THREE DIMENSIONAL NUMERICAL INVESTIGATION OF FLOW AND COMBUSTION CHARACTERISTICS IN AN AMMONIA FUELED MULTI-INLET CYCLONE COMBUSTOR

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Abstract

The cyclone combustors generally operate with high swirl numbers (3-20). The multi-inlet cyclone combustor that has been simulated in this study has 14 gas/air tangential inlets each of 9.525 mm ID and are inclined towards the front end of the combustion chamber by 30^0 in 2 symmetrical rows of seven. In this study, numerical modelling of a multi inlet cyclone combustor fueled by ammonia has been performed by using a CFD code. Boundary conditions are taken from the literature. The choice of the turbulent model is very important for complex highly swirling flows such as those generated by swirl combustors. In the multi-inlet cyclone combustor, very long residence times have been achieved. Two main flows are noticed in the combustion chamber, one spiralling towards the exit, the other towards the base plate where the boundary flow carries it into the central ascending flow. It is concluded that ammonia and ammonia added methane can be used as emerging fuels in the combustor by obtaining uniform temperature fields and low emissions.

Keywords: The Multi-Inlet Cyclone Combustor, CFD Modelling, Ammonia Combustion

1 INTRODUCTION

Energy plays an extremely important role in ensuring the sustainable and safe development of society. The sufficiency and reliability of providing electricity and heat to the growing needs of the economy and the population are of decisive importance. Traditional energy provides about half of the world's technogenic emissions of greenhouse gases and harmful substances into the environment [1].

Combustion is present continuously in our lives. It is a major source of energy conversion for power generation, transportation, manufacturing, indoor heating and air conditioning, cooking, etc. Its uncontrolled use may have damaging health effects through contamination of air and water [2].

However, achieving emission reduction targets requires the use of alternative, low-carbohydrate or non-carbon fuels in power generation and industrial sectors using combustion systems.

The urgency of the problem of searching for new energy carriers is determined primarily by the need for strict economy of oil products and, secondly, by the need to significantly reduce the toxicity of exhaust gases.

Among the many synthetic substances, only some alcohols, hydrogen and ammonia meet these requirements. According to the majority of world scientists, hydrogen should become the main alternative to hydrocarbon fuel, and the development of hydrogen technologies is considered the most promising.

Hydrogen is seen as the fuel of the future, allowing to solve energy and environmental problems. It has great advantages over fossil fuels. Its heat of combustion is almost three times higher than that of gasoline, and the energy required for ignition is 1.5 times less [3]. When hydrogen is burned in pure oxygen, the combustion products are absolutely harmless - water vapor; when burned in air, nitrogen oxides can be formed, but in smaller quantities than when burning conventional fuels. Hydrogen resources in nature are practically inexhaustible if water is used as a source. When hydrogen is burned, water is formed, which is again involved in the natural cycle.

At the same time, the use of ammonia as a secondary carrier of hydrogen converted into a non-cryogenic safe form is of great practical interest. The prospect of using ammonia as a fuel is due to a number of its positive properties. Ammonia has a higher energy density in terms of hydrogen content than gaseous, liquid hydrogen and metal hydrides, but has a lower calorific value compared to gasoline. Ammonia

is promising as a fuel due to its relatively low cost and virtually unlimited resource base. With the complete combustion of ammonia, only one harmful component is formed - NO_X, and its content is negligible [4].

In this research study, a multi-inlet cyclone combustor is modeled to burn these fuels. Some of the previous studies on this subject have been examined in the literature.

Tunçer investigated the laminar flame velocities of hydrogen-rich methane fuel with chemical kinetic simulations based on the GRI 3.0 mechanism. It was determined that hydrogen enrichment increased the flame as expected. The effect of hydrogen ratio and pressure on flame velocities and emissions was investigated. He found that increasing pressure reduces flame velocities, but in turn increases emissions. Emissions and flame rates increase with increasing hydrogen content. He focused on one- and zero-dimensional simulations. The focus in zero-dimensional simulations is the effect of equivalence coefficient fluctuations resulting from thermo-acoustic instability on lean flame extinction and emissions. In this study, it was observed that hydrogen-rich mixtures were more resistant to equivalence ratio fluctuations [5].

Yılmaz and İlbaş presented temperature distributions from turbulent chemical reactive flow in a model burner for hydrogen-methane fuel mixtures. Gas emissions were also obtained at the combustion chamber exit. Axial and radial temperature measurements were taken from six different distances and four distances, respectively. Experimental measurements were made at extreme air ratios of 1.2 and 1.7, two different thermal powers, 40 and 60 kW, and two different hydrogen-methane fuels. According to the results, it was determined that when the hydrogen content in the fuels is increased, the temperature level increases and the CO and CO_2 emissions decrease [6].

Medhat, Yehia, Khalil et al. have computationally evaluated its performance when a carbonless ammonia-hydrogen mixture is burned in a gas turbine-like combustor. The use of ammonia/hydrogen mixture provides increased flame stability and flame speed. Numerical two-dimensional model simulations of a turbulent flame containing a k-ε turbulence scheme that can be realized with the aid of a chemical mechanism on Reynolds Averaged Navier Stokes (RANS) were performed under various conditions. They chose a partially premixed combustion model with a flame release concept and took into account radiation effects. When the results were evaluated, they found that for constant operating conditions, such as a constant equivalence ratio of 0.8, increased hydrogen content resulted in increased NO emissions. Also, for constant ammonia/hydrogen concentrations, NO emissions increase with the equivalence ratio, then decrease under rich conditions, and NH_3 emissions are generally low. An equivalence ratio of less than 1.2 will be preferred to reduce the amount of unburned NH_3 formation [7].

Ayman M. Elbaz et al. in their article, they emphasize the importance of ammonia as an energy carrier and offer the basics of ammonia combustion. Measures to address the problem of low ammonia reactivity and its impact on NOx emissions are also presented. In this research work emphasizes the role of crucial reaction differences, the updates in the NO_x and De-NO_x pathways, NH_i recombination reactions and H_2NO chemistry. Various strategies have also been discussed to reduce NO emissions from the use of ammonia in gas turbines and industrial applications [8].

Kobayashi et al. In their paper, they discuss the successful use of ammonia as a fuel in gas turbines and in industrial furnaces. It also discusses the fundamental aspects of ammonia combustion, including characteristics of laminar premixed flames of a premixed. In addition, details are given on the combustion of ammonia to form NOx, NOx reduction processes, and testing of several models of ammonia oxidation kinetics.

Eventually, LES results for a gas turbine swirl burner are presented for the development of single-fuel ammonia gas turbines with low NOx emissions [9].

2 THE COMBUSTOR AND NUMERICAL METHOD

Cyclone combustors have been developed that give very good results with very low NO_x emissions. These combustors are mainly used to burn low calorific value fuels and previous studies have shown that such combustors provide efficient combustion systems for low calorific value gases. The multi-inlet cyclone combustor that has been simulated in this study is shown in Figure 1. It has 14 gas/air tangential inlets each of 9.525 mm ID and are inclined

towards the front end of the combustion chamber by 30^0 in 2 symmetrical rows of seven. The features of the multi-inlet cyclone combustor are as follows;

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

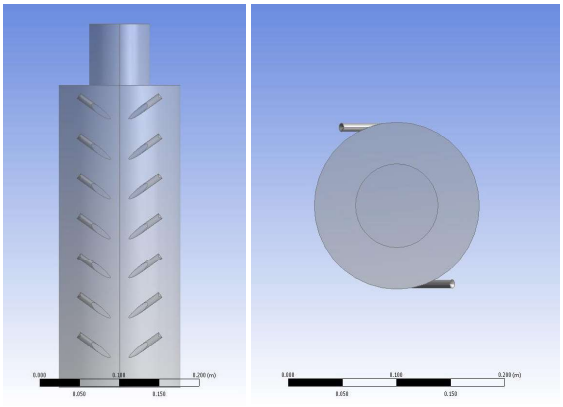


Figure 1. Multi-Inlet Cyclone Combustor

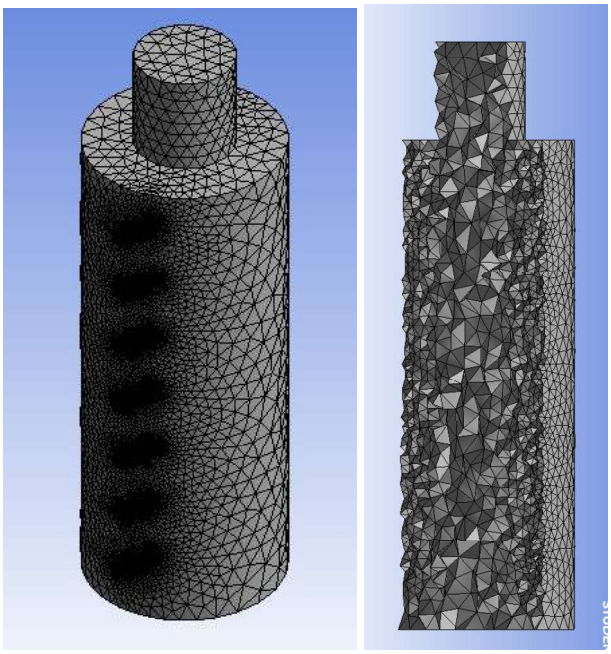


Figure 2. Mesh for the Multi-Inlet Cyclone Combustor

The cyclone combustor has been designed to be fully premixed and normally unlined. To provide a fully premixed combustor a copper tube of 20 mm ID with numerous entry holes was soldered into the main air supply tube. This design, due to the location of the main gas supply tube, which is far enough from the tangential inlets, gives good premixing of fuel and air, thus a more uniform combustion took place inside the cyclone combustor and the flame fully occupied the combustor body [10]. The mesh structure of the combustor is given in Figure 2.

3 RESULTS AND CONCLUSIONS

In this study, numerical analyzes of methane-air and ammonia-air mixtures were made using the ANSYS Fluent CFD code. Inlet velocities were calculated from the known volumetric flowrate according to mixture ratio. The boundary conditions were defined in terms of temperature and constant both for inlets and walls. The gas law was used to calculate the fluid density. The other physical constants of fluid were taken from the literature which are specific heat, thermal conductivity and viscosity. The computational default value was used for the operating pressure. Turbulence intensity was taken as to be default value of 10 %, Characteristic length scale was of 9.525e - 03m. Next the chemical species mass fractions at the inlet were defined by input of mass fractions of the Methane (CH_4), Ammonium (NH_3), Oxygen (O_2) and Nitrogen (N_2) according to mixture ratio. Inlet temperature of fluid was taken as to be 300 K in all cases. The turbulence model k - ε was used. The number of iterations was 2500. The results of modeling the combustion of a mixture of methane-air are shown in Figures 3 to 8.

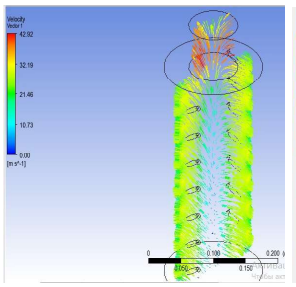


Figure 3. Velocity Distributions

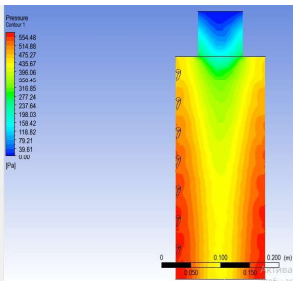


Figure 4. Pressure Distributions

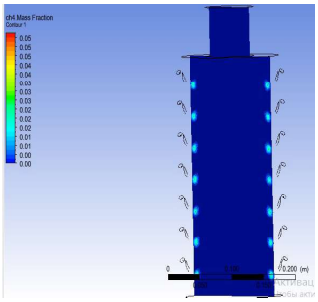


Figure 5. CH_4 Mass Fractions

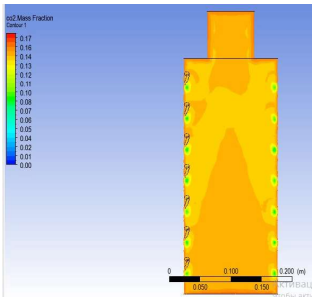


Figure 6. CO_2 Mass Fractions

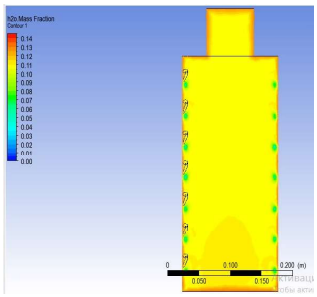


Figure 7. H_2O Mass Fractions

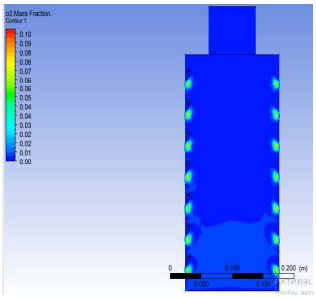


Figure 8. O_2 Mass Fractions

Figures 9-17 show the results of modeling the combustion of an ammonia-air mixture.

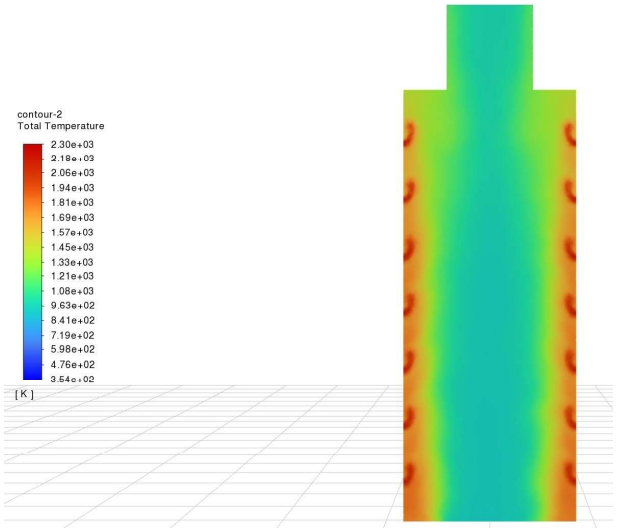


Figure 9. Temperature Distributions (K)

Figure 9 shows the temperature distribution when simulating the combustion of an ammonia-air mixture in a combustor.

The maximum temperature level was about 2300 K.

Uniform temperature distributions throughout the combustor length with the flame front being located next to the chamber wall. This can be explained by the location of the tangential inlets along the chamber and flame stabilization near the wall. Temperature levels are reduced (963 K) in the central core vortex region. This is because of the recirculation of slightly cooler burnt products from the exhaust zone.

The predicted turbulence distributions for isothermal conditions with the extended grid is given in Figure 12. At the inlet boundary, the inlet turbulence intensity was set at 10 % (default value of Fluent). Maximum value of turbulence is about 16 m^2/s^2 at the bottom wall inside the combustor main chamber and 28 m^2/ s^2 just outside the combustor exhaust.

Figures 5-8, 14-17 show the mass fractions of CH_4, NH_3, O_2, CO_2, H_2O and N_2.

The predictions show that methane and ammonia are consumed in the region very close to inlets. Furthermore methane and ammonia are consumed as soon as they enter the combustion chamber. The distributions of O_2, mass fractions (Figures 8, 15) and CH_4/NH_3 mass fractions were similar in shape. This was likely because of the premixing of the methane/ammonia and oxygen.

Figure 6 presents distributions of the predicted CO_2 mass fractions. The maximum predicted CO_2 level was 15 % which was produced from the conversion of CO to CO_2 in the second reaction. Distributions of the predicted H_2O mass fractions are given in Figures 7, 16. The maximum H_2O level was about 11 % and 20.7 % for these conditions and for N_2 (figure 17) about 10%.

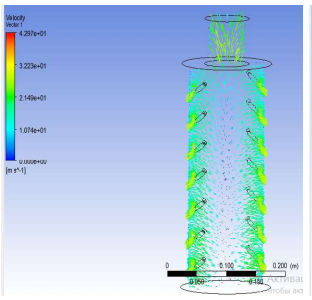


Figure 10. Velocity Distributions

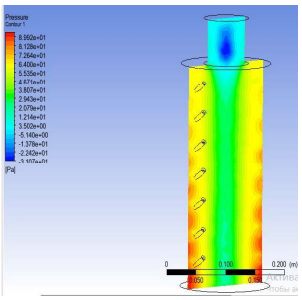


Figure 11. Pressure Distributions

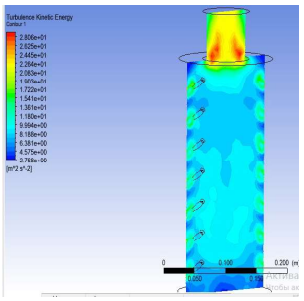


Figure 12. Turbulence Kinetic Energy

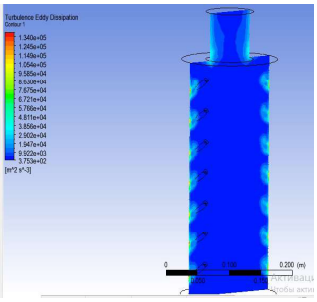


Figure 13. Turbulence Eddy Dissipation

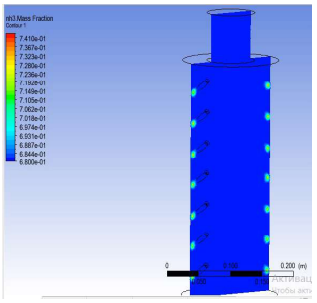


Figure 14. NH_3 Mass Fractions

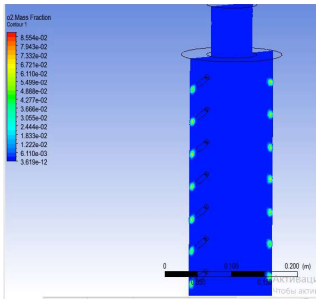


Figure 15. O_2 Mass Fractions

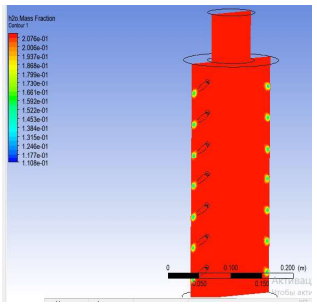


Figure 16. H_2O Mass Fractions

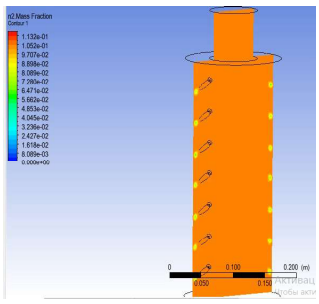


Figure 17. N_2 Mass Fractions

Based on the results obtained was concluded that ammonia and ammonia-added methane can be used as emerging fuels in the combustor by obtaining uniform temperature fields and low emissions.

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