International Journal For Advanced Research In Science & Technology
A peer reviewed international journal
www.ijarst.in
ISSN: 2457-0362

MODELING AND ANALYSIS OF COMBUSTION INSTABILITY USING FUEL INJECTION

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ABSTRACT: Combustion instability is induced by the coupling effect of the unsteady heat release of the combustion process and the change in the acoustic pressure in the gas manifold of the combustion chamber. Such instabilities can cause various problems in the combustion system such as poor efficiency, premature degradation of components, and even a catastrophic failure of the system.Combustion instability is a major issue in design of gas turbine combustors for efficient operation with low emissions. A transfer matrix-based approach is developed in this work for the stability analysis of gas turbine combustors. By viewing the combustor cavity as a one-dimensional acoustic system with a side branch, the heat source located inside the cavity can be described as the input to the system. The combustion process is modelled as a closed-loop feed-back system, which enables utilization of well-established classic control theories for the stability analysis. Due to the inherent advantage of the transfer matrix method and control system representation, modelling and analysis of the system becomes a straightforward task even for a combustor of the complex geometry. The approach is applied to the stability analysis of a simple combustion system to demonstrate its validity and effectiveness.

CFD analysis to determine the pressure, velocity, heat transfer rate, heat transfer coefficient, acoustic power and emissions(O_2, Co_2 and H_2O) at different Mach numbers 3,5,8 and at different fluent castor biodiesel, methanol and ethanol.

Keywords: *fuel injection, bell nozzle, CFD analysis, Mach number, acoustic power, emissions.*

I.INTRODUCTION

A nozzle is a device designed to control the direction or characteristics of a fluid flow(especially to increase velocity) as it exits (or enters) an enclosed chamber. A nozzle is often a pipe or tube of varying cross-sectional area and it can be used to direct or modify the flow of a fluid (liquid or gas). Nozzles are frequently used to control the rate of flow, speed, direction, mass, shape, and the pressure of the stream that emerges from them. A jet exhaust produces a net thrust from the energy obtained from combusting fuel which is added to the inducted air. This hot air is passed through a high-speed nozzle, a propelling nozzle which enormously increases its kinetic energy. The goal of nozzle is to increase the kinetic energy of the flowing medium at the expense of its pressure and internal energy.

NOZZLES BASIC REVIEW: A rocket nozzle includes three main elements i.e., a converging section, a throat, and a diverging section. The combustion exhaust gas first enters the converging section. The gas moves at subsonic speeds through this area, accelerating as the cross-sectional area decreases. In order to reach supersonic speeds, the gas must first pass through an area of minimum cross-sectional area called the throat. From here, the supersonic gas expands through the converging section and then out of the nozzle. Supersonic flow accelerates as it expands. The following are the features of nozzle,

• Nozzle produces thrust.
• Convert thermal energy of hot chamber gases into kinetic energy and direct that energy along nozzle axis.
• Exhaust gases from combustion are pushed into throat region of nozzle.
• Throat is smaller cross-sectional area than rest of engine; here gases are compressed to high pressure.
• Nozzle gradually increases in cross-sectional area allowing gases to expand and push against walls creating thrust.
• Mathematically, ultimate purpose of nozzle is to expand gases as efficiently as possible so as to maximize exit velocity.

EXPANSION AREA RATIO: Most important parameter in nozzle design is expansion area ratio i.e., Fixing other variables (primarily chamber pressure)only one ratio that optimizes performance for a given altitude (or ambient pressure). However, we have to keep in mind that rocket does not travel at only one altitude, so we should know trajectory to select expansion ratio that maximizes performance over a range of ambient pressures.

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Thus variable expansion ratio nozzles are preferred for space travel.

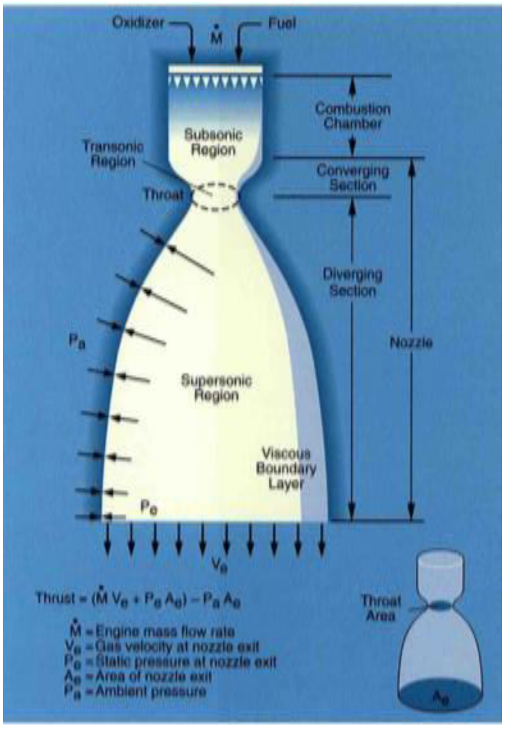

Fig. 1.1 Nozzle sections

PRINCIPLE OF OPERATION:Rocket engines produce thrust by the expulsion of a high-speed fluid exhaust. This fluid is nearly always a gas which is created by high pressure (10-200 bar) combustion of solid or liquid propellants, consisting of fuel and oxidizer components, within a combustion chamber.

The fluid exhaust is thenpassed through a supersonic propelling nozzle which uses heat energy of the gas to accelerate the exhaust to very high speed, and the reaction to this pushes the engine in the opposite direction. In rocket engines, high temperatures and pressures are highly desirable for good performance as this permits a longer nozzle to be fitted to the engine, which gives higher exhaust speeds, as well as giving better thermodynamic efficiency. Below is an approximate equation for calculating the net thrust of a rocket engine:

$$F_n = \dot{m}\, v_e = \dot{m}\, \breve{v}_{e-act} + A_e(p_e - p_{amb})$$

Since, unlike a jet engine, a conventional rocket motor lacks an air intake, there is no 'ram drag' to deduct from the gross thrust. Consequently, the net thrust of a rocket motor is equal to the gross thrust.

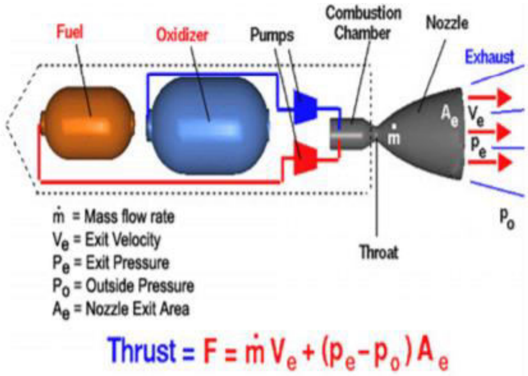

Fig. 1.2 Principle of Rocket

BELL-SHAPED NOZZLE: This nozzle concept was studied at the Jet Propulsion Laboratory in 1949. In the late 1960s, Rocket dyne patented this nozzle concept, which has received attention in recent years in the U.S. and Europe. The design of this nozzle concept with its typical inner base nozzle, the wall in section, and the outer nozzle extension can be seen. This nozzle concept offers an altitude adaptation achieved only by nozzle wall in section

.In flow altitudes, controlled and symmetrical flow separation occurs at this wall in section, which results in a lower effective area ratio. For higher altitudes, the nozzle flow is attached to the wall until the exit plane, and the full geometrical area ratio is used. Because of the higher area ratio, an improvedvacuumperformanceisachieved.However, additional performance losses are induced in dual-bell nozzles.

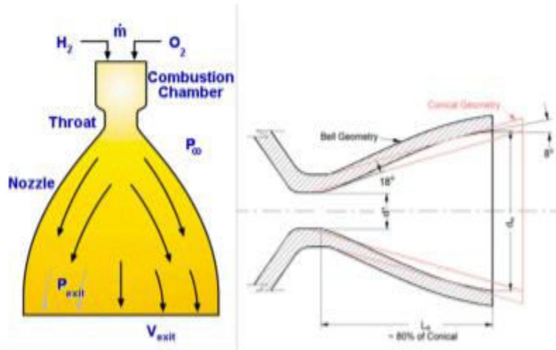

Fig. 1.3 Bell Nozzle

II. LITERATURE REVIEW

A Kalyan Charan et , al [1]2014 The main objective of this project is to determine the best one from and comparison of numerical simulation to a predefined Mach number distribution of in viscid solution and viscous simulation using the kmodel will be attempted. Geometry designs and Meshing were made in ICEM CFD 13.0 and an analysis is carried out in FLUENT 13.0. Based on the flow analysis it is found that nozzle with 4 clovers/gates provides better results when compared with the other i.e., 3 or 5 clovers/gates and it is one of the suggested and effective design of the nozzle.

K.M.Pandey et al [2] 2010 In this paper CFD analysis of pressure and temperature for a rocket nozzle with four inlets at Mach 2.1 is analyzed with the help of fluent software. when the fuel and air enter in the combustion chamber according to the x and y plot, it is burning due to high velocity and temperature and then temperature increases rapidly in combustion chamber and convergent part of the nozzle and after that temperature decreases in the exit part of the nozzle.

Nirmith Kumar Mishra et,al[3] 2014 This project develops a computer code which uses the Method of Characteristics and the Stream Function to define high efficiency nozzle contours for isentropic, inviscid, irrotational supersonic flows of any working fluid for any user-defined exit Mach number. The contours are compared to theoretical isentropic area ratios for the selected fluid and desired exit Mach number. The accuracy of the nozzle to produce the desired exit Mach number is also checked. The flow field of the nozzles created by the code are independently checked with the commercial Computational Fluid Dynamics (CFD) code ANSYS-FLUENT.

III. MATERIALS AND METHODS

A rocket engine uses a nozzle to accelerate hot exhaust to produce thrust as described by Newton's third law of motion. The amount of thrust produced by the engine depends on the mass flow rate through the engine, the exit velocity of the flow, and the pressure at the exit of the engine. The flow in the throat is sonic which means the Mach number is equal to one in the throat.The expansion of a supersonic flow causes thestatic pressure and temperature to decrease fromthe throat to the exit, so the amount of the expansion also determines the exit pressure and temperature.

We use variety of software to make our work easy, fast and accurate. The software required will be on two categories. They are designing and analysis. Bell shape nozzle designed in CATIA software and analysed in ANSYS software.

Inlet diameter	48
Exit diameter	91
Inlet pressure	210000Pa
Total temperature	300k

Table 3.1: Bell Nozzle dimensions and boundary conditions.

CFD analysis to determine the pressure, velocity, heat transfer rate, heat transfer coefficient, acoustic power and emissions(O2, Co2 and H2O) at different Mach numbers 3,5,8 and at different fluent castor biodiesel, methanol and ethanol.

Castor Biodiesel:

Biodiesel is a fuel composed mainly of mono-alkyl esters derived from renewable vegetable oils oranimal fats meeting the ASTM D6751 requirements.Effect of castor biodiesel blends on diesel engine performance and emissions was studied. Specific fuel consumption, thermal efficiency, and exhaust emissions were analysed.Volume percentages of biodiesel with diesel fuel of 5, 10, 15, 20 and 30% were used.

Ethanol:

Ethanol(C_2H_5OH) is a renewable fuel made from various plant materials collectively known as "biomass." More than 98%of U.S. gasoline contains ethanol, typically E10 (10% ethanol, 90% gasoline), to oxygenate the fuel, which reduces air pollution.Ethanol is a clean burning and renewable fuel with high potential as a next generation fuel and nitrous oxide has potential as an oxidizer for use in both hybrid and liquid bi-propellant rocket engines, and can be simpler to handle than cryogenic liquid oxygen.

Methanol:

Methanolcanbedecomposed endothermically, in the presence of a catalyst, into carbon monoxide and hydrogen, absorbing a great deal of enthalpy in the process. It can also absorb more enthalpy for a given temperature change than hydrogen, making it a superior coolant.Methanol is a colourless liquid that boils at 64.96 °C (148.93 °F) and solidifies at −93.9 °C (−137 °F).

Here, we use three different fuels castor biodiesel, ethanol and methanol. They are injected with the help of fuel injectors by addition of liquid oxygen(LOX) into combustion chamber. In that chamber, they get mixed and burnt,then it will exhaust through the nozzle.

IV. Bell shape shortened nozzle

Bell Nozzle gets its name from the fact that the parabolic shape converges and diverge in a bell shape. It has a high angle expansion section right behind the nozzle throat; this is followed by a gradual reversal of nozzle contour slope so that the nozzle exit divergence angle is small, usually less than a 10-degree half angle. Greater thrust produced due to the parabolic shape maximizes the axial component of exit velocity and produces a high specific impulse. Contour the nozzle to avoid oblique shocks and maximize performance is the most important design issue.

Bell shape shortened nozzle designed in CATIA parametric software:

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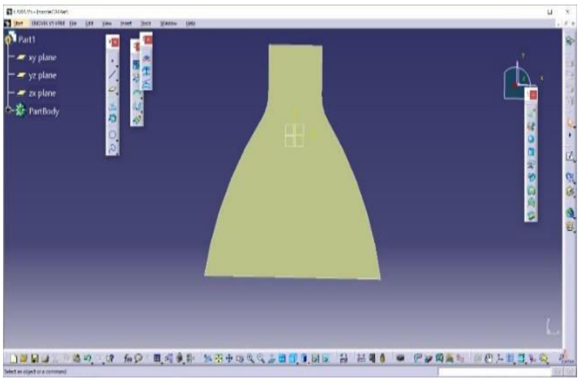

V. Analysis of bell shape shortened nozzle

Flow analysis for the bell nozzle is carried out using ANSYS 18.2 Fluent software. In this process first the models are meshed, imported and flow analysis is carried out in major three steps:ANSYS, where the meshed model is drawn and boundaries are created and corresponding boundary conditions are assigned to the boundaries. FLUENT-SOLVER, where the solutions are obtained by solving the equations and process is highlighted in terms of codes and graphs and once the run is over it reaches next step.FLUENT, where the corresponding contours are created for following major parameters such a Pressure, Temperature and Mach number.

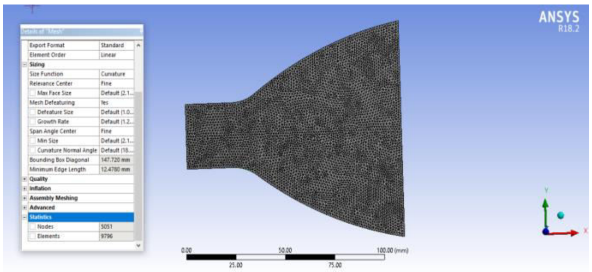

Fig:Meshed model of bell shape nozzle

Meshing is an integral part of the computer-aided engineering (CAE) simulation process. The mesh influences the accuracy, convergence and speed of the solution. Furthermore, the time it takes to create a mesh model is often a significant portion of the time it takes to get results from a CAE solution.Finite element analysis or FEA representing a real project as a "mesh" a series of small, regularly shaped tetrahedron connected elements, as shown in the above fig. And then setting up and solving huge arrays of simultaneous equations. The finer the mesh, the more accurate the results but more computing power is required. No of nodes 5051 and no of elements 9796.

Mach number: Mach number, in fluid mechanics, ratio of the velocity of a fluid to the velocity of sound in that fluid, named after Ernst Mach (1838–1916), an Austrian physicist and philosopher.Mach numbers less than one indicate subsonic flow; those greater than one, supersonic flow. Fluid flow, in addition, is classified as compressible or incompressible on the basis of the Mach number.

5.1 FLUID: CASTOR BIODIESEL

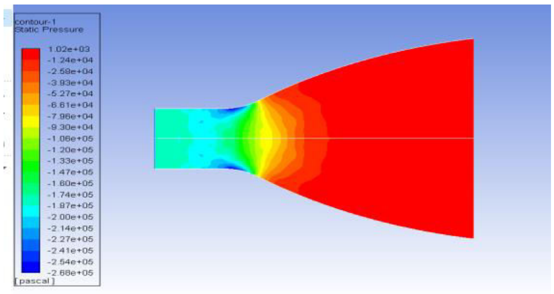

Fig 5.1.1 Pressure

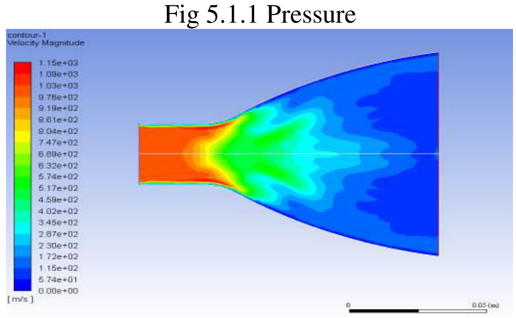

Fig 5.1.2 Velocity

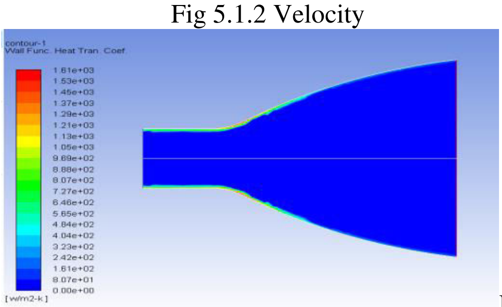

Fig 5.1.3 Heat transfer coefficient

```
Total Heat Transfer Rate                    (w)
-------------------------------- --------------------
                         inlet           168503.86
                        outlet          -174440.48
                   wall-fill.1_                  -0
                ---------------- --------------------
                           Net           -5936.625
```

Fig 5.1.4 Heat transfer rate

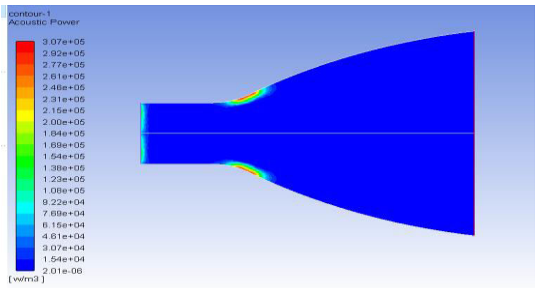

Fig 5.1.5 Acoustic power

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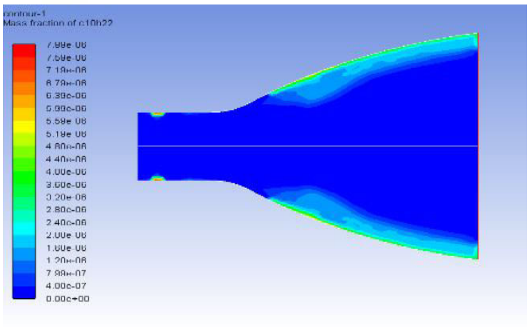

Fig 5.1.6 Mass fraction of Castor Biodiesel

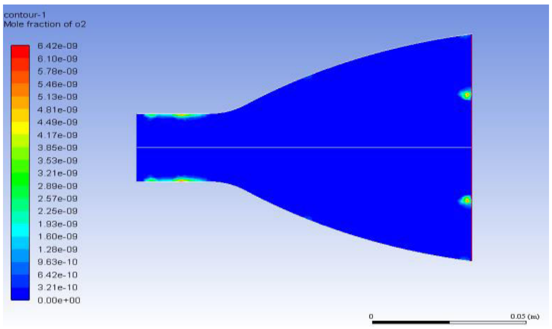

Fig 5.1.11 mole fraction of O2

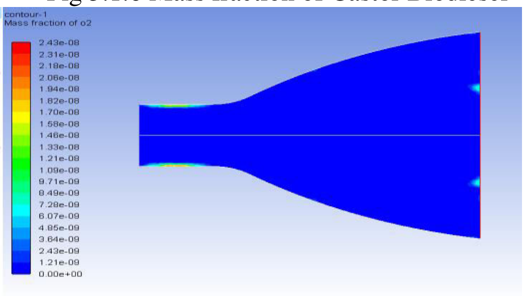

Fig 5.1.7 mass fraction of O2

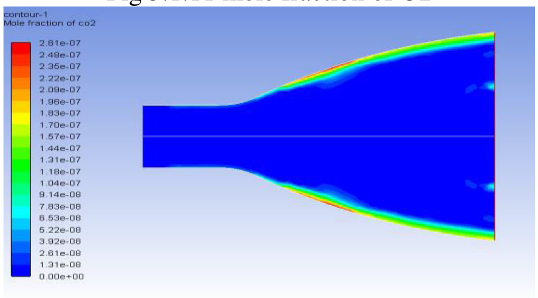

Fig 5.1.12 mole fraction of Co2

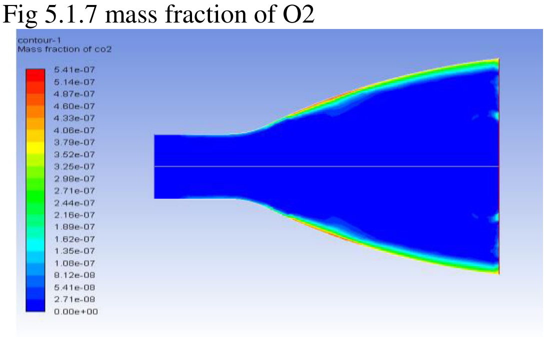

Fig 5.1.8 mass fraction of Co2

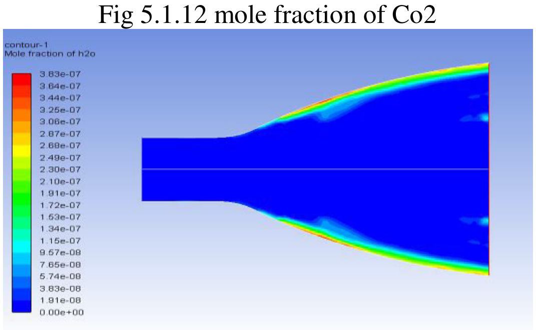

Fig 5.1.13 mole fraction of H2O

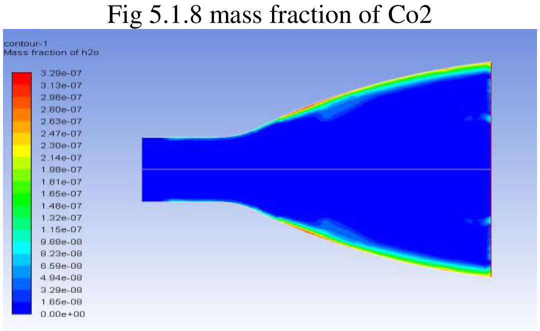

Fig 5.1.9 mass fraction of H2O

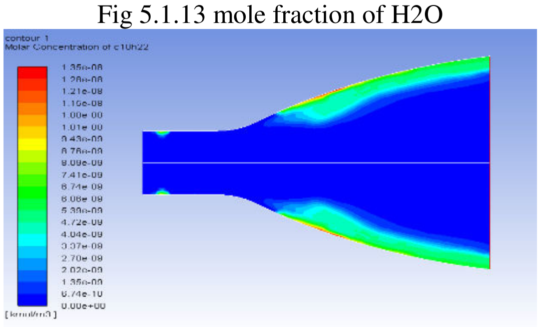

Fig 5.1.14 molar concentration of castor biodiesel

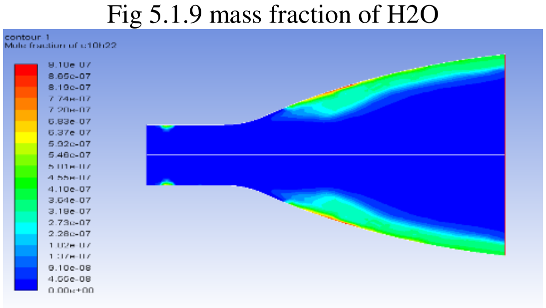

Fig 5.1.10 mole fraction of castor biodiesel

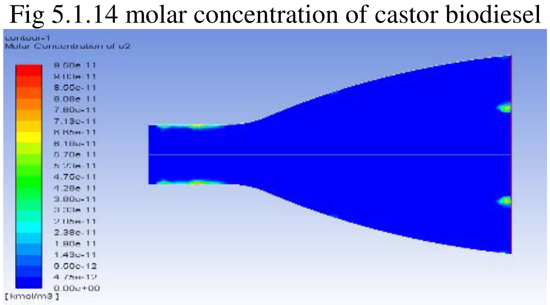

Fig 5.1.15 molar concentration of O2

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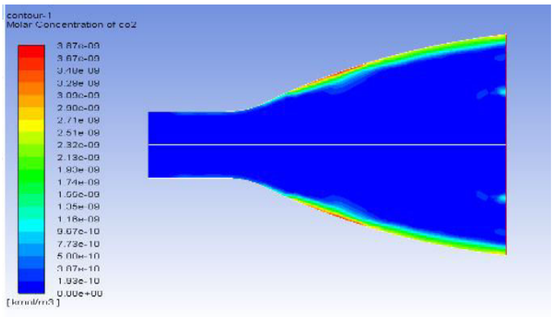

Fig 5.1.16 molar concentration of Co2

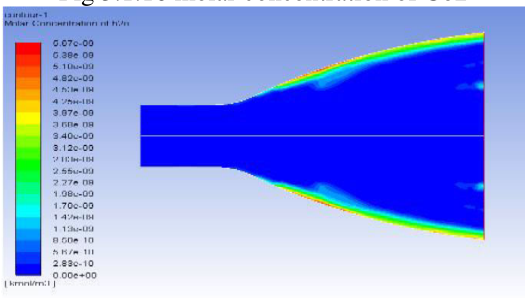

Fig 5.1.17 molar concentration of H2O

5.2 FLUID: ETHANOL

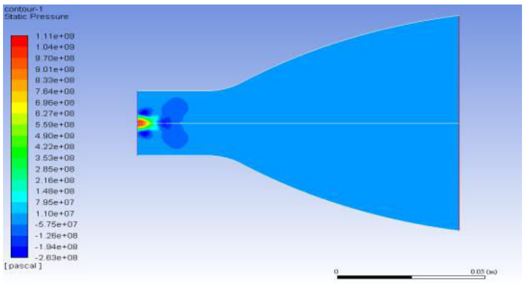

Fig:5.2.1 Pressure

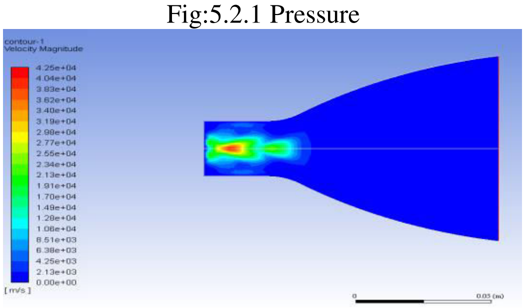

Fig 5.2.2 Velocity

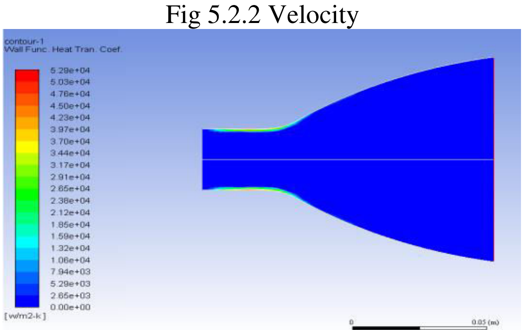

Fig 5.2.3 Heat transfer coefficient

```
Total Heat Transfer Rate                        (w)
--------------------------- --------------------
                      inlet            51411.023
                     outlet           -31733.604
               wall-fill.1__                   -0
              ---------------- --------------------
                        Net             19677.42
```

Fig 5.2.4 Heat transfer rate

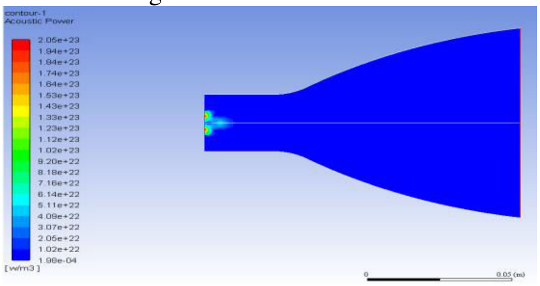

Fig 5.2.5 Acoustic power

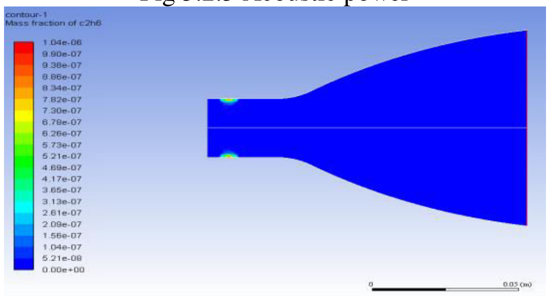

Fig 5.2.6 mass fraction of ethanol

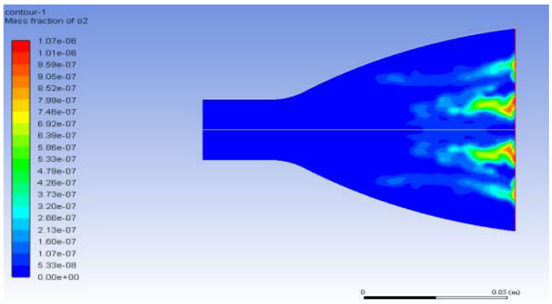

Fig 5.2.7 mass fraction of O2

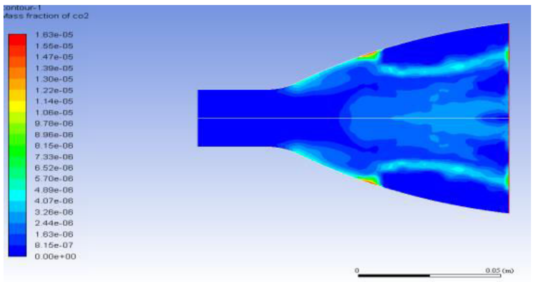

Fig 5.2.8 mass fraction of Co2

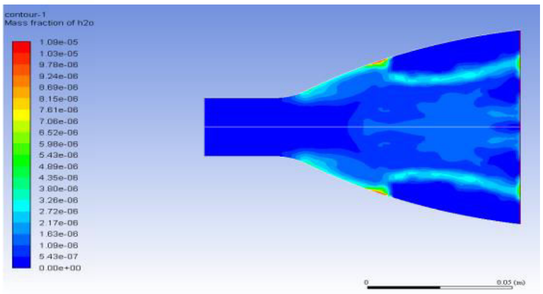

Fig 5.2.9 mass fraction of H2O

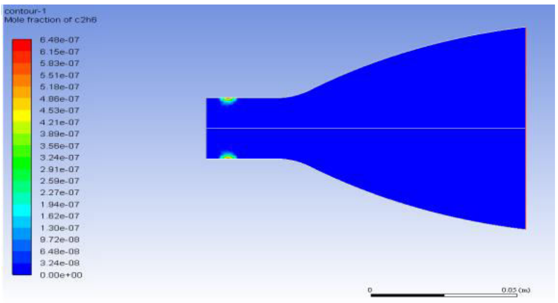

Fig 5.2.10 mole fraction of ethanol

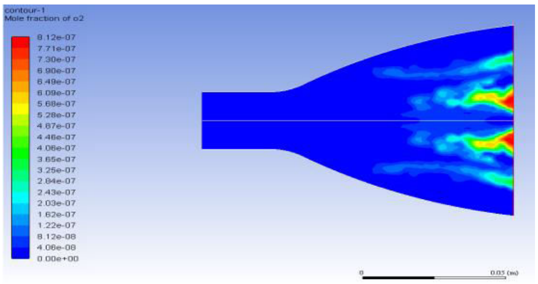

Fig 5.2.11 mole fraction of O2

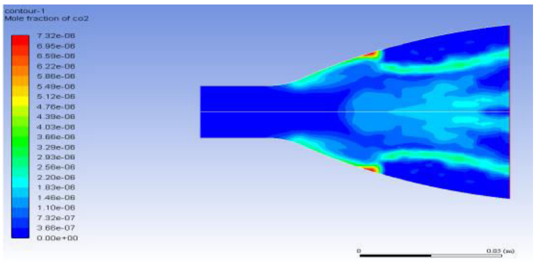

Fig 5.2.12 mole fraction of Co2

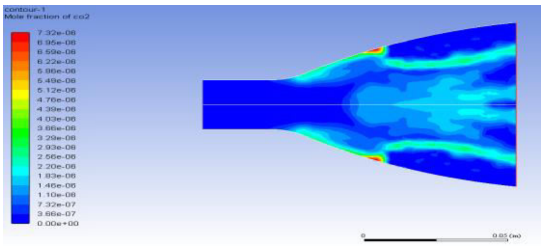

Fig 5.2.13 mole fraction of H2O

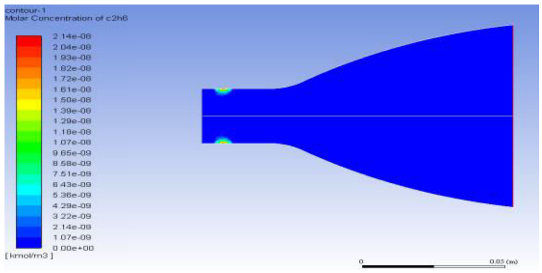

Fig 5.2.14 molar concentration of ethanol

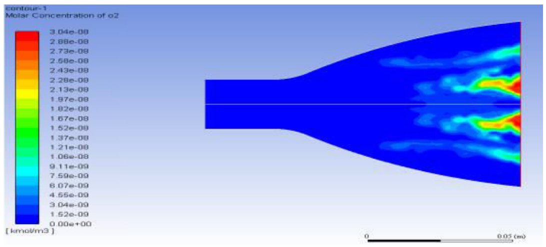

Fig 5.2.15 molar concentration of O2

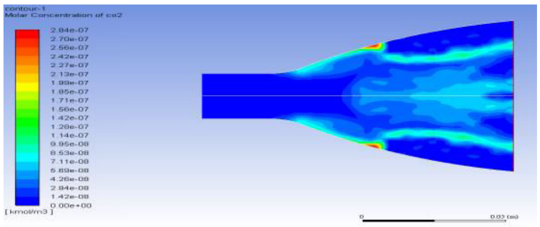

Fig 5.2.16 molar concentration of Co2

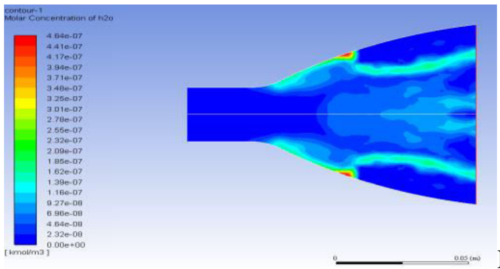

Fig 5.2.17 molar concentration of H2O

5.3. Fluid- Methanol

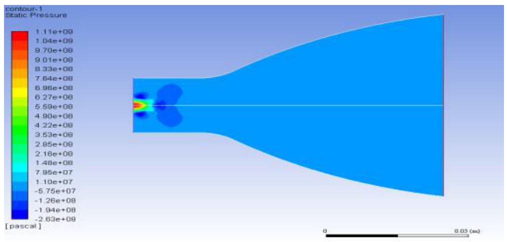

Fig5.3.1 Pressure

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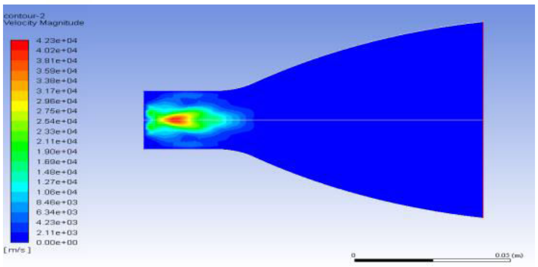

Fig 5.3.2 Velocity

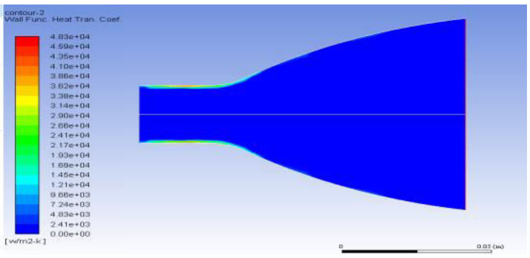

Fig 5.3.3 Heat transfer coefficient

```
 Total Heat Transfer Rate                         (w)
-------------------------------- --------------------
                     inlet              51310.355
                    outlet             -105071.59
              wall-fill.1__                    -0
          ---------------- --------------------
                       Net              -53761.23
```

Fig 5.3.4 Heat transfer rate

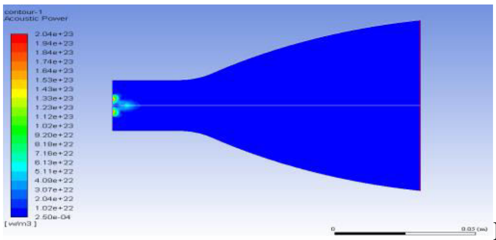

Fig 5.3.5 Acoustic power

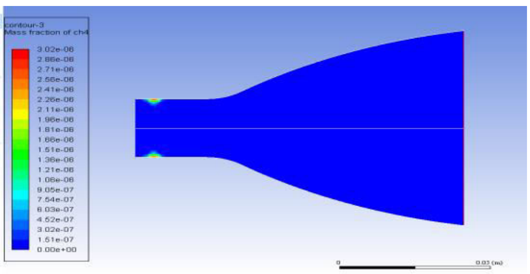

Fig 5.3.6 mass fraction of methanol

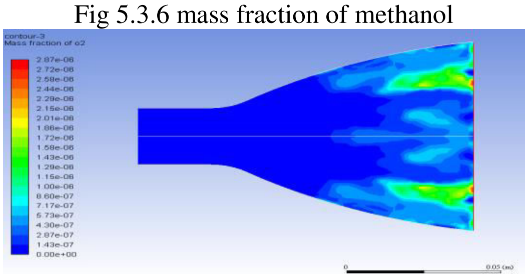

Fig 5.3.7 mass fraction of O2

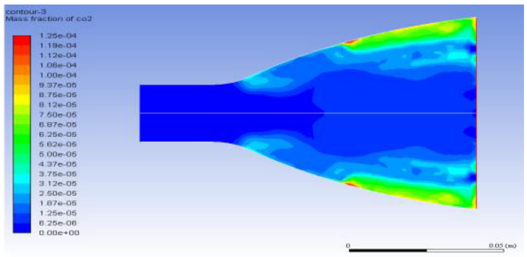

Fig 5.3.8 mass fraction of Co2

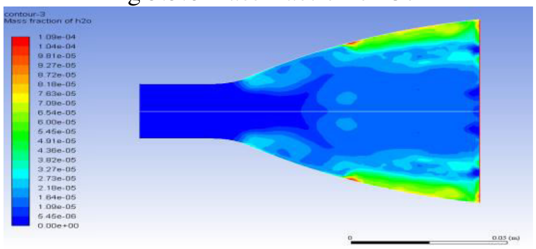

Fig 5.3.9 mass fraction of H2O

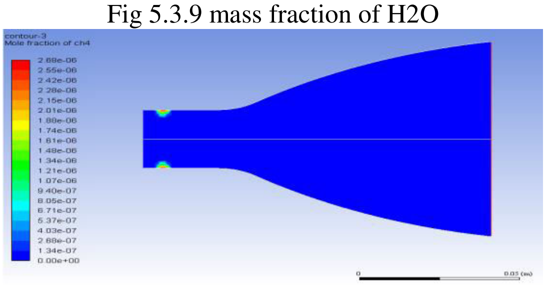

Fig 5.3.10 mole fraction of methanol

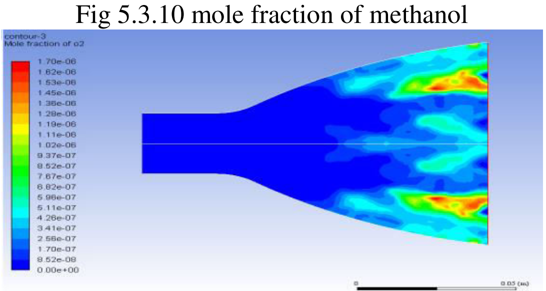

Fig 5.3.11 mole fraction of O2

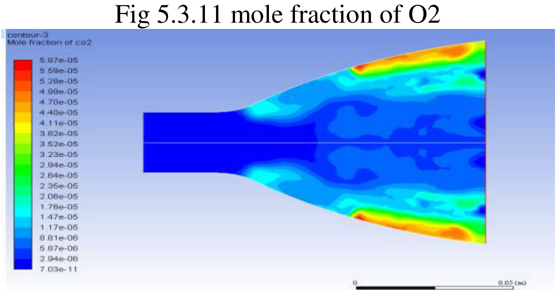

Fig 5.3.12 mole fraction of Co2

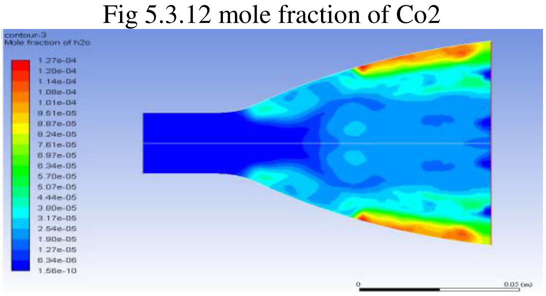

Fig 5.3.13 mole fraction of H2O

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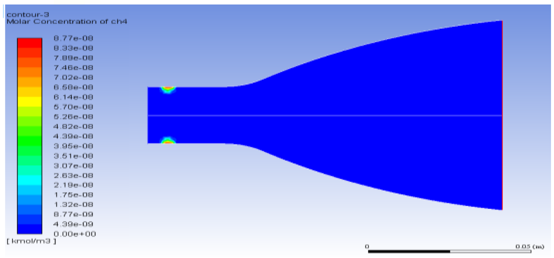

Fig 5.3.14 molar concentration of methanol

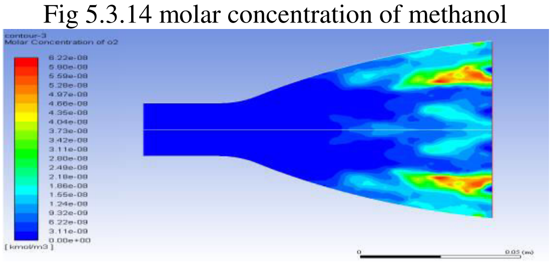

Fig 5.3.15 molar concentration of O2

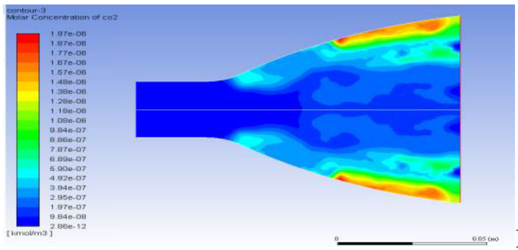

Fig 5.3.16 molar concentration of Co2

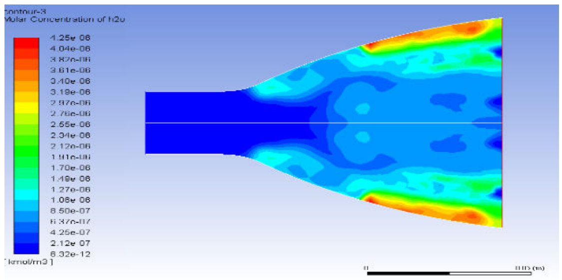

Fig 5.3.17 molar concentration of H2O

VI RESULTS AND DISCUSSION

Result table

Mach numbers	Fuels	Pressure(Pa)	Velocity (m/s)	Heat transfer coefficient (w/m2-k)	Heat transfer rate(w)	Acoustic power (w/m3)
3	Castor Biodiesel	1.02e+03	1.15e+03	1.61e+03	5936.625	3.07e+05
	Ethanol	1.07e+09	4.25e+04	5.29e+04	19677.42	2.05e+23
	Methanol	1.11e+09	4.23e+04	4.83e+04	53761.23	2.04e+23
5	Castor Biodiesel	1.05e+04	1.26e+04	2.2e+04	6589.325	4.32e+06
	Ethanol	2.01e+10	5.12e+05	5.65e+05	22166.21	3.10e+23
	Methanol	2.21e+10	5.53e+05	5.14e+05	59635.45	3.90e+23
8	Castor Biodiesel	1.09e+05	1.93e+05	3.91e+05	6993.485	4.98e+07
	Ethanol	3.62e+11	6.2e+06	6.15e+06	28924.52	4.26e+23
	Methanol	3.95e+11	6.33e+06	6.19e+06	65125.32	4.65e+23

Emissions table for mass fraction

Mach numbers	Fuels	Mass fraction	Mass fraction of O2	Mass fraction of Co2	Mass fraction of h2O
3	Castor Biodiesel	7.99e-06	2.43e-08	5.41e-07	3.29e-07
	Ethanol	1.04e-06	1.07e-06	1.63e-05	1.09e-05
	Methanol	3.02e-06	2.87e-06	1.25e-04	1.09e-04
5	Castor Biodiesel	8.10e-05	2.31e-07	4.24e-06	3.21e-06
	Ethanol	1.90e-05	1.61e-05	1.36e-04	1.68e-06
	Methanol	2.91e-05	2.65e-05	1.65e-03	1.19e-03
8	Castor Biodiesel	7.14e-04	2.69e-06	5.31e-05	4.68-05
	Ethanol	1.19e-04	1.02e-04	2.51e-03	1.26e-05
	Methanol	2.21e-04	2.23e-04	6.97e-02	1.14ee-03e

Emissions table for mole fraction

Mach numbers	Fuels	Mole fraction	Mole fraction of O2	Mole fraction of Co2	Mole fraction of h2O

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3	Castor Biodiesel	9.10e-07	6.42e-09	2.61e-07	3.83e-07
	Ethanol	6.48e-07	8.12e-07	7.32e-06	1.19e-05
	Methanol	2.68e-06	1.70e-06	5.87e-05	1.27e-04
5	Castor Biodiesel	9.92e-06	5.5e-08	3.97e-06	5.98e-06
	Ethanol	6.39e-06	7.28e-06	5.528e-05	2.27e-04
	Methanol	2.01e-05	2.58e-05	4.987e-04	2.36e-03
8	Castor Biodiesel	8.95e-05	4.35e-07	4.59e-05	6.98e-05
	Ethanol	5.25e-05	6.98e-04	5.39e-04	6.85e-03
	Methanol	2.89e-04	5.97e-03	9.87e-03	2.96e-02

Emissions table for molar concentration

Mach numbers	Fuels	molar concentration	molar concentration of O2	molar concentration of Co2	molar concentration of h2O
3	Castor Biodiesel	1.35e-08	9.50e-11	3.87e-09	5.67e-09
	Ethanol	2.14e-08	3.04e-08	2.84e-07	4.64e-07
	Methanol	8.77e-08	6.22e-08	1.97e-06	4.25e-06
5	Castor Biodiesel	1.39e-07	9.10e-10	3.42e-08	5.68e-08
	Ethanol	2.68e-07	2.57e-07	2.96e-06	4.58e-06
	Methanol	3.57e-07	6.87e-07	1.32e-05	5.32e-05
8	Castor Biodiesel	1.97e-06	5.97e-09	3.82e-09	5.32e-07
	Ethanol	2.91e-06	3.84e-06	3.10e-05	6.45e-05
	Methanol	2.92e-06	6.13e-05	1..08e-04	5.29e-04

VII. CONCLUSION

Many factors are involved when the fuel interacts with the gas charge in a diesel combustion chamber. The mechanics and thermodynamics involved in droplet break up, fuel vaporization, combustion, NOx-formation, soot formation and oxidation are not yet fully understood. The secret behind a high efficiency, low emission diesel combustion process is to find a "way" through the combustion process where the fuel is completely burnt without high soot emissions while avoiding excessively high temperatures. High temperature in combination with residence time promotes formation of nitrous oxides. The profile of the heat release also has to be suited for the particular engine in order to result in high efficiency.

In this project, used fuels are castoroil biodiesel, ethanol and methanol and compared Mach numbers 3,5 and 8.

In this thesis the emissions are calculated at different Mach numbers and different fuels.

The emissions values are increases by increasing the Mach numbers. Here emissions calculated mass fraction, mole fraction and molar concentrations of O2, CO2, and H2O.

By observing CFD analysis results the pressure, velocity, heat transfer coefficient and heat transfer rate and acoustic power values are increases by increasing the Mach number. The methanol fluid has more heat transfer rate and the maximum values are more for methanol fluid.

So it can be concluded the methanol fluid is better for fuel injector nozzle.

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