from above tables. Since there is no geometric change in the design for oxy-fuel combustion application, there is no need for a mesh independency check for the mentioned case. The fourth grid density has been chosen for the simulations for each application, since the maximum difference between the fourth and the fifth grids in the residuals are below 5% for the evaluated entities given.

Figure 6 shows that a temperature drop in the outlet region due to the cooling effect of flue gas, passing over the flame zone, and also due to its large specific heat capacity (it contains CO_2, H_2O). By this way, average temperature at the outlet boundary, drops almost 450 K, when conventional case is compared to the IFGR application. The other techniques alone does not show a significant difference or improvement in many of the desired and important outputs.

It can easily be seen that temperature levels are a little bit high and it is due to the hydrogen addition. Moreover, it becomes even higher for oxy-fuel case, because of the pure

oxygen that has been added to the oxidizer. This situation is beneficial in some way, and questionable in other ways. The explanation of this phenomena is due to the fuel's heightened ability to mix with oxygen, thus forming a higher temperature flame. Due to the drop in the amount of air and N_2 in the oxidizer. NO_x compounds would occur at a smaller pace via prompt NO_x mechanism in the mixture through the combustion process. On the other hand, the temperature would reach higher values which leads to thermal NO_x mechanism to gain dominance over NO_x emission pathways **[24]**.

Averaged numerical results at the outlet boundary such as average temperature and velocity, CO, HC, H_2 and NO emissions can be found in Table 6 below for each design concept. All the emission values have been given in mass fractions.

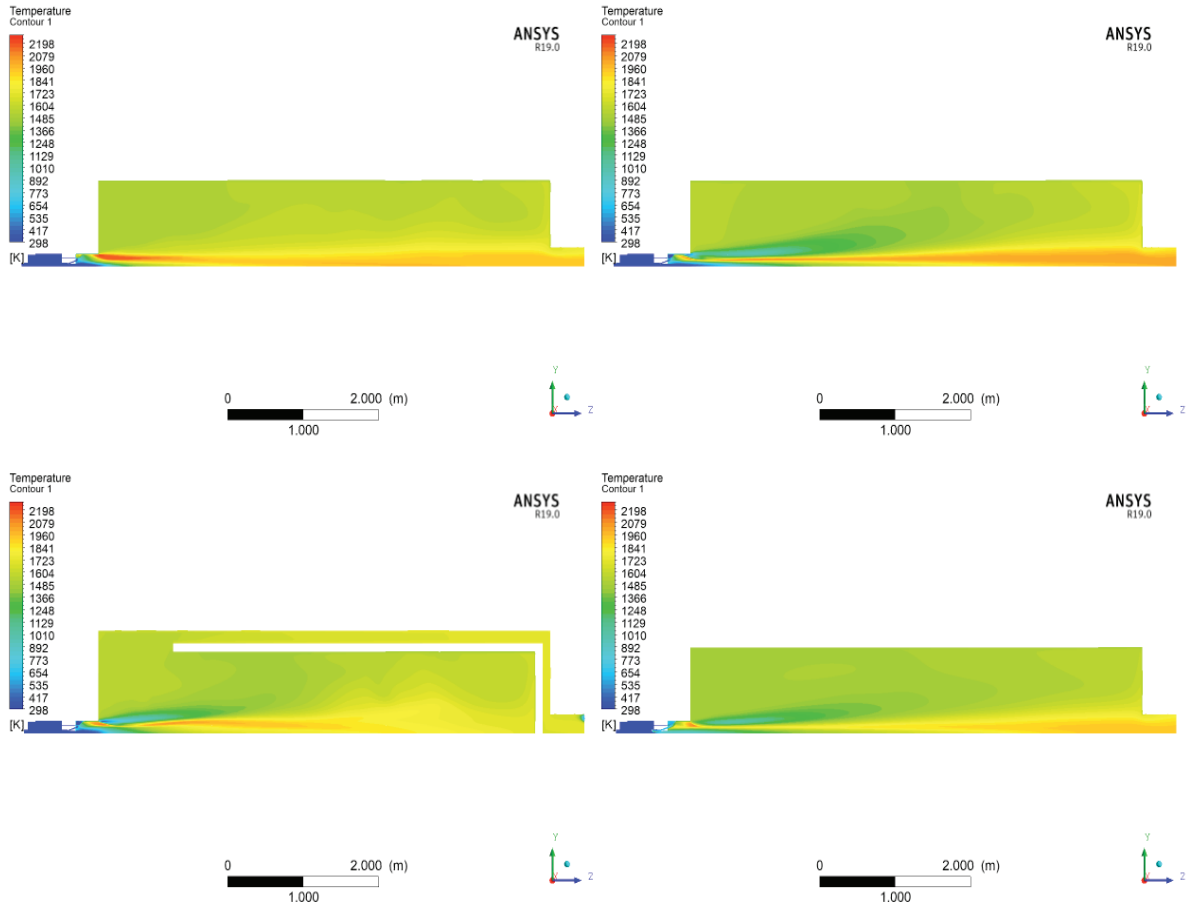

Figure 6. Temperature distribution in the burners; a) Conventional design, b) Oxy-fuel application, c) IFGR app., d) Partially-premixed design,

Table 6. Some important results from the simulations (temperature, velocity and emissions at the outlet zone)

	Conventional design	**Oxy-fuel application**	**IFGR application**	**Partially – premixed design**
Av. outlet temperature [K]	1866.8	1911.6	1365.8	1811.9
Av. velocity at the outlet [m/s]	27.3	23.7	24.5	26.3
Mass fraction of CO emissions from the outlet	0.005377	0.005285	0.001611	0.002111
Mass fraction of HC emissions from the outlet	0.001592	0.001502	0.000237	0.001458
Mass fraction of H_2 emissions from the outlet	0.000235	0.000219	0.000088	0.000108
Mass fraction of NO emissions from the outlet	0.000154	0.000473	0.000070	0.000086

When compared with other simulation results, IFGR application stands out as the best in terms of waste energy. This is due to its lower emissions and the amount of heat that has been lost to the environment. The average temperatures at the outlet shows that oxy-fuel application is the highest followed by conventional design, partially-premixed design and IFGR having the lowest value. This seems reasonable and it is compatible with the publications in the literature **[25]**.

Velocities at the outlet are quite close to each other. This can be explained by the equal amount of gas feed and air supply to the system. Since, all the entries and the exits are identical, the velocities should be very similar regarding the conservation of mass law. Though, the differences can be explained by grid sensitivities since some geometries have different inner domains.

As it can be seen from the Table 6, IFGR application gives the lowest amount of CO emissions creating a 70% of reduction when compared with the conventional burner. When the results of burner with partially-premixed design is analyzed, the CO emission reduction can be seen as 60%. However, these reduction in CO emission levels were not obtained when oxy-fuel design was implemented to a conventional burner. The reduction efficiency is only 17% when compared with conventional one (Table 6).

The same behavior of design effect was seen for the unburnt hydrocarbon emissions. Same as the CO emission reduction, IFGR design again resulted in with more effect. Burner with IFGR has the lowest value in unburnt hydrocarbon emissions. Thus, this design had the highest effect on unburnt HC emission reduction with a rate of 85% when compared with conventional burner. On the other hand, there is no significant difference between the other three cases.

As can be seen in Table 6, when all the above mentioned emissions and H_2 emissions are compared, the same performance in design is obtained. Conventional and the oxy-fuel applications design, which are very close to each other in H_2 emissions, stand out to be the worst in this category. Thus, it can be stated that oxy-fuel applications design needs to be coupled with other designs to improve its effect. Once more the effect of IFGR application became the best concept design among others having 62% of reduction rate in the emissions. When the effect of partially-premixed design is compared for emission reductions of H_2 and unburnt hydrocarbon, the best performance was achieved in reducing H_2 emissions.

NO_x emission values has shown that IFGR is on the top. Then, partially-premixed design had the second highest NO_x emission values. These results were expected. Since, the rise in oxy-fuel application compared to the conventional burner design had found to have higher flame temperatures. When combustion is realized with higher flame temperatures, Zeldovich mechanism **[26]** gets enabled forming a pathway that becomes dominant in NO_x formation.

IV. CONCLUSION

In the current study, numerical simulations have been carried out to investigate the effects of different concepts/applications on emission levels of a certain scale/type burner-furnace design. Equivalence ratio, fuel composition and cross-sectional areas of the outlet, the air and fuel inlet were kept constant. Thus, only concerns about the effects of the changes in operation type such as partial-premixing or oxy-fuel combustion system could be analyzed in detail.

Simulation results have shown that significant amount of improvement can be achieved using mentioned techniques above. The biggest difference in average outlet temperature found to be reaching up to 500 K when conventional and IFGR applications were compared. On the other hand, other concepts have appeared to be less effective on their own in reducing the heat loss from the chimney of the burner.

Burner with flue gas recirculation technique has provided the best possible option in emission discharge when compared with other techniques investigated in this study. However, many more design alternatives, such as combined techniques, can be investigated to create more thermally efficient and less pollutant burner.

With the state-of-the-art technologies on burner and furnace designs and integrating them together in an optimized design, the results obtained in this study can be improved. Thus, a parametric study will be carried out in the future.

V. REFERENCES

[1] International Energy Agency, World Energy Outlook, https://www.iea.org/weo2017/, (May **2018**).

[2] Hatfield-Dodds, S., Schandl, H., Newth, D., Obersteiner, M., Cai, Y., Baynes, T., … Havlik, P. (2017). Assessing global resource use and greenhouse emissions to 2050, with ambitious resource efficiency and climate mitigation policies. Journal of Cleaner Production, 144, 403-414.

[3] Fernando, Y., & Hor, W. L. (2017). Impacts of energy management practices on energy efficiency and carbon emissions reduction: A survey of malaysian manufacturing firms. Resources, Conservation and Recycling, 126, 62-73.

[4] Cellek, M. S., & Pınarbaşı, A. (2018). Investigations on performance and emission characteristics of an industrial low swirl burner while burning natural gas, methane, hydrogen-enriched

natural gas and hydrogen as fuels. International Journal of Hydrogen Energy, 43(2), 1194-1207.

[5] Cappelletti, A., & Martelli, F. (2017). Investigation of a pure hydrogen fueled gas turbine burner. International Journal of Hydrogen Energy, 42(15), 10513-10523.

[6] Ilbas, M., Yilmaz, I., Veziroglu, T. N., & Kaplan, Y. (2005). Hydrogen as burner fuel: Modelling of hydrogen-hydrocarbon composite fuel combustion and NOx formation in a small burner. International Journal of Energy Research, 29(11), 973-990.

[7] Yapici, H., Baştürk, G., Kayataş, N., & Albayrak, B. (2006). Effect of oxygen fraction on local entropy generation in a hydrogen-air burner. Heat and Mass Transfer, 43, 37-53.

[8] Syred, N., Abdulsada, M., Griffiths, A., O'Doherty, T., & Bowen, P. (2012). The effect of hydrogen containing fuel blends upon flashback in swirl burners. Applied Energy, 89(1), 106-110.

[9] Bell, J. B., Day, M. S., & Lijewski, M. J. (2013). Simulation of nitrogen emissions in a premixed hydrogen flame stabilized on a low swirl burner. Proceedings of the Combustion Institute, 34(1), 1173-1182.

[10] Riahi, Z., Bounaouara, H., Hraiech, I., Ali Mergheni, M., Sautet, J.-C., & Ben Nasrallah, S. (2017). Combustion with mixed enrichment of oxygen and hydrogen in lean regime. International Journal of Hydrogen Energy, 42(13), 8870-8880.

[11] Lamas, M. I., & Rodriguez, C. G. (2017). Numerical model to analyze Nox reduction by ammonia injection in diesel-hydrogen engines. International Journal of Hydrogen Energy, 42(41), 26132-26141.

[12] U.S. Department of Energy (DOE), Alternative Fuels Data Center, https://www.afdc.energy.gov/fuels/fuel_properties.php, (May **2018**).

[13] Turns, S. R. (2012). An introduction to combustion : concepts and applications. 3rd Edition, McGraw-Hill, New York, U.S.A., p. 170-174.

[14] Correa, S. M., & Smooke, M. D. (1991). Nox in parametrically varied methane flames. Symposium (International) on Combustion, 23(1), 289-295.

[15] Miller, J. A., & Bowman, C. T. (1989). Mechanism and modeling of nitrogen chemistry in combustion. Progress in Energy and Combustion Science, 15(4), 287-338.

[16] Baukal Jr, C. E. (2013). The John Zink Hamworthy Combustion Handbook, Design and Operations (Vol. 2), 2nd Edition, CRC Press, Florida, U.S.A..

[17] Zevenhoven, R., & Kilpinen, P. (2001). Control of Pollutants in Flue Gases and Fuel Gases. 1st Edition, Espoo: Helsinki University of Technology, Helsinki, Finland.

[18] Bachmaier, F., Eberius, K. H., & Just, T. (1973). The Formation of Nitric Oxide and the Detection of HCN in Premixed Hydrocarbon-Air Flames at 1 Atmosphere. Combustion Science and Technology, 7(2), 77-84.

[19] Kakaç, S., Pramuanjaroenkij, A., & Zhou, X. Y. (2007). A review of numerical modeling of solid oxide fuel cells. Int. J. Hydrogen Energy, 32(7), 761-786.

[20] Craft, T. J., Launder, B. E., & Suga, K. (1996). Development and application of cubic eddy viscosity model of turbulence. International Journal of Heat and Fluid Flow, 17, 108–115.

[21] Hanjalić, K., & Launder, B. (2011). Modelling turbulence in engineering and the environment: second-moment routes to closure. 1st Edition, Cambridge University Press, Cambridge, U.K.

[22] Launder, B., Reece, G., Rodi W. (1975). Progress in the development of a Reynolds-stress turbulence closure. Journal of Fluid Mechanics, 68(3), 537-566.

[23] Rotta J. (1951). Statistische Theorie nichthomogener Turbulenz. Zeitschrift für Physik, 129(6), 547-572.

[24] Scheffknecht, G., Al-Makhadmeh, L., Schnell, U., & Maier, J. (2011). Oxy-fuel coal combustion—A review of the current state-of-the-art. International Journal of Greenhouse Gas Control, 5, 16-35.

[25] Yu, B., Kum, S.-M., Lee, C.-E., & Lee, S. (2013). Study on the combustion characteristics of a premixed combustion system with exhaust gas recirculation. Energy, 61, 345-353.

[26] Flagan, R. C., & Seinfeld, J. H. (2012). Fundamentals of air pollution engineering. 1st Edition, Prentice-Hall Inc., New Jersey, U.S.A.