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Computational evaluation of strut based scramjet engine combustion with different conventional fuel/oxidizer

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Abstract —
The high performance and instability in combustion chamber are the most challenging requirements for faster developments and technical advances in most of the engines. The design and development challenges of such engines are highly influenced by its combustion behavior taking place inside the combustion chamber. Studies on the injection, vaporization and combustion phenomena inside combustion chamber are a growing challenge and difficult entities in design and vigorously investigated by researchers. In this domain, the present research is formulated for analyzing the combustion performance of hydrogen/hydrocarbon and oxygen computationally in a strut based combustion chamber. This work leads way to identify the injection flow behavior and the hypersonic combustion nature of various fuels with comparison of different parameters. CFD simulations of the hydrogen/hydrocarbon fuelled strut based scramjet combustor are performed at Mach 2 airstream having typical Mach 10 flying conditions. The primary objective of this study is to numerically evaluate the combustor performance for varying fuels and its injection parameters .Mixing and reacting flow characteristics of the combustor are studied for the centrally located strut based scramjet combustor solving three dimensional RANS equations k-epsilon turbulence model using coupled implicit solver based on finite volume approach. Salient results of non-reacting and reacting flow simulations are presented. Performance parameter like mixing efficiency, total pressure recovery and hydrogen/hydrocarbon consumption are computed and compared for different cases. The computation is performed by using a CFD solver FLUENT and analyzed for LES model of four different fuels.

Keywords— **Hydrogen fuel, Hypersonic combustion, Combustion performance, Strut injector, Air breathing hypersonic vehicle**

I. INTRODUCTION

The success of an efficient design of a hypersonic air breathing cruise vehicle largely depends on the proper choice of propulsion system. This type of vehicle, according to current proposals, will use scramjet propulsion system. Both hydrogen and hydrocarbon fuels are considered depending on applications and speed range. Although, hydrogen has attractive features in terms of specific impulse, ignition characteristics, etc., liquid hydrocarbon fuel is preferred for volume limited applications in the lower hypersonic region (M<8). Starting from the pioneering work of significant advances is made in the design of scramjet engines. Over the last few decades, great emphases were placed on analytical, experimental and CFD techniques to understand the mixing and combustion processes in the scramjet combustors. In a recent review, Emerging hypersonic air breathing propulsion systems offer the potential to enable new classes of flight vehicles that allow rapid response at long range, more maneuverable flight, better survivability, and routine and assured access to space. Historically, rocket boosters have been used to propel hypersonic vehicles (i.e., those flying faster than 5 times the local speed of sound) for applications such as space launch, long-range ballistic flight, and air-defense interceptor missiles. Air breathing propulsion systems currently under development will provide a means for sustained and accelerating flight within the atmosphere at hypersonic speeds long-range cruise missiles for attack of time-sensitive targets, flexible high-altitude atmospheric interceptors, responsive hypersonic aircraft for global payload delivery, and reusable launch vehicles for efficient space access.

Using kerosene fuel and commercial CFD Behera and Chakraborty1 numerically studied the flow field of a ramp cavity based scramjet combustor. Their computational results had shown good agreement with experimental values, and the computed combustion efficiency was near unity, when the fuel equivalence ratio was small

The requirements of numerical simulation for modelling turbulent combusting flows and the problems associated with it were studied by Borgi et al. 2. The author observed that the reactive zones were very thin leads to problems in modelling of mean reaction rates. The authors found out that the temperature and concentration fluctuations influenced strongly the chemistry of combustion.

To assess the merits of kerosene and methane for future reusable booster stage was investigated by Burkhardt et al. 3. They used liquid oxygen as the oxidizer for both fuels. Initially they identified the thermodynamic and chemical properties of kerosene and methane. They found that methane fueled propulsive systems are disadvantageous, when cost was considered

Grueing and Mayinger 4 carried out an experimental investigation of supersonic combustion of liquid hydrocarbons. They burnt kerosene in air flow at Mach 2.5 in a modelled scramjet combustor. On comparing the results with hydrogen combustion they found that the kerosene combustion by a gas dynamic feedback mechanism strongly affected the supersonic combustion process.

Town end 5 reported about the best possible applications of scramjets in the current scenario. Citing several examples he proved the value of hydrocarbons for the initial stages of launcher acceleration and reduction of bulky tankage by selection of kerosene as the fuel. Through his findings the author came to a conclusion that the use of hydrocarbons.

II. CFD ANALYSIS

For the ideal thrust chamber, some of the parameters are directly dealt by design parameters such as combustor geometry, size, and injector element design and nozzle configuration. Here an attempt has been carried out to analyse the sizable parameters related to thrust chamber design through numerical modelling of thrust chamber performance encompassing a wide range of approaches of CFD. Hence, the results of the numerical analysis have been found out in two major domain of thrust chamber.

1) Injection system using strut injector,
2) Analysis of various fuels.

Thus the investigation of combustion and flow behaviour in a propulsion system's thrust chamber has been carried out with the help of numerical scheme using the governing equations as follows

The mass flow rate of an injector can be determined using the continuity equation:

$$\dot{m} = \rho U_1 A_1 = \rho U_2 A_2 \qquad (2.1)$$

and the Bernoulli equation:

$$p_{01} = p_1 + \frac{\rho U_1^2}{2} = p_2 + \frac{\rho U_2^2}{2} + \Delta p_{1-2} \qquad (2.2)$$

a) Equation of conservation of mass:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho \vec{v}) = 0 \qquad (2.3)$$

b) Equation of conservation of momentum

$$\frac{\partial(\rho\vec{v})}{\partial t} + \nabla.(\rho\vec{\upsilon}\vec{\upsilon}) = -\nabla p + \nabla.(\overline{\overline{\tau}}) + \rho g + \vec{F} \qquad (2.4)$$

where $\overline{\overline{\tau}} = \mu\left[\left(\nabla\vec{\upsilon} + \nabla\vec{\upsilon}^T\right) - \frac{2}{3}\nabla.\vec{\upsilon}I\right]$

c) Equation of conservation of energy:

$$\frac{\partial}{\partial t}(\rho E) + \nabla.\left(\vec{\upsilon}(\rho E + p)\right) = \nabla.\left[k_{eff}\nabla T - \sum_j h_j \vec{J}_j + (\vec{\upsilon}.\overline{\overline{\tau_{eff}}})\right] + Q \qquad (2.5)$$

d) Equation of state:

$$p = \rho RT \qquad (2.6)$$

For numerical modelling of multiphase flows existing in the flow field, the above equations are slightly modified to adjust the effect of the liquid-vapour mixture.

3. Material and Design

a. Length of strut - 0.39m.
b. Radius of injector - 0.005m.
c. Breadth - 0.01m.
d. Wedge angle - 10^0.

The above mentioned data's are the geometric dimensions of channel that is taken for analysis. It is designed using AutoCAD or Gambit in a 2 dimensional aspect. The purpose of these studies was to determine the hypersonic combustion analyses of various fuels are analyzed. This strut is placed along the flow distribution with the blunt leading edge

A. Computational Modelling

The computational domain is created with proper dimensions. The dimension of the channel is .039 x 0.1m with the half wedge angle is 100 and the radius of the injector is 0.005m. This 2-D model is designed by using the GAMBIT software. Before design the proper dimension should be selected and after the design is to be meshed.

B. Meshing of Model

The grid was generated by using the gambit software and size of the meshed file is 0.1 spacing between the grid points. In the figure shown below rectangular obstacle were used. Similarly for others the grid was generated.

The above mentioned data's are the geometric dimensions of channel that is taken for analysis. It is designed using AutoCAD or Gambit in a 2 dimensional aspect. The purpose of these studies was to determine the supersonic combustion using this strut based centrally located injector. Even the hypersonic combustion analysis of various fuels is analyzed. This strut is placed along the flow distribution with the blunt leading edge

C. Boundary Conditions

The flow domain has been formed inside the combustion channel. The dimension of combustion channel has been taken as 1600mm × 38mm. The fuel Injection having diameter 10mm, located at the leading edge of the combustion channel has been made for computation. The following boundary condition has been assigned. For modelling purpose oxygen velocity inlet boundary condition has been assigned for the inlet domain and pressure outlet condition has been assigned to the outlet domain. Other boundary condition includes the default hard interior of the wall created using Gambit. The boundary conditions are given in the table 4.1 for the inlet and outlet.

III. RESULTS AND DISCUSSIONS

A comparative histogram showing exit velocities of scramjet combustor for various fuels are shown fig 6.6e. In that plot kerosene found to be most efficient, the next lays ethanol, then methanol. Hydrogen is pollution free fuel but not suitable for air breathing engines at hypersonic velocities. The plots clearly show that kerosene is best efficient fuel for our combustor model. The exit velocity found to increase with respect to time in fig .13

From the plot, the next efficient fuel is ethanol, having 6 hydrogen bonds. Based the number of hydrogen bond, the performance is rated. The numerical investigation also shows a similar result. Methanol having 4 hydrogen bonds showing results lesser than ethanol. Hydrogen stands last in the analysis. The performance results of analysis shows a very lower velocity magnitude for hydrogen fuel.

IV. CONCLUSION

Designs for hypersonic engines have been around since the early 1900's. Ramjet technology has been developing over the past eight decades and, except for marginal improvements, has been shown to be suited for atmospheric flight speeds up to Mach 5. The desire for faster, more efficient engines gave birth to the idea of a scramjet, utilizing supersonic combustion and potentially expanding the speed envelope to the Mach 15 range. The promise of covering the entire planet at high speed from horizontal takeoff for both civil and military aircraft is an attractive prospect. However, along with new technology and discoveries also come new obstacles to be addressed.

In order to study the establishment of the major flow features in a generic scramjet combustor several numerical simulations were carried out. A question still prevails in efficient fuel for hypersonic regions. We considered 4 fuels for our analysis (Hydrogen, kerosene, ethanol & methanol).

On comparing performance of all the fuels, we concluded that kerosene has higher ejection velocity. The reason is number of hydrogen bonds. Breaking up of hydrogen bonds releases heat energy, since kerosene has several hydrogen bonds ($C_{12}H_{23}$) the energy released is much higher than other fuel under specified operating conditions.

In this project seeing all these analysis and numerical simulations we conclude that air breathing engine (scramjet engine) found to show better result using kerosene fuel at 8.8 Mach and 21500 Pascal when fuel injected by strut. The ejection velocity finally we got near 4400m/s, which comes around 13 Mach. This shows combustor is performing in Hyper-sonic regimes

V. FUTURE SCOPE OF WORK

The work done gives a satisfactory result with present combustor model and for more concise dealing we can change some design parameters. The future scopes in this work are:

The problem we solved is 2D and single plane mixing is analyzed. In future we can extend to 3D, and double plane mixing is possible. We can predict the flow at each nook and corner of combustor.

We analyzed for a fuel velocity of 660m/s. In future we shall do it by changing velocities of fuel and air flow. It may give a better understanding of fuel performance at various ranges.

New type of injector other than strut such as aerodynamic, ramp based or cantilever shall be employed to see results.

We defined our fuel temperature at injector. In alternate we can specify the interior and exterior wall temperature of the combustor.

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11. Table and Figure

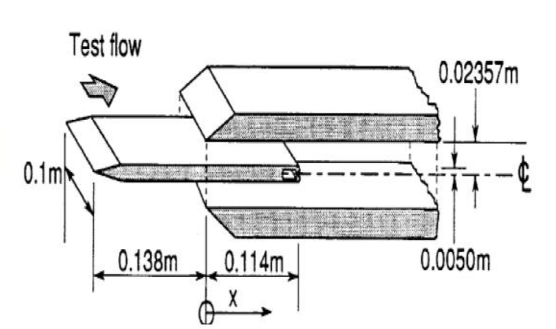

Fig.1 A generic scramjet combustor with centrally located Fuel injector strut. (From NASA Contractor Report 187467)

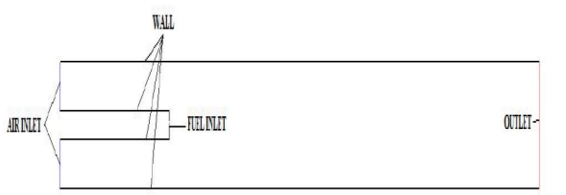

Fig.3 Combustor boundary conditions

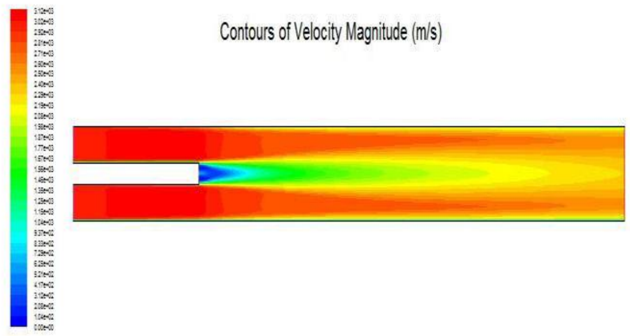

Fig.4 Contours of Velocity Magnitude after Combustion

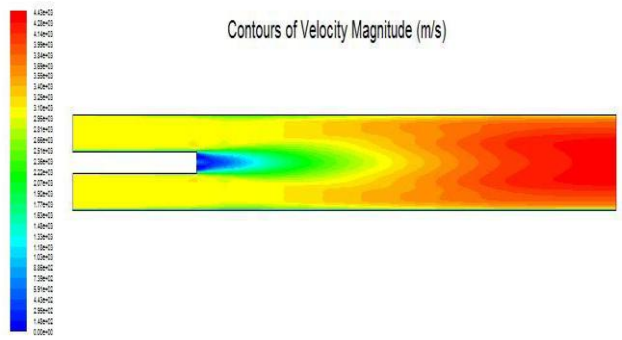

Fig.5 Contours of Velocity Magnitude after Combustion

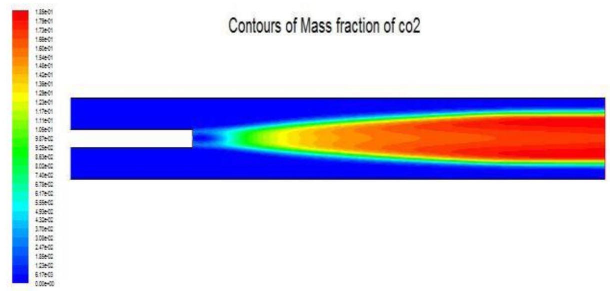

Fig.6 Contours of Mass Fraction of co_2

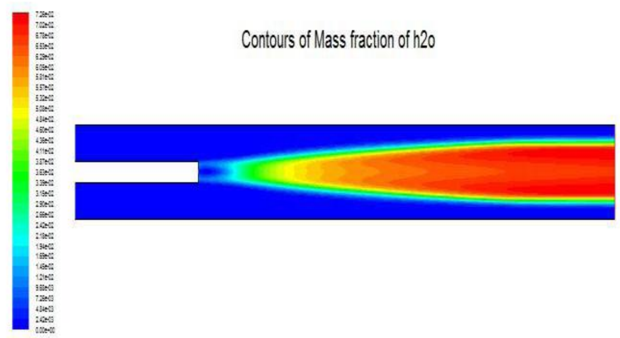

Fig.7 Contours of Mass Fraction of H_2o

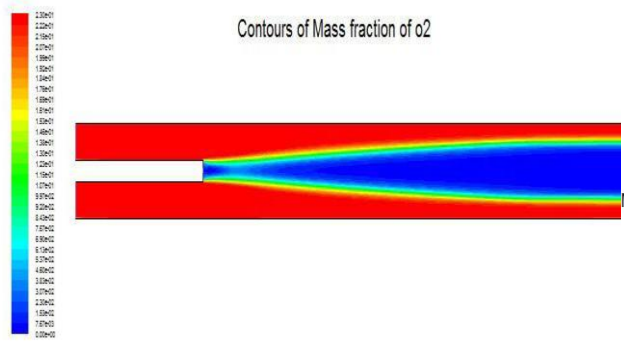

Fig.8 Contours of Mass Fraction of O2

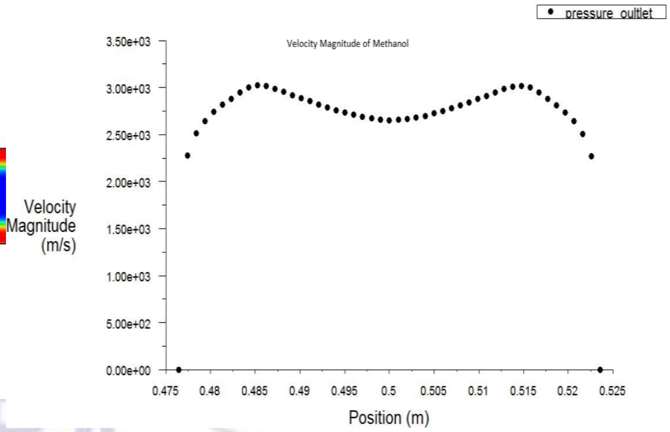

Fig. 12 Plot of Velocity Magnitude of Methanol

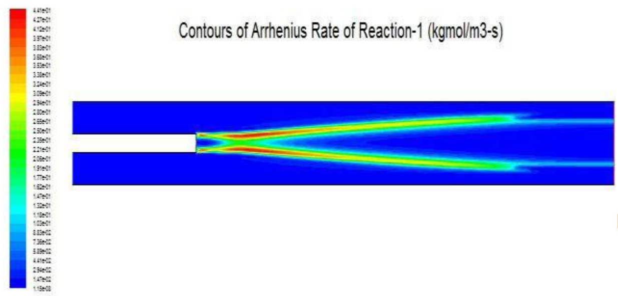

Fig.9 contour of Arrhenius rate of reaction

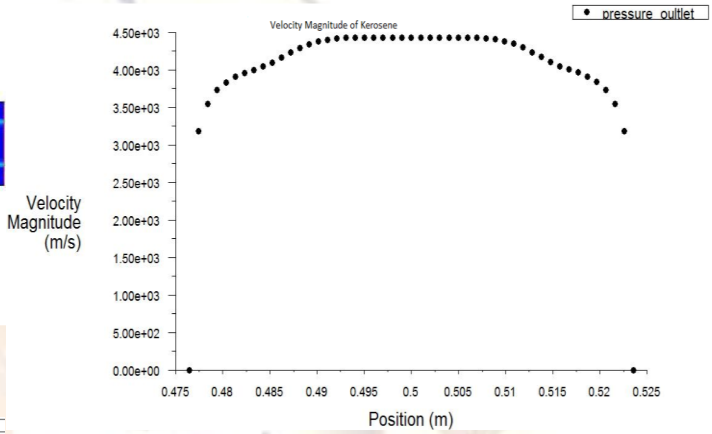

Fig.13 Plot of Velocity Magnitude of Kerosene

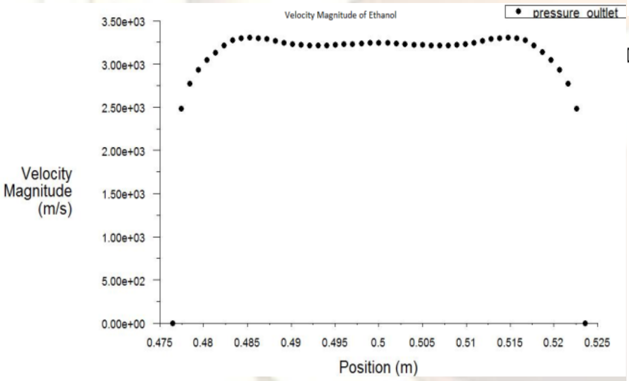

Fig.10 Plot of Velocity Magnitude of Ethanol

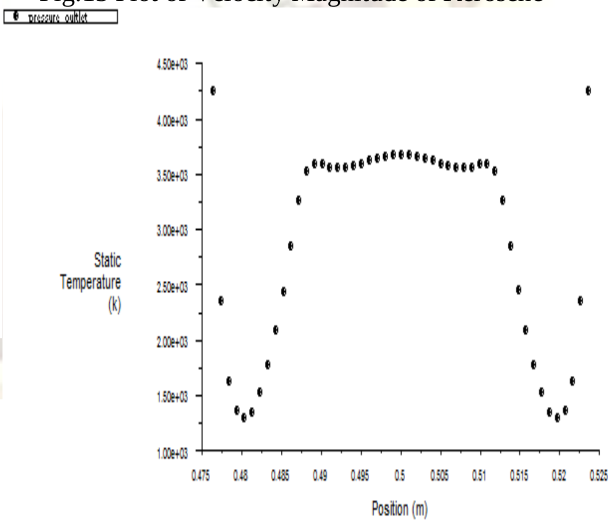

Fig. 14 Static temperature of kerosene as fuel

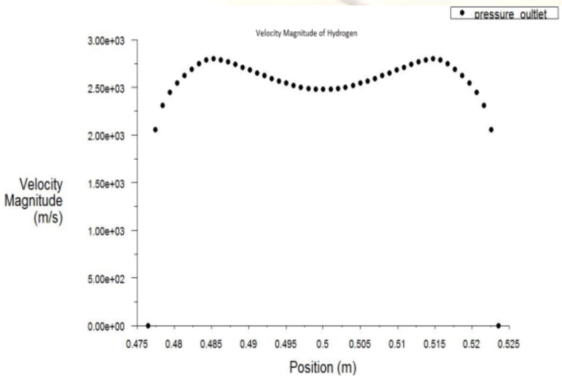

Fig. 11 Plot of Velocity Magnitude of Hydrogen

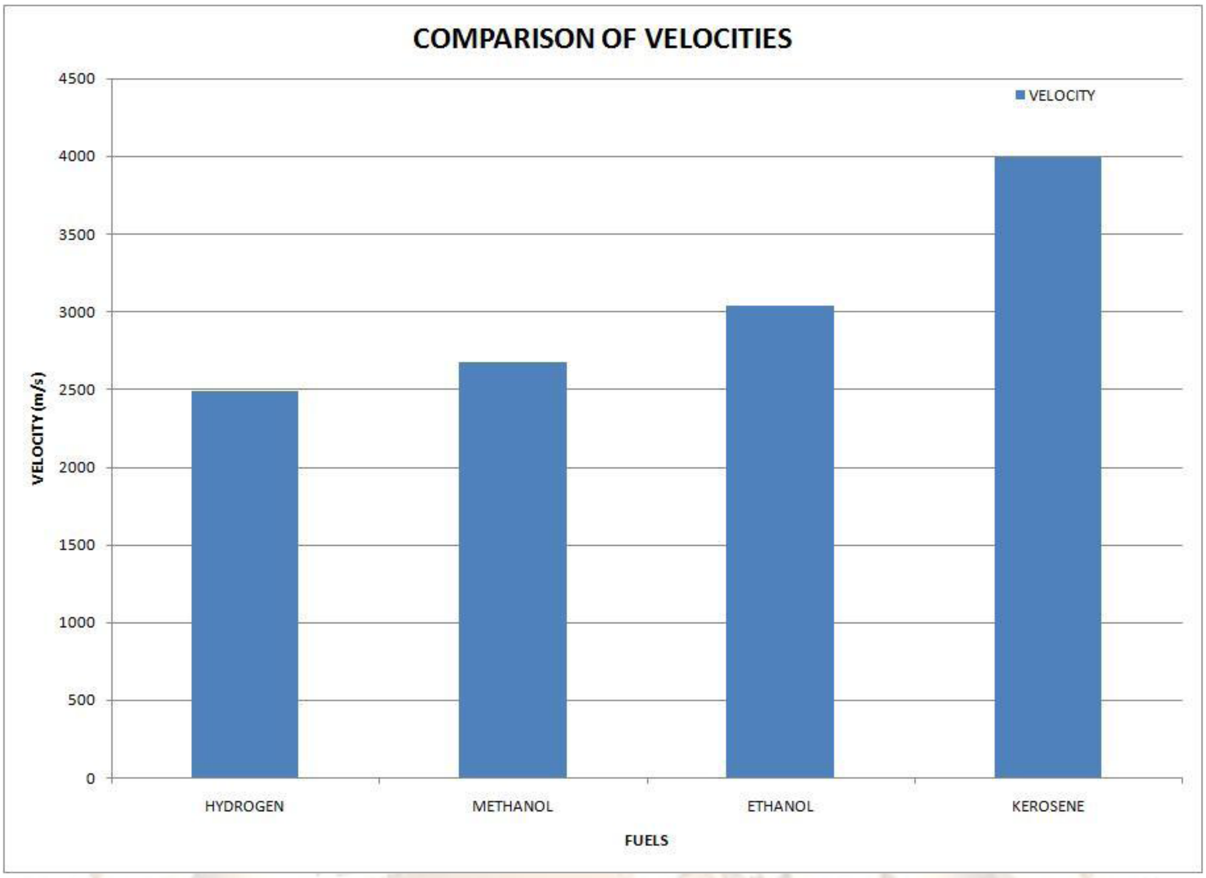

Fig. 15 Histogram comparing velocity of all fuel