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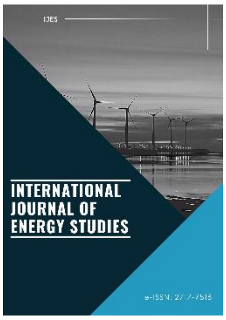

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Reduced oxygen concentration effects on scramjet engine combustion characteristics

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Highlights

- Different oxygen concentrations were studied.
- A hydrogen fueled Scramjet engine model was used.
- Reduced oxygen concentrations affected Scramjet engine characteristics

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ABSTRACT

Air vehicles have began to develop with advancing technology. In order to increase the thrust and reduce pollutant levels at high speeds, researchers focus on different combustion techniques. For this purpose, within the scope of this study, A Scramjet engine combustor has been studied. The effect of reduced oxygen concentration in the air on Scramjet engine combustion was investigated. A hydrogen fueled Scramjet engine is used. In order to seek oxygen concentration effects on combustion characteristics of the Scramjet engine combustor, oxygen concentration in the oxidizer (by mass) was reduced, and the concentration conditions were performed at 23.2%, 21%, 20%, 19%, 18%, 17%, 16%, and 15%. Fort he modelings Reynolds Average Navier-Stokes (RANS) standard turbulence model is preferred for turbulent modeling. A combination of Eddy Dissipation and Finite Rate combustion model was selected to model combustion. The data obtained through the modelings were compared with the experimental data, and the results are in good agreement with the measurements. The results predicted are evaluated, and it was concluded that the velocity increased as the oxygen concentration was increased. It was also predicted that the temperature difference caused by the oxygen concentration decreased with moving away the flame position from the combustor.

Keywords: Scramjet, Hydrogen, Combustion, Reduced oxygen concentration

1. INTRODUCTION

Scramjet engines are high-sound engines. Many different parameters can be examined for the development of this engine, which serves at high speeds. Strut shape can be considered as one of them. Researchers have studied different strut shapes. in this article, wedge-shape, parallel shape and diamond-shape can be given as examples of different strut shapes [1,2,3]. Fuel and combustion are also one of the important parameters. Efforts are also underway to achieve high thrust and to reduce carbon emissions. Hydrogen, on the other hand, can be considered the fuel of the future in terms of emissions and high thrust [4]. In this study, combustion was focused on. A model used in the German Aerospace Center(DLR) was preferred due to its good results in the combustion of hydrogen with a simple model [5,6]. In the model using a wedge-shaped sturt, hydrogen fuel is sent to the combustor at Mach 1 speed. It is assumed that the air entering the combustor with vitiated air is 23.2% for the beginning [7]. After that, analysis was made according to the assumption that the vitiated air with the values of 21%, 20%, 19%, 18%, 17%, 16%, 15% entered the combustor. The model was used because the flow is turbulent. Enhanced wall treatment was also used to observe the wall effects [8]. Adiabatic boundary conditions are considered for the lower wall, upper wall and strut wall [6]. For better observation of turbulent flow fields Probability Density Function (PDF) model was used [9]. Although Direct Numerical Simulation (DNS) method gives good results, it has not become widespread yet due to long analysis time and cost [10]. The Large Eddy Simulation (LES) model is promising for the analysis of high velocity combustion models. It is located between DNS and RANS method. However, just like the DNS method, it is a method that needs improvement in terms of cost and calculations [11]. Studies on hypersonic, subsonic, and transonic flows have been conducted to validate the RANS model [12]. The RANS model may not be sufficient for complex combustion models. It can be used as a hybrid with LES [13]. In this study, the RANS model was preferred because it is simple and common. Two-dimensional Navier-Stokes equations were used as a solution. Włodzimierz BALICKI et al. presented the relationship between density and altitude in their study. It was observed that the air density decreased for four conditions (Cold, Hot, Tropical, ISA) as the altitude increased [14]. If we accept that the oxygen concentration decreases with the decrease in air density, this study will be a source for further research and examining the changes in the outputs that will occur due to the altitude change in a Scramjet engine. Studies in the literature mostly focused on oxygen enrichment. Razzaqi et al. studied the effects of oxygen enrichment for scramjet operation at high altitude and high speed. [15]. Capra, on the other hand, used a porous injection and worked on gradual oxygen enrichment [16]. Augosto et al., on the other hand, investigated the effect of oxygen enrichment at different rates on combustion [17]. These studies were carried out to improve combustion with different amounts of oxygen. In this study, the effects of different oxygen concentrations on combustion and combustion result parameters were investigated. The study without the application of enrichment will provide a different perspective on the combustion effects at different oxygen concentrations.

2. MATERIAL AND METHODS

The model used in the study is shown in Figure-1. The model shown is the German Aerospace Center (DLR) Combustor modeled in two dimensions. Analysis was done using Fluent program. The entrance part of the combustor is 0.05m and its length is 0.3m. The distance between the entrance and the strut is 0.035 m. The distance of the Strut to the lower and upper walls is 0.025 m, the angle between the lower and upper walls is 12°. The part that produces hydrogen fuel is 0.001m.

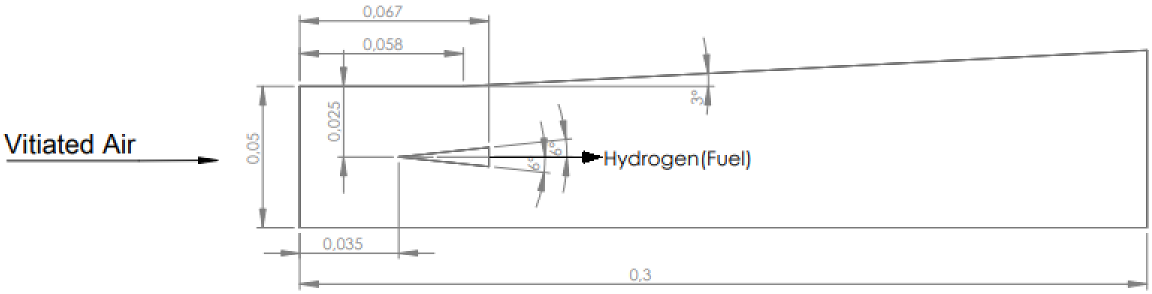


Figure 1. 2D German Aerospace Center (DLR) Combustor

The mesh model used in the research is shown in Figure-2. The model shown has 23437 nodes and 22780 elements. For the mesh method, Multizone Quad/Tri Method was preferred.

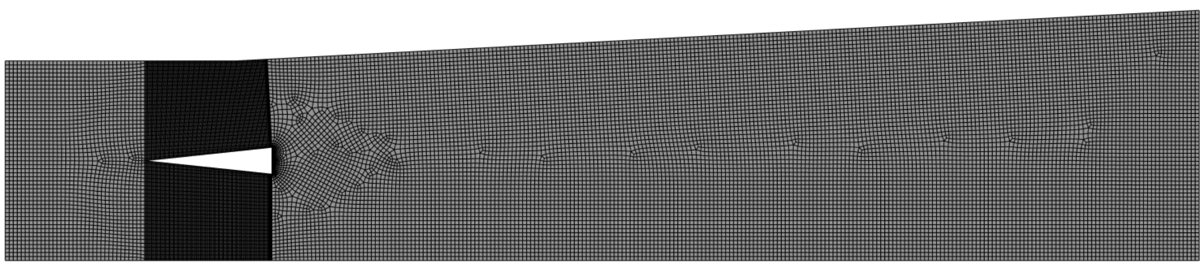


Figure 2. Mesh model

Table 1 gives initial values for 23.2% O_2. During the analysis, the oxygen value and the nitrogen value were variable, except for the given boundary conditions were kept constant.

Table 1. Initial values for 23.2% O_2

Boundary Conditions	Air	Hydrogen
Mach Number	2.0	1.0
Axial velocity(m/s)	730	1200
Static Temperature(K)	340	250
Static Pressure(bar)	1	1
Density(kg/m^3)	1.002	0.097
O_2 Mass Fraction	0.232	0
H_2O Mass Fraction	0.032	0
N_2 Mass Fraction	0.736	0
H_2 Mass Fraction	0	1

3. COMPUTATIONAL METHOD

The working model was modeled in two dimensions. The standard turbulence model was applied to the system. In this model, k is the turbulent kinetic energy, and ε is the turbulent energy dissipation rate.

The equation of the standard model can be written as(k − ε):

Turbulent kinetic energy (k);

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_k}(\rho k u_k) = \frac{\partial}{\partial x_k}\left[\left(\frac{\mu_l}{P_r} + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_k}\right] + S_k \tag{1}$$

Turbulence kinetic energy ratio(ε);

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_k}(\rho u_k \varepsilon) = \frac{\partial}{\partial x_k}\left(\left(\frac{\mu_l}{P_r} + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_k}\right) + S_\varepsilon \tag{2}$$

Enhanced wall treatment mode is used to observe the effects on the walls. Eddy Dissipation and Finite Rate were used together for combustion modelling. The following single-step reversible chemical model was used in the scramjet engine to calculate the reaction rate in the combustor;

$$2H_2 + O_2 \leftrightarrow 2H_2O \tag{3}$$

4. RESULTS AND DISCUSSION

Experimental results in temperature values as a result of the analysis and the results obtained with the CFD program are presented.It is seen that the temperature in the center of the flow has reached the maximum level in all three graphs. It is seen that the temperature decreases with distance from the center. The x=0.0.78 position can be accepted as the first contact point of the shock and the wall. It is seen that the temperature values decrease in this position. In the graphs shown in Figure 3, close graphs have emerged in terms of the characters drawn by the point clusters.

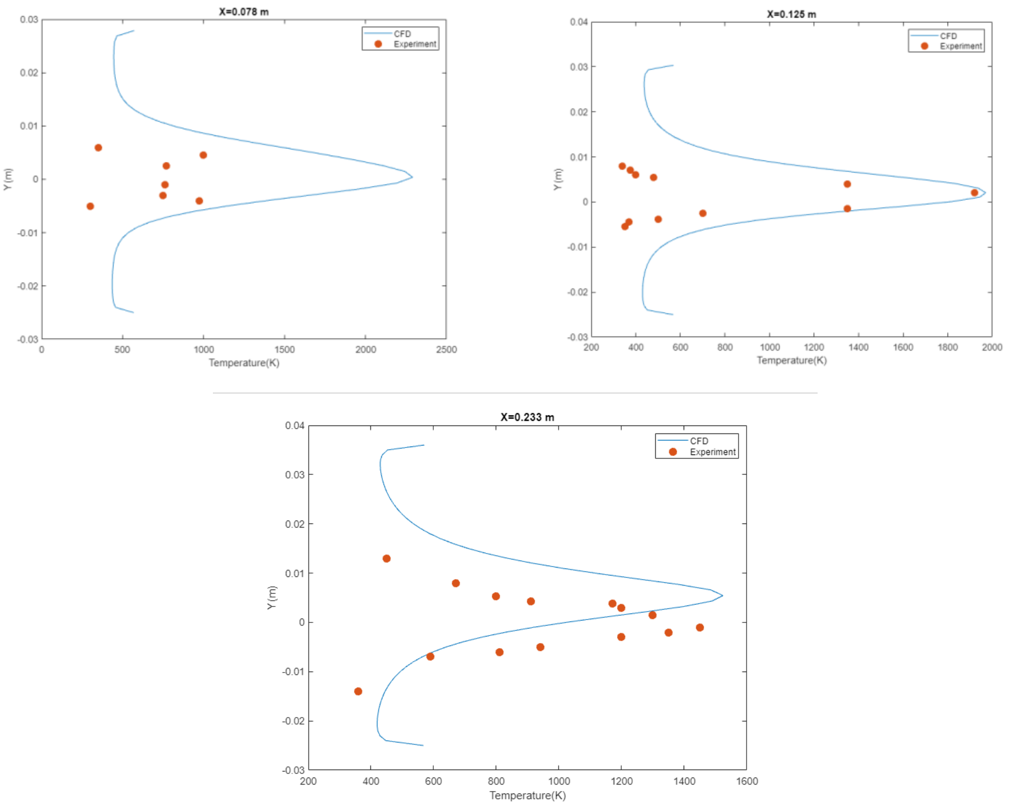


Figure 3. Comparison of experimental and analysis results for x=0.078m, x=0.125m and x=0.233m

It is observed that the experimental data are clustered as they get closer to the combustion zone, and show a wider distribution as they get farther away.

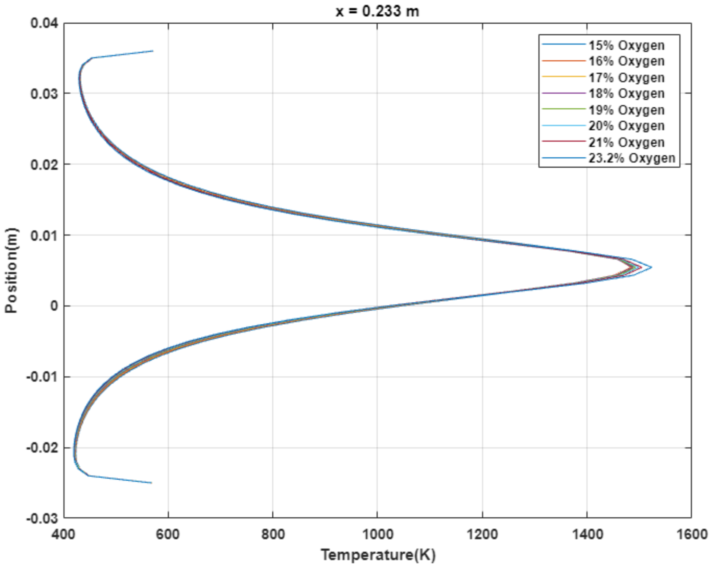


Figure 4. Temperature graphs for x=0.233 m

In the graphs shown in Figures 3,4,5 and 6, position 0 is the starting point of the strut. In Figure 6, it is seen that the temperature values reached their highest values. This graph is very close to the starting point of the combustion. It is seen that the 23.2% oxygen concentration has reached the highest temperature value. Looking at Figure 4, it is seen that the difference between the oxygen concentrations for the x=0.233 point has decreased.

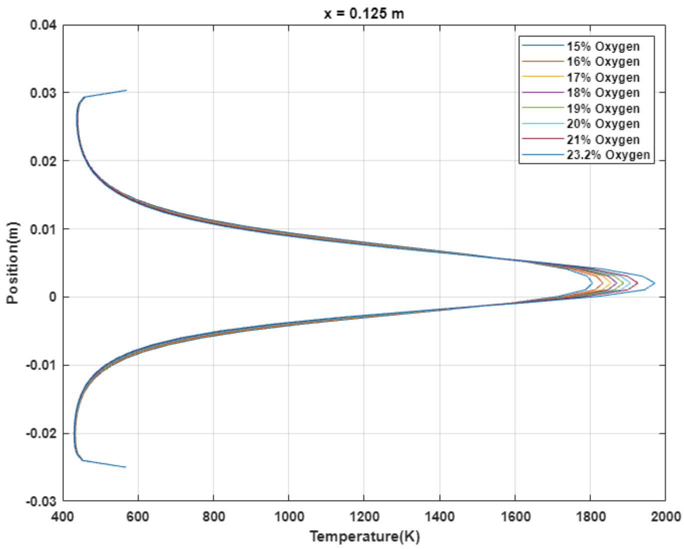


Figure 5. Temperature graphs for x=0.125 m

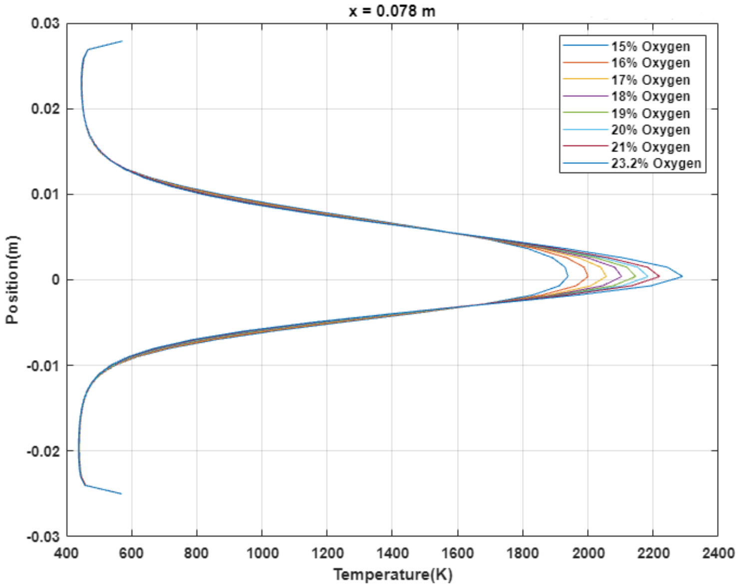


Figure 6. Temperature graphs for x=0.078 m

In the contours obtained as a result of the analysis, shock effects are clearly observed around the strut. Table-2,3,4 shows the contours obtained as a result of the analysis for density, pressure and velocity. The maximum value for Density is 2.8355773 kg/m^3 and the minimum value is 0.1725655 kg/m^3. The maximum value for Velocity is 888.6466 m/s and the minimum value is 0 m/s. The maximum value for pressure is 341335.9 Pa and the minimum value is -17212.71 Pa. Density contours are shown with Table 2. It is seen that the density is at low levels along the part where the hydrogen comes out during combustion. Speed contours are shown with Table 3. It is seen that the speed is at high levels in the same locations. As the density decreased, the speed increased. On the other hand, an increase in density was observed in the lower and upper parts of the hydrogen source. A decrease in velocity magnitude is observed in the same regions in the velocity contours. Shock is observed at the beginning of the strut for all three contours. Pressure contours are shown in Table 4. It was observed that the pressure increased in the regions where the density in the contours in Table 2 increased. In Table 3, it is observed that the velocity contours decrease near the wall. Friction is also effective in the fall. It is observed that the fluid slows down considerably as it enters the region where the reaction takes place.

Table 2. Density contours for different oxygen concentrations

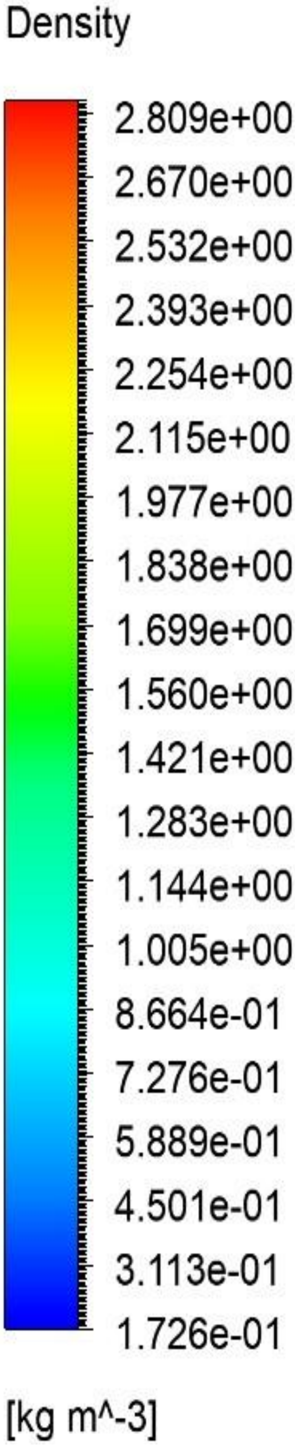
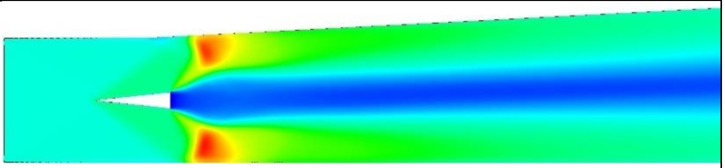
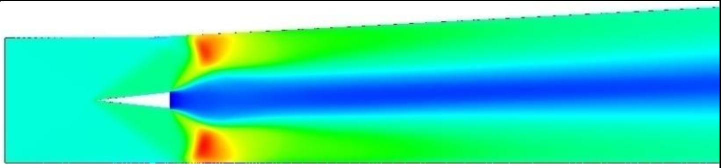
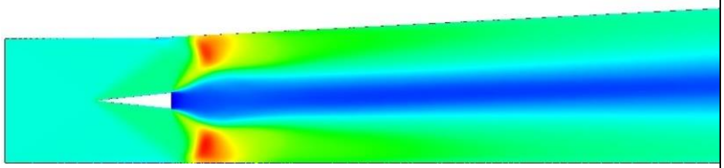
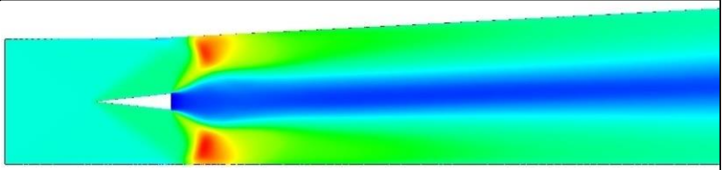
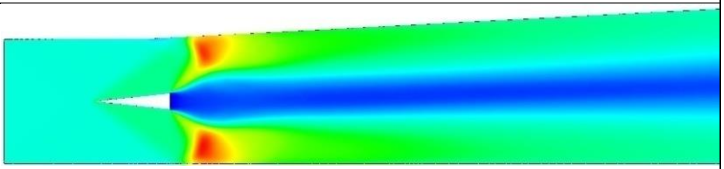
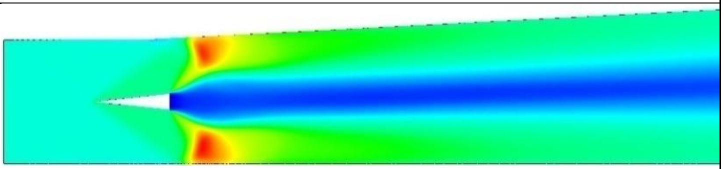
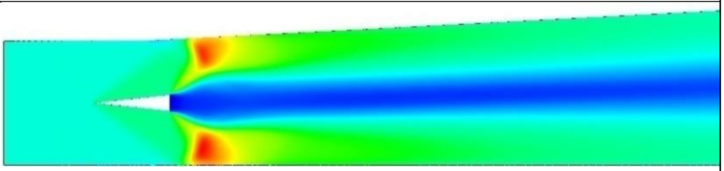
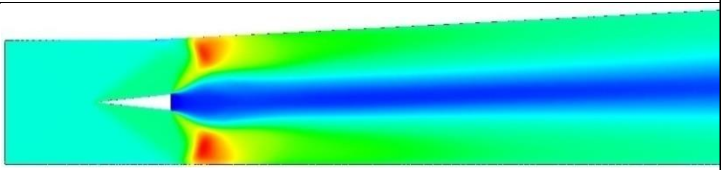
Density Scale	Oxygen Concentration	Density Contour
	%15 O_2	
	%16 O_2	
	%17 O_2	
	%18 O_2	
	%19 O_2	
	%20 O_2	
	%21 O_2	
	%23.2 O_2	

Table 3. Velocity contours for different oxygen concentrations

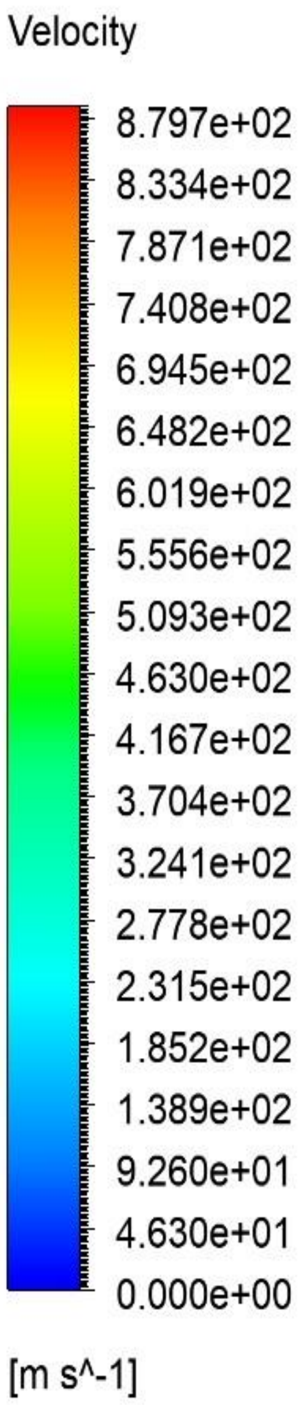
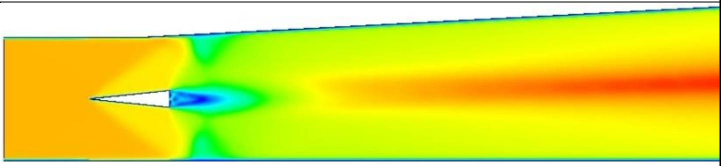
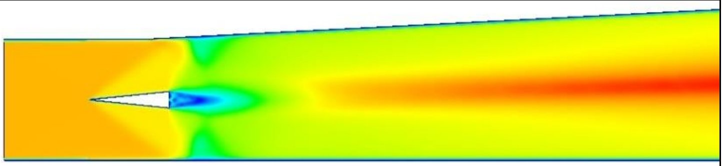
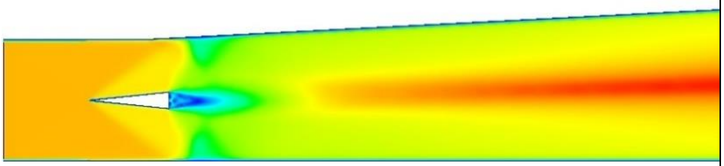
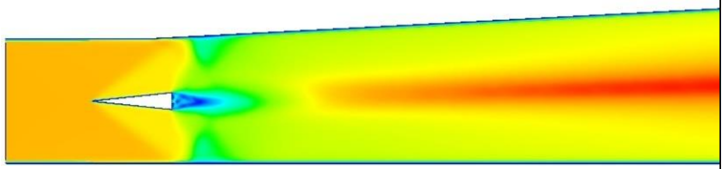
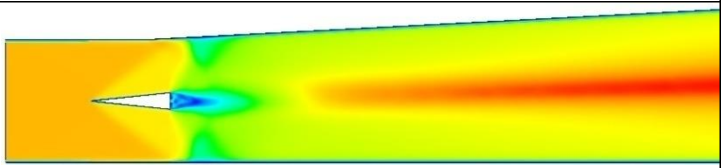
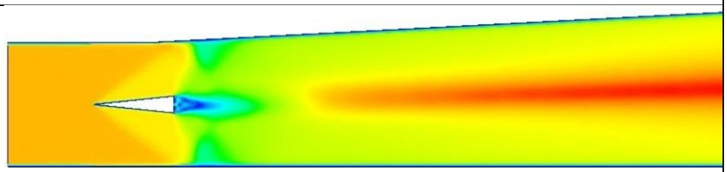
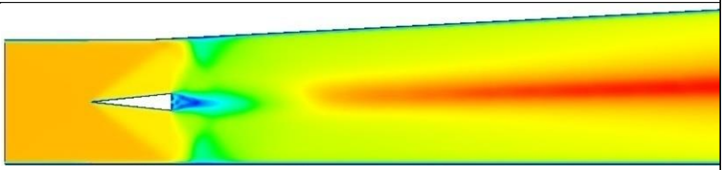
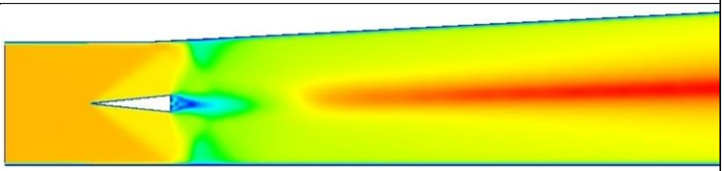
Velocity Scale	Oxygen Concentration	Velocity Contour
	%15 O_2	
	%16 O_2	
	%17 O_2	
	%18 O_2	
	%19 O_2	
	%20 O_2	
	%21 O_2	
	%23.2 O_2	

Table 4. Pressure contours for different oxygen concentrations

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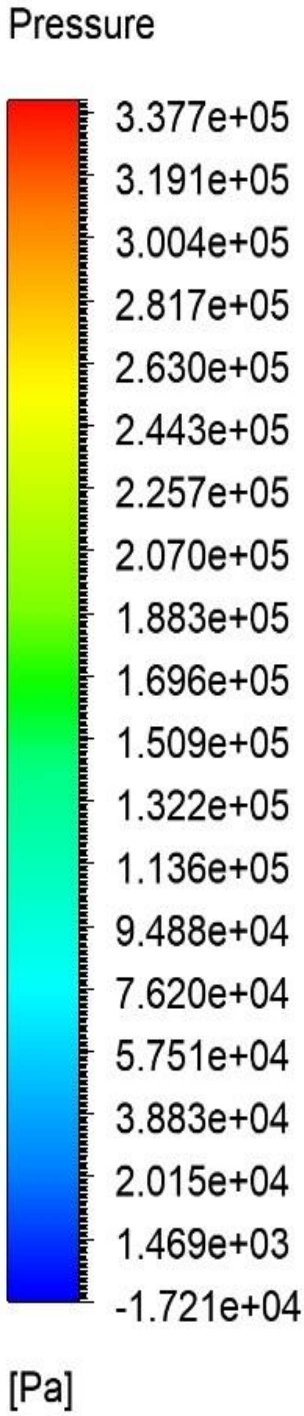
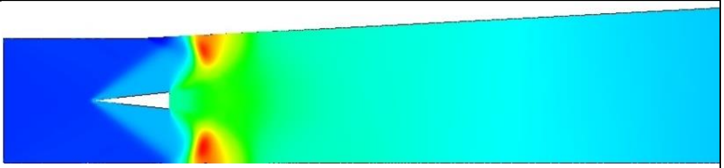
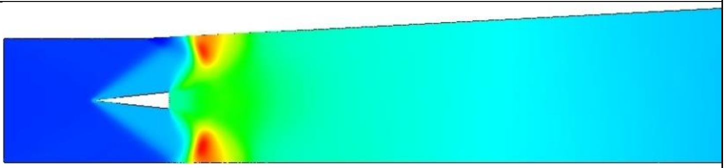
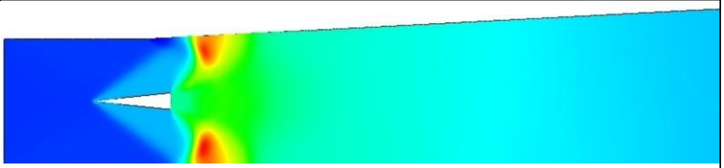
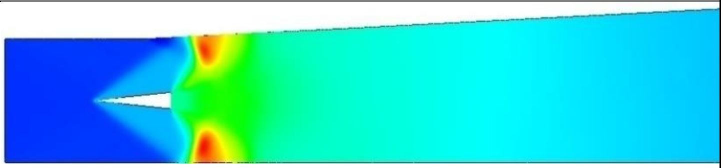
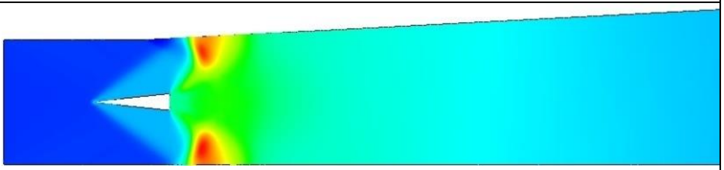
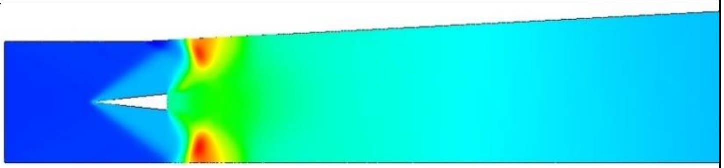
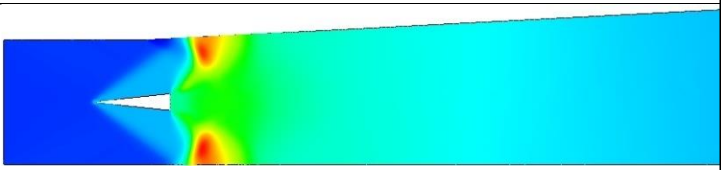
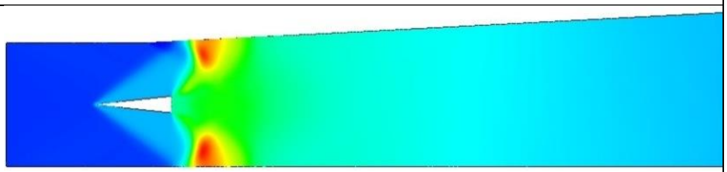
<tr><td rowspan="8">
</td><td>%15 O_2</td><td></td></tr>
<tr><td>%16 O_2</td><td></td></tr>
<tr><td>%17 O_2</td><td></td></tr>
<tr><td>%18 O_2</td><td></td></tr>
<tr><td>%19 O_2</td><td></td></tr>
<tr><td>%20 O_2</td><td></td></tr>
<tr><td>%21 O_2</td><td></td></tr>
<tr><td>%23.2 O_2</td><td></td></tr>
</table>

5. CONCLUSION

23.2%, 21%, 20%, 19%, 18%, 17%, 16% and 15% oxygen concentrations were analyzed. Numerical differences are obtained. As a result of these analyzes and studies, the following results emerged;

- It was observed that as the oxygen density increased, the density data obtained as a result of the analysis also increased. This increase does not occur at very high levels. As a result of combustion with 15% oxygen, the maximum density is 2.81498 kg/m^3, while for 23.2% oxygen it is 2.835773 kg/m^3. It was concluded that the increase in the oxygen ratio affected the density increase positively.
- As the oxygen density decreases, the combustion quality also decreases. As can be seen in Figure 3, Figure 4 and Figure 5 and the graphics, it is observed that as the oxygen ratio in the air decreases, the temperature formed as a result of combustion in the same position decreases.
- It is visually evident that the velocity around the hydrogen injection increases from 15% to 23.2% oxygen level. Numerically, the maximum value for Velocity Magnitude for 15% oxygen rate was 866.0826 m/s, and 888.6466 m/s for 23.2% oxygen level. An increase of approximately 22.5 m/s was observed.
- In Figure 4, it is seen that the difference between the temperature values due to the oxygen values for the x=0.233 m point decreases. With this data, it is seen that the difference due to the percentage of oxygen loses its effect as you move away from the combustion zone.

DECLARATION OF ETHICAL STANDARDS

The authors of the paper submitted declare that nothing which is necessary for achieving the paper requires ethical committee and/or legal-special permissions.

CONTRIBUTION OF THE AUTHORS

Afşin Kılıçarslan Özbek: Performed the experiments and analyse the results.

Serhat Karyeyen: Wrote the manuscript.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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