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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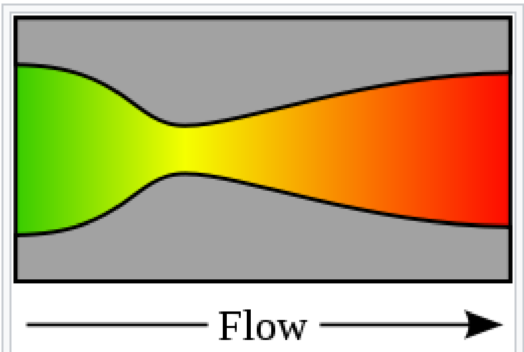
Abstract: Combustion instability is induced by the coupling effect of the unsteady heat release of the combustion process and the change in the acoustic pressure in the gas manifold of the combustion chamber. Such instabilities can cause various problems in the combustion system such as poor efficiency, 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 modeled 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, modeling 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.

I.INTRODUCTION

A rocket engine nozzle is a propelling nozzle (usually of the de Laval type) used in a rocket engine to expand and accelerate the combustion gases produced by burning propellants so that the exhaust gases exit the nozzle at hypersonic velocities.

Simply: the rocket (pumps and a combustion chamber) generates high pressure, a few hundred atmospheres (Bar). The nozzle turns the static high pressure high temperature gas into rapidly moving gas at near-ambient pressure.



One-dimensional analysis of gas flow in rocket engine nozzles

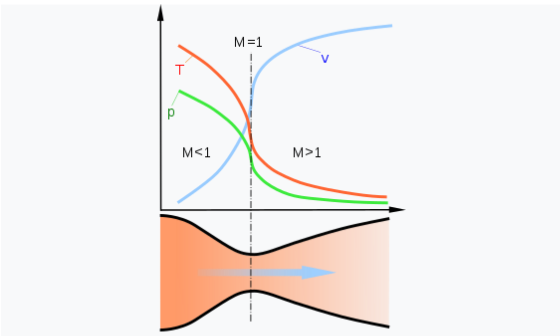


Diagram of a de Laval nozzle, showing flow MACH NUMBER (v) increasing in the direction of flow, with decreases in temperature (t) and pressure (p). The Mach number (M) increases from subsonic, to sonic at the throat, to supersonic.

The analysis of gas flow through de Laval nozzles involves a number of concepts and simplifying assumptions:

- The combustion gas is assumed to be an ideal gas.
- The gas flow is isentropic i.e., at constant entropy, as the result of the assumption of non-viscous fluid, and adiabatic process.
- The gas flow is constant (i.e., steady) during the period of the propellant burn.

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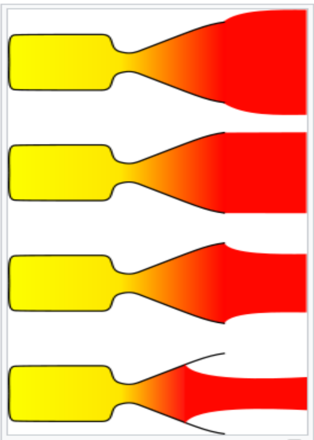
- The gas flow is non-turbulent and axisymmetric from gas inlet to exhaust gas exit (i.e., along the nozzle's axis of symmetry)
- The flow behaviour is compressible since the fluid is a gas.

As the combustion gas enters the rocket nozzle, it is traveling at subsonic velocities. As the throat constricts, the gas is forced to accelerate until at the nozzle throat, where the cross-sectional area is the least, the linear MACH NUMBER becomes sonic. From the throat the cross-sectional area then increases, the gas expands and the linear MACH NUMBER becomes progressively more supersonic.

Other design aspects affect the efficiency of a rocket nozzle. The nozzle's throat should have a smooth radius. The internal angle that narrows to the throat also has an effect on the overall efficiency, but this is small. The exit angle of the nozzle needs to be as small as possible (about 12°) in order to minimize the chances of separation problems at low exit pressures.



1.1 Advanced designs

Number of more sophisticated designs has been proposed for altitude compensation and other uses.

Nozzles with an atmospheric boundary include:

Expansion-deflection nozzle

Plug nozzle

1.1.1 Aero spike

Single Expansion Ramp Nozzle (SERN), a linear expansion nozzle, where the gas pressure transfers work only on one side and which could be described as a single-sided aerospike nozzle.

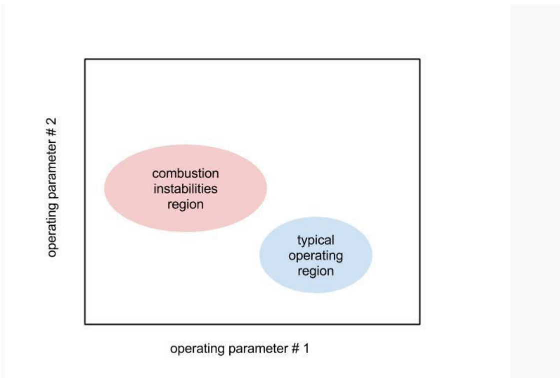
1.2 Classification of combustion instabilities

In applications directed towards engines, combustion instability has been classified into three categories, not entirely distinct. This classification was first introduced by Marcel Barrère and Forman A. Williams in 1969. The three categories are

- **Chamber instabilities** - instabilities arising due to the occurrence of combustion inside a chamber (acoustic instabilities, shock instabilities, fluid-dynamic instabilities associated with the chamber, etc.,)
- **Intrinsic instabilities** - instabilities arising irrespective of whether combustion occurs inside a chamber or not (chemical-kinetic instabilities, diffusive-thermal instabilities, hydrodynamic instabilities, etc.,)
- **Systeminstabilities** - instabilities arising due to the interaction between combustion processes in the chamber and anywhere else in the system (feed-system interactions, exhaust-system interactions, etc.,)

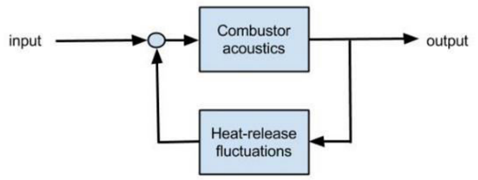
1.3 Thermoacoustic combustion instabilities

In this type of instabilities, the perturbations that grow and alter the features of the flow are of an acoustics nature. Their associated pressure oscillations can have well defined frequencies with amplitudes high enough to pose a serious hazard to combustion systems. For example, in rocket engines, such as the Rocketdyne F-1 rocket engine in the Saturn V program, instabilities can lead to massive damage of the combustion chamber and surrounding components. Furthermore, instabilities are known to destroy gas-turbine-engine components during testing. They represent a hazard to any type of combustion system.



Stability map of a hypothetical combustor. This combustor operates at conditions in which no dangerous combustion-instabilities will happen.

This feedback between the acoustic waves in the combustor and the heat-release fluctuations from the flame is a hallmark of thermoacoustic combustion instabilities. It is typically represented with a block diagram. Under some conditions, the perturbations will grow and then saturate, producing a particular noise. In fact, it is said that the flame of a Rijke tube sings.



Combustion instabilities represented with a block diagram as a feedback amplifier.

II. LITERATURE REVIEW

A Kalyan Charan et , al [1]2014 The main objective of this project is to determine the best one from (3clover, 4clover and 5 clovers) 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

Materials Refined castor oil supplied by Morgan Company for Chemical Industry, was trans esterified using anhydrous methanol and KOHpellets.2.2. Transesterification experiments Transesterification reactions were performed in a 250 ml batch reactor equipped with a reflux condenser and a magnetic stirrer, the reaction mixture containing castor oil, methanol and the catalyst (KOH). The oil is first loaded into the reactor, and the temperature adjusted to the desired value. Once the oil reached this value, the alcohol catalyst mixture is added to the reactor and the reaction mixture was continuously stirred at 400 rpm. The experiments were carried out and adopted considering the variables, temperatures (30 & 60°C) and methanol: castor oil molar ratios (6:1–24:1), catalyst concentrations (0.5–2 wt%) of castor oil; and reaction time of (30–120) min. After an appropriate period of time, excess alcohol was evaporated at a mild temperature under moderate vacuum on a rotary evaporator. The mixture was transferred to a separating funnel, and then allowed to stand for phase separation. After phase separation the remaining mixture was neutralized and subsequently traces of catalyst and alcohol were washed out from the ester mixture with distilled water until the water layer remains completely translucent.

castor oil

Materials Refined castor oil supplied by Morgan Company for Chemical Industry, was trans esterified using anhydrous methanol and KOHpellets.2.2. Transesterification experiments Transesterification reactions were performed in a 250 ml batch reactor equipped with a reflux condenser and a magnetic stirrer, the reaction mixture containing castor oil, methanol and the catalyst (KOH). The oil is first loaded into the reactor, and the temperature adjusted to the desired value.

Methanol + air

Methanol, also known as methyl alcohol amongst other names, is a chemical and the simplest alcohol, with the formula CH_3OH (a methyl group linked to a hydroxyl group, often abbreviated MeOH).

Ethanol+ air

Ethanol is a renewable fuel made from various plant materials collectively known as "biomass."

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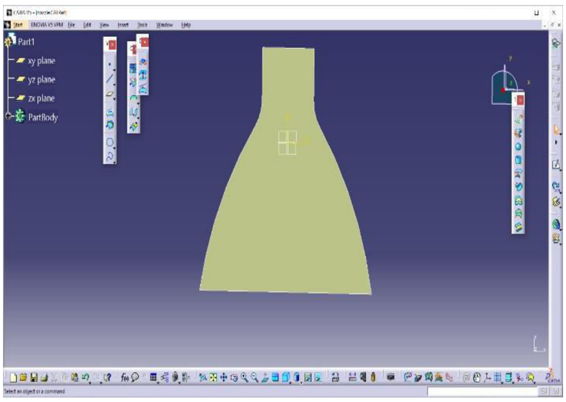
More than 98% of U.S. gasoline contains ethanol, typically E10 (10% ethanol, 90% gasoline), to oxygenate the fuel, which reduces air pollution.

IV. Bell shape shortened nozzle

Bell Nozzle gets its name from the fact that the parabolic shape converge 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.



V. ANALYSIS OF BELL SHAPE SHORTENED NOZZLE

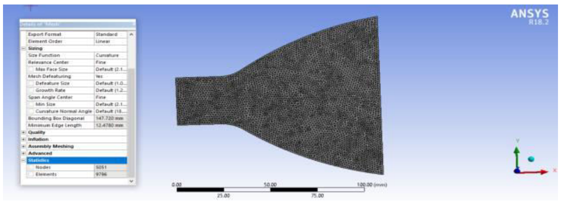
Flow analysis for the bell nozzle is carried out using ANSYS 18.2 Fluent software. In this process first the models are meshed, imported and flow analysis is carried out in major three steps.

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.

Meshed model



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. In the case of an object moving through a fluid, such as an aircraft in flight, the Mach number is equal to the velocity of the object relative to the fluid divided by the velocity of sound in that fluid. 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. For example, gas flowing with a Mach number of less than three-tenths may be considered incompressible, or of constant density, an approximation that greatly simplifies the analysis of its behaviour.

MACH NUMBER 3

5.1.1 FLUID : CASTER BIO DIESEL

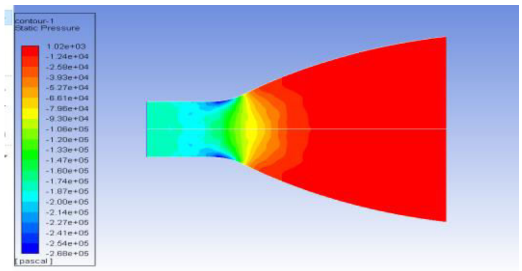


Fig 5.1.1 Pressure

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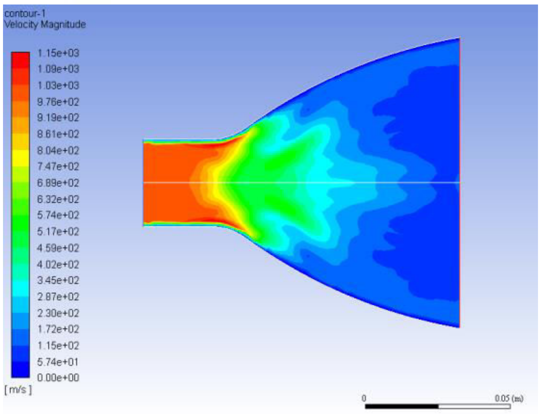

Fig 5.1.2 Velocity

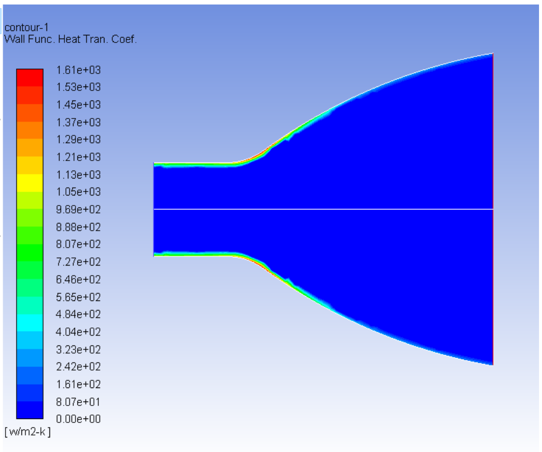

Fig 5.1.3 Heat transfer coefficient

```
         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

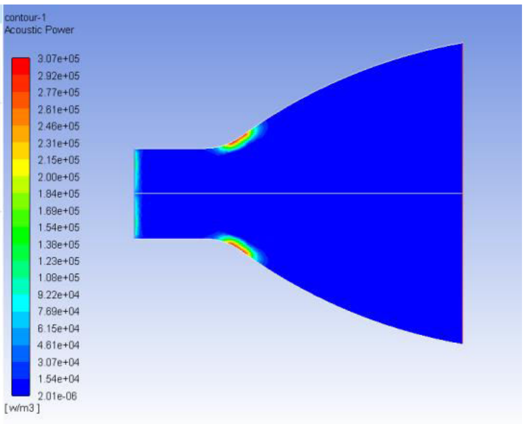

Fig 5.1.5 acoustic power

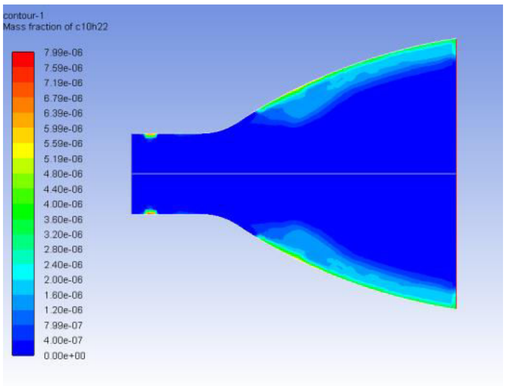

Fig 5.1.6 mass fraction of CASTER BIO DIESEL

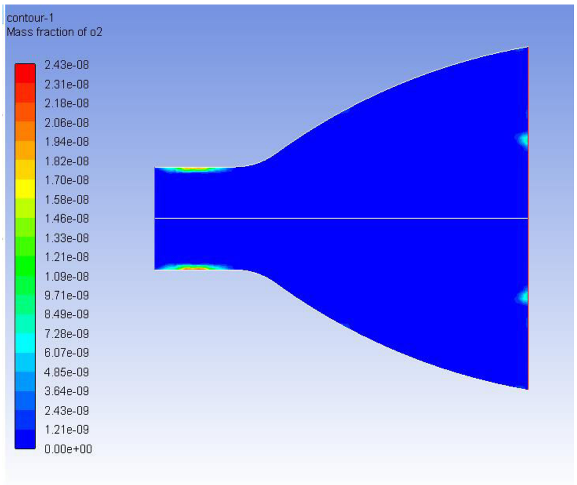

Fig 5.1.7 mass fraction of O2

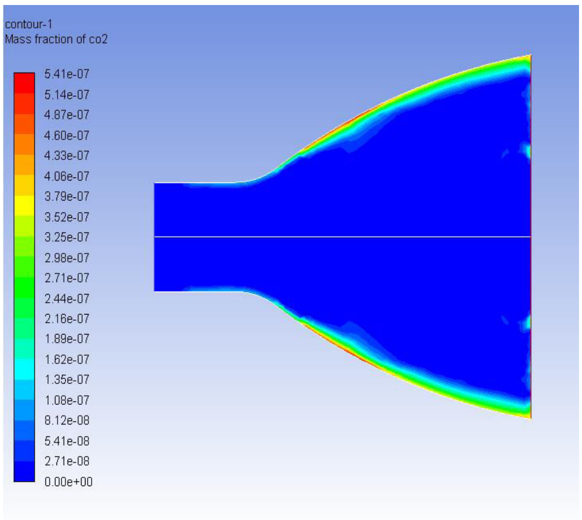

Fig 5.1.8 mass fraction of Co2

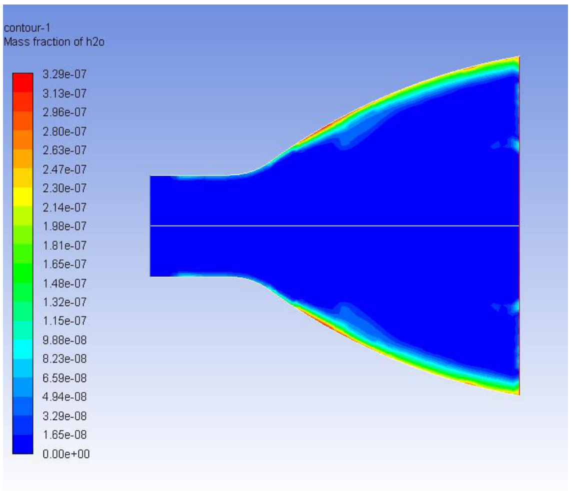

Fig 5.1.9 mass fraction of H2O

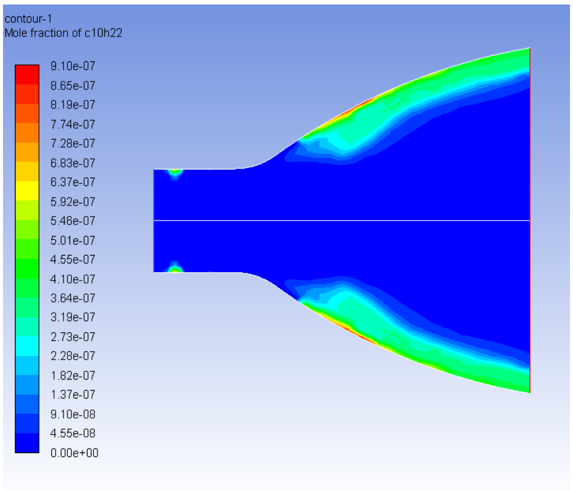

Fig 5.1.10 mole fraction of CASTER BIO DIESEL

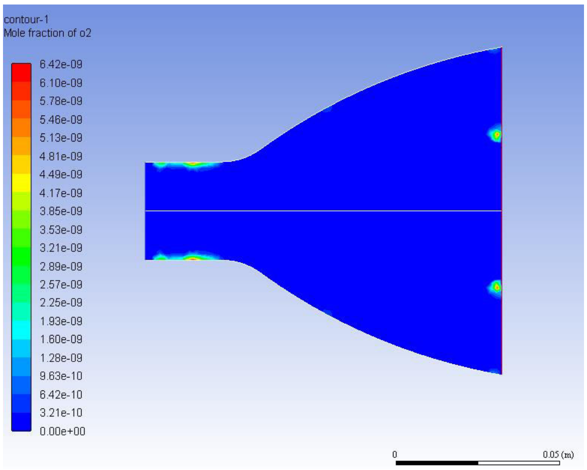

Fig 5.1.11 mole fraction of O2

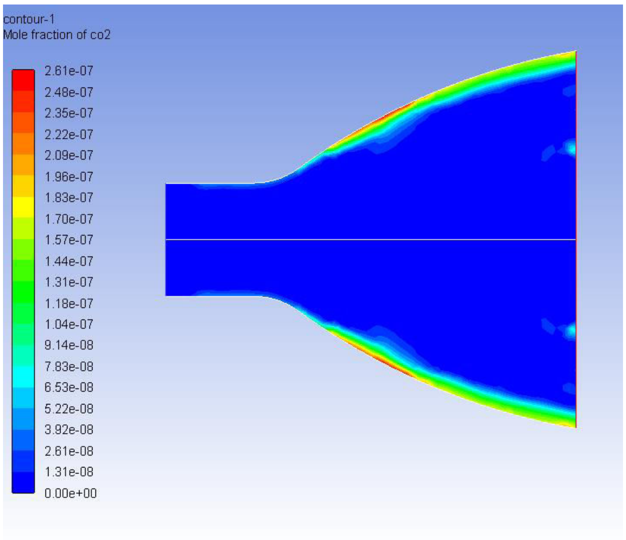

Fig 5.1.12 mole fraction of Co2

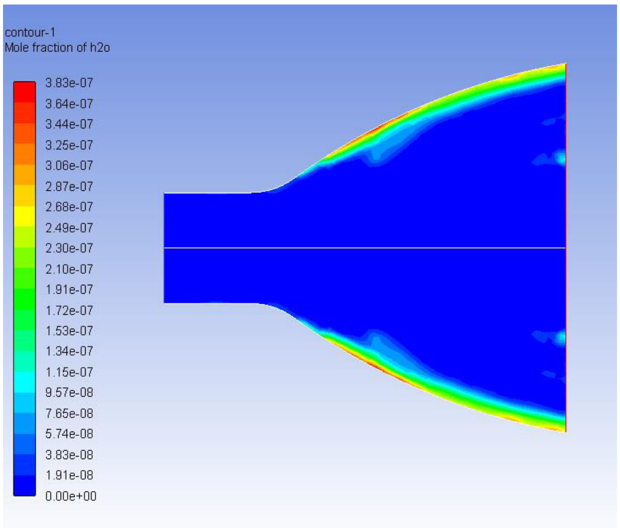

Fig 5.1.13 mole fraction of H2O

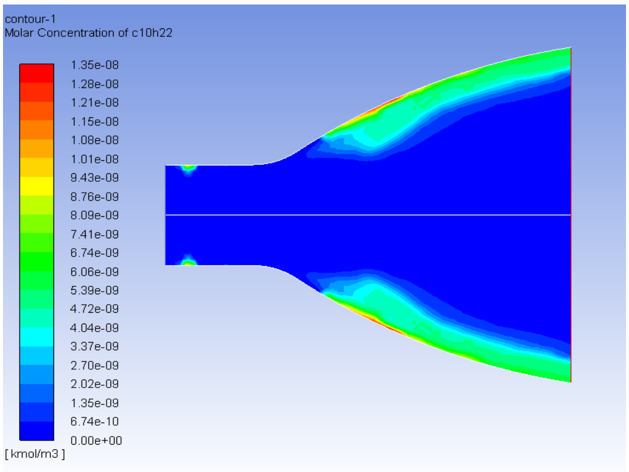

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Fig 5.1.14 molar concentration of CASTER BIO DIESEL

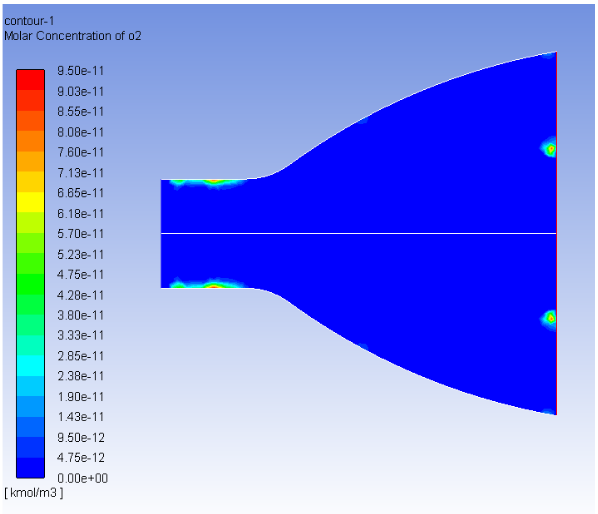

Fig 5.1.15 molar concentration of O2

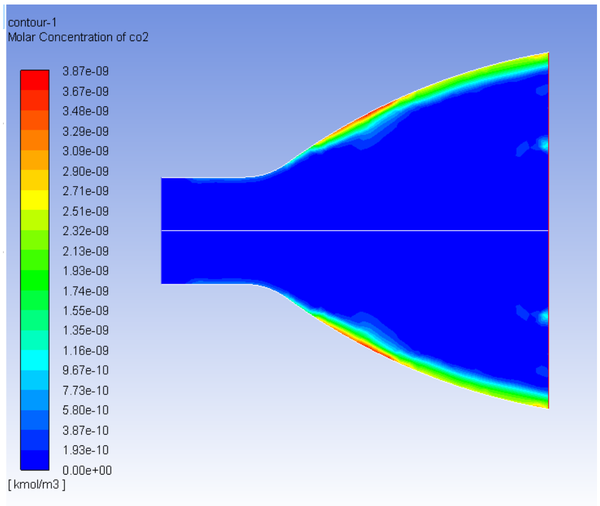

Fig 5.1.16 molar concentration of Co2

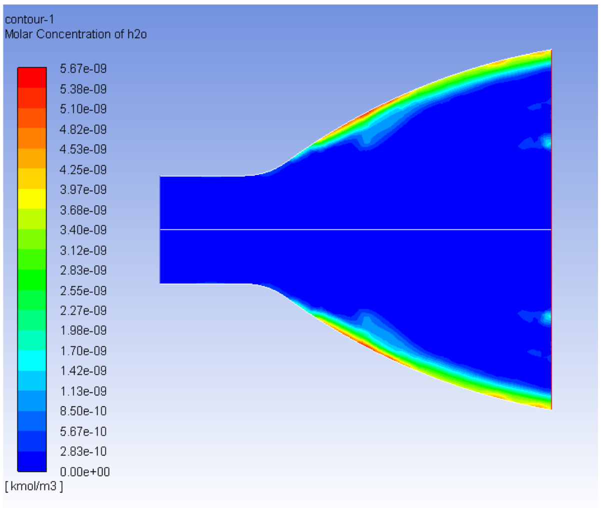

Fig 5.1.17 molar concentration of H2O

5.1.2 FLUID : ETHANE+ AIR

Fig:5.2.1 pressure

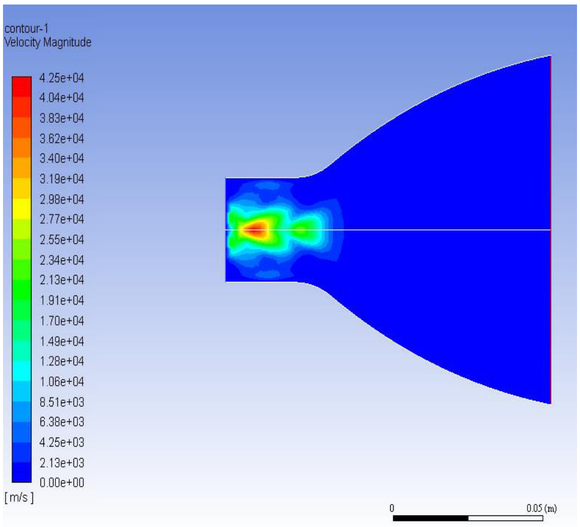

Fig 5.2.2 Velocity

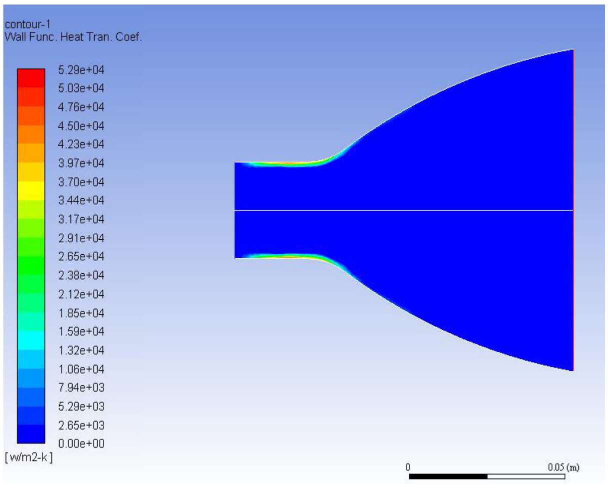

Fig 5.2.3 Heat transfer coefficient

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

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Fig 5.2.4 Heat transfer rate

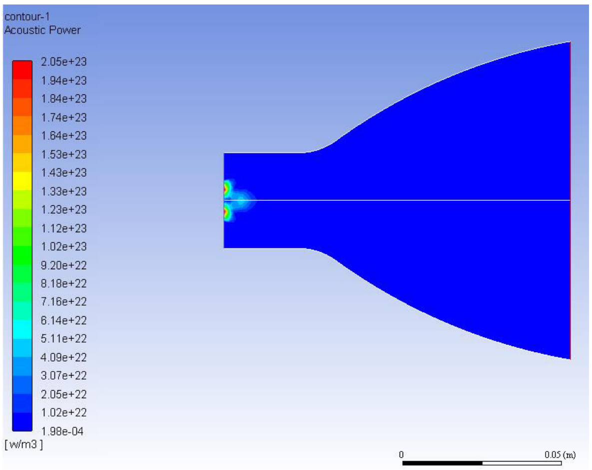

Fig 5.2.5 acoustic power

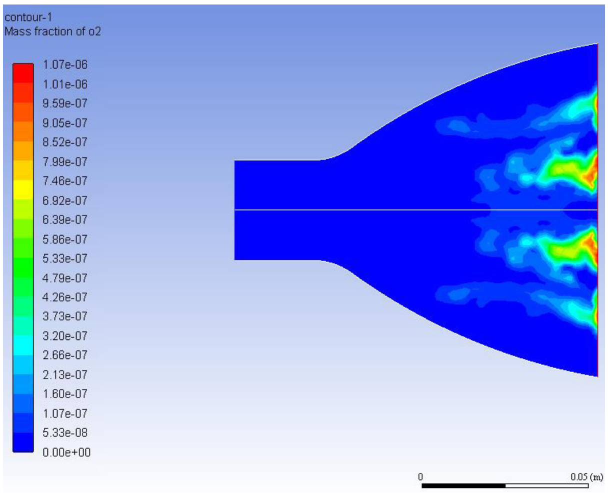

Fig 5.2.7 mass fraction of O2

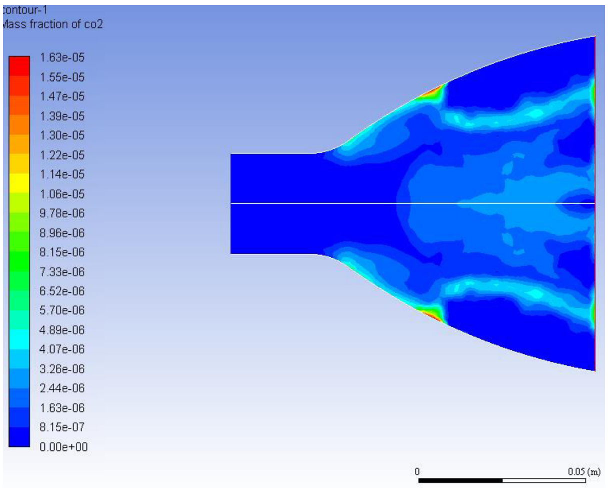

Fig 5.2.8 mass fraction of Co2

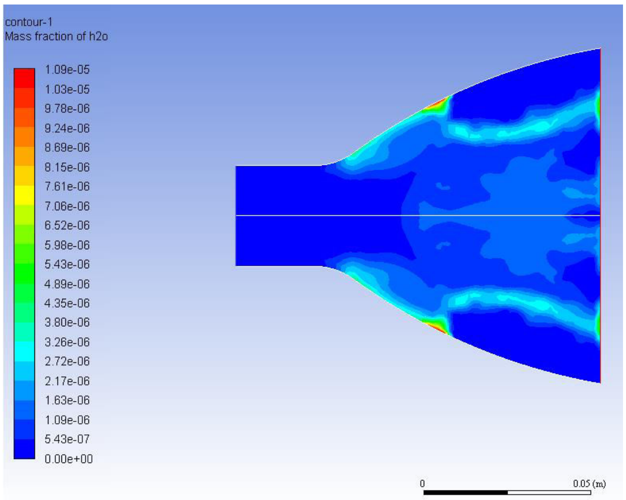

Fig 5.2.9 mass fraction of H2O

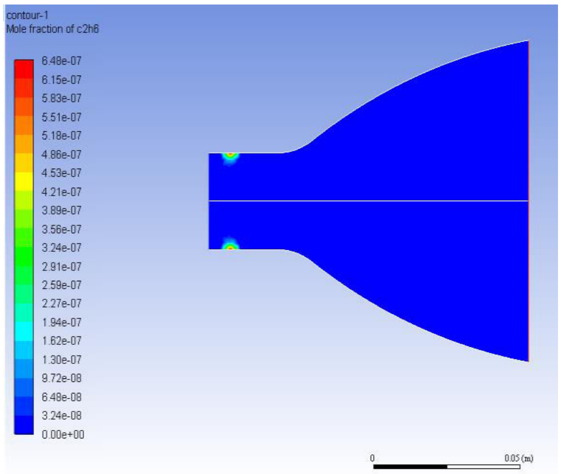

Fig 5.2.10 mole fraction of ethane + air

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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	Caster diesel	1.02e+03	1.15e+03	1.61e+03	5936.625	3.07e+05
	ethane	1.07e+09	4.25e+04	5.29e+04	19677.42	2.05e+23
	methane	1.11e+09	4.23e+04	4.83e+04	53761.23	2.04e+23
5	Caster diesel	1.05e+04	1.26e+04	2.2e+04	6589.325	4.32e+06
	ethane	2.01e+10	5.12e+05	5.65e+05	22166.21	3.10e+23
	methane	2.21e+10	5.53e+05	5.14e+05	59635.45	3.90e+23
8	Caster diesel	1.09e+05	1.93e+05	3.91e+05	6993.485	4.98e+07
	ethane	3.62e+11	6.2e+06	6.15e+06	28924.52	4.26e+23
	methane	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	Caster diesel	7.99e-06	2.43e-08	5.41e-07	3.29e-07
	ethane	1.04e-06	1.07e-06	1.63e-05	1.09e-05
	methane	3.02e-06	2.87e-06	1.25e-04	1.09e-04
5	Caster diesel	8.10e-05	2.31e-07	4.24e-06	3.21e-06
	ethane	1.90e-05	1.61e-05	1.36e-04	1.68e-06
	methane	2.91e-05	2.65e-05	1.65e-03	1.19e-03
8	Caster diesel	7.14e-04	2.69e-06	5.31e-05	4.68-05
	ethane	1.19e-04	1.02e-04	2.51e-03	1.26e-05
	methane	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
3	Caster diesel	9.10e-07	6.42e-09	2.61e-07	3.83e-07
	ethane	6.48e-07	8.12e-07	7.32e-06	1.19e-05
	methane	2.68e-06	1.70e-06	5.87e-05	1.27e-04
5	Caster diesel	9.92e-06	5.5e-08	3.97e-06	5.98e-06
	ethane	6.39e-06	7.28e-06	5.528e-05	2.27e-04
	methane	2.01e-05	2.58e-05	4.987e-04	2.36e-03
8	Caster diesel	8.95e-05	4.35e-07	4.59e-05	6.98e-05
	ethane	5.25e-05	6.98e-04	5.39e-04	6.85e-03
	methane	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	Caster diesel	1.35e-08	9.50e-11	3.87e-09	5.67e-09
	ethane	2.14e-08	3.04e-08	2.84e-07	4.64e-07
	methane	8.77e-08	6.22e-08	1.97e-06	4.25e-06
5	Caster diesel	1.39e-07	9.10e-10	3.42e-08	5.68e-08
	ethane	2.68e-07	2.57e-07	2.96e-06	4.58e-06
	methane	3.57e-07	6.87e-07	1.32e-05	5.32e-05

8	Caster diesel	1.97e-06	5.97e-09	3.82e-09	5.32e-07
	ethane	2.91e-06	3.84e-06	3.10e-05	6.45e-05
	methane	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 caster oil diesel , ethane+ air and methane +air 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 mass 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 methane +air fluid has more heat transfer rate and the maximum values are more for methane+air fluid.

So it can be concluded the methane + air fluid is better for fuel injector nozzle.

VIII. REFERENCES

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