MIXING OF LIQUID KEROSENE IN A SUPERSONIC CROSSFLOW FOR A SCRAMJET ENGINE

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Abstract - *Even after decades of development, aircrafts still travel at subsonic speeds. This can be changed by using supersonic vechiles with air breathing engines in this case the scramjet engine. Many difficulties are encountered while designing highly efficient combustion systems. Fuel penetration and mixing of fuel are considered as primary parameters. Basic parameters for effective mixing of fuel in scramjet engine are Height of penetration and Plume spread area. Since height of penetration and plume spread area are proportional to momentum flux ratios this is considered as prime parameter to work on. Injection pressures which is a direct function of momentum flux ratio are varied. For different injection pressure regimes are set-up and the consequence of varying J-ratios for individual injectors are evaluated. The varying J-ratio accounted for the variation in penetration and mixing are qualitatively studied. Using MIE scattering flow visualisation technique images are captured at various distances in order to gather more information about the penetration. These images are processed using MATLAB using which the area of plume and height of penetration with respect to different momentum flux ratios were calculated.*

Key Words**: Supersonic crossflow, Scramjet engines, Mixing of fuels, Fuel penetration, Plume spread area**

1.INTRODUCTION

Aviation and space industries have developed a lot in the last 100 years, but still the fastest planes travel at subsonic speeds while rockets reach escape velocities and deploy satellites into orbit. This massive difference in speed can be brought down by the use of supersonic vehicles powered by air breathing jet engines.

There are many difficulties encountered while designing highly efficient combustion systems with wide operability. Injector design, injector placement, mixing features and flame holding are the properties that are important for any robust combustion system designed to operate over very short residence times.

The effective fuel injection is one of the main problems as the fuel has very short combustor residence times, compressibility effects cause poor mixing and reaction must occur almost Instantaneously.

There are inherent losses in the supersonic incoming airstream. Additional losses due to fuel injection, mixing and combustion, shock wave loses, pressure and friction drag, shear layer mixing losses and loss of momentum of fuel jets should be kept minimum whilst the complete fuel-air mixing and fuel chemical release must be achieved maximum.

Research studies for designing an optimal injector that fulfils all above requirements for air breathing propulsion systems for hypersonic or supersonic flight is yet to be developed. Many injector concepts are developed and tested for different high speed propulsion systems.

Absence of an optimal injector design and lack of reliable analytical tools are the massive challenges for the development of high-speed propulsion systems.

1.1 AIR BREATHING RAMJET AND SCRAMJET ENGINES

Ramjet engines does not have any big moving parts. Instead the forward motion of the engine is used to compress the air.

The ramjet engine consists of three regions:

- Diffuser
- Nozzle
- Combustion chamber

The flow gets decelerated to subsonic level in the diffuser and the combustion happens in the chamber. Then the flow is acclerated to supersonic level using a divergent nozzle. The only difference between ramjet and scramjet engines is that in the latter the flow is not declerated to subsonic levels in the diffuser.

2. SCRAMJET FUEL INJECTORS

The location of the heat release should be managed relative to the appropriate flow area within the combustor for accelerating the vehicle. Peak pressure too forward can change the inlet conditions whereas peak pressure too backwards decreases the combustor inlet pressure.

Operating the engine at a high equivalence ratio, change in fuel phase as the engine structure heats after ignition and change in fuel composition with variation in the thermal load of the engine structure are the other challenges faced during fuel injection.

Scramjet engines cruise and accelerate at a high equivalence ratio which requires injectors with adequate penetration and rapid dispersion within the high speed crossflow.

3. SCOPE OF THE EXPERIMENT

Two basic parameters for the effective mixing of fuel in scramjet engine are

- Height of penetration
- Plume spread area

Penetration height and plume spread area are proportional to the momentum flux ratio therefore this parameter of fuel jet was the prime consideration to work on. Injection pressures in supersonic crossflow experiments are varied, which is a function of momentum flux ratio.

For different injection pressures (4,8,12,16 bars) regimes are set-up and the consequence of varying J-ratios for individual injectors are evaluated. The varying J-ratio accounted for the variation in penetration and mixing are qualitatively studied.

To gather more information of the penetration, a flow visualisation technique had to be used. MIE scattering flow visualisation technique is used as it is easy to operate, accurate and requires short experiment time.

Images are also captured at different positions at a relative distance to the MIE setup. These images will be qualitatively analysed to evaluate jet penetration and spread for the various J-ratios.

4. CALCULATION OF MOMENTUM FLUX RATIO

The experiment is carried out at different J-ratios

$$J=\rho_{fuel}u^2_{fuel}/\rho_{air}u^2_{air}$$

Density of the fuel ρfuel – 800 Kg/m3

- $u_{fuel} = (2(p_L - p_s)/ \rho_{fuel})0.5$

  $P_0/Ps = [1+(-1)/2*M^2]^{/ -1}$

  $2.89/0.408= [1+(1.4-1)/2 *M^2]^{1.4/(1.4-1)}$

- **M= 1.93**

  $To/Ts=1+(-1)/2*M^2$
  $300/Ts = 1 +(1.4-1)/2 * 1.93^2$

  Ts = 171.92K

- $\rho_{air} =P_s/ Rts$

  ρ_{air} = 0.408/(287*171.92) =**0.826 Kg/m3**

- $u_{air} = M(RTs)0.5$
  u_{air} = 1.93(1.4*287*171.92)0.5

  u_{air} = 503.86 m/s

Fuel injection Pressure – P1 (bar)	Momentum flux ratio (J)
4.239	3.7
8.2867	7.7
12.216	11.6
16.25	15.3

By varying the injection pressures we can vary the momentum flux ratios. For the following pressures the above tabulated J ratio values were found.

5. EXPERIMENTAL SETUP

The experimental setup developed by the national aerospace laboratory, propulsion division, Bangalore was used for this experiment.

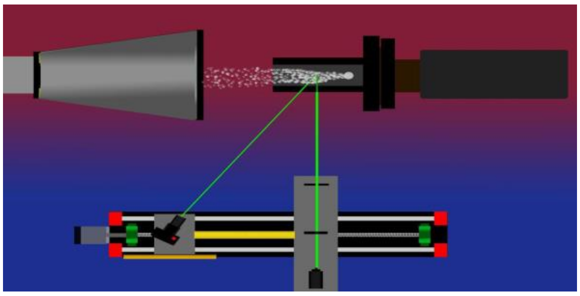


Fig- 1 : Experimental Layout

The setup consists of a settling chamber, rectangular air supply chamber, test section containing an injector under investigation and two windows for optical access to the spray. Air is supplied to the test section from the main compressor line along the settling chamber.

There is an opening at the front end of the test section to provide airflow to the exhaust of the air and fuel mixture. The chamber has a flanged mouth air intake. One end of the flange is fitted to the settling and the other end is attached to the test section. Two metal plates with windows are bolted orthogonally to the air flow at this end of the channel creating a test section.

Two quartz windows 1/8 inches thick are fixed in the slots of the metal plates using rubber gaskets. A stand over the test section is provided to mount heater to avoid condensation of moisture around the windows.A fuel injector is located on the centreline of the horizontal plate.The entire assembly is installed on a fixed metal pillar which supports the assembly at different positions in such a way that all are parallel to the ground.The design of the test section provides full confinement of air flow in the spray region.

The two windows of the test section are parallel to each other to provide optical access for the light source and camera to distinguish the spraying from both sides. This allowed for the capturing of flow images at different planes along the test section window.Mie scattering visualisation technique was adopted in this testing, which consists of a laser light source ,cylindrical lens and a spherical lens all mounted in the same order to form a sheet of laser which is incident onto the section window. It provides precise movement on the optical bench in a direction similar to air flow using step motors and electronic drivers.

Fig- 2 : Experimental Setup

6. WORKING

After installation of the apparatus on the optical bench, the laser light source is turned on and the laser sheet is formed as a consequence of laser light passing through a cylindrical lens followed by a spherical lens made incident on the test section. The sheet is perpendicular to the flow inside the wind tunnel, illuminating the plane at the injection point.

This position in the traversing apparatus is marked as zero point.This is followed by turning on the power supply to the traverse apparatus. The flow control valve in the supply line of the wind tunnel is opened. The total gauge pressure is ideally maintained at 2 bar for the experiment.

The fuel supply switch is turned on and the injection pressure is set to 4 bar for the first case of the experiment. Constant injection pressure is monitored from the control room and on achieving the same, three to four pictures are captured by the camera focusing on the regime.

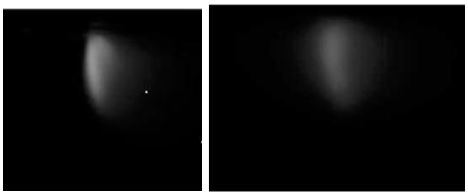
On pressing the forward button in the traverse control, the channel moves to the next step resulting in a laser sheet focussing on the second regime in the test section. Again at this position pictures are captured by the camera.

This is done for three more steps, i.e., up to five regimes along the flow. Upon completing the above steps and on pressing the forward switch again, the traverse moves backwards, positioning the channel back to zero position. Now, the injection pressures are changed to 8, 12 and 16bar as different cases and the same procedure is carried out for capturing the flow images.

7. IMAGE PROCESSING

Images are captured at five different downstream distances from injector position and at different momentum flux ratios which are a function of injection pressure and processed in MATLAB. MIE scattering technique is used for the visualisation of the fuel-air mixture in the test section for image processing.

Large number of fuel molecules are present near the initial position of the laser producing higher intensity image whilst 40mm from the injector position the molecules are distributed all over the session producing lower injection image which is shown below.



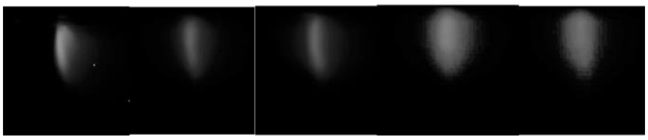
At x=0, j=3.3 **At x=40mm, j=3.3**

The above images are taken at initial and final positions for momentum flux ratio j=3.3.

Minimum and maximum intensity values are obtained from the processed image which is provided as the inputs to find the fuel penetration and fuel dispersion.

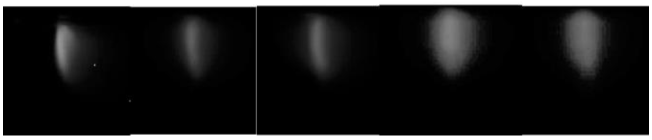
Images are captured for four momentum flux ratios at five different downstream positions for each momentum flux ratios.

At Injection pressure p_{inj}=4.3 bar , Momentum flux ratio j=3.7



X=0mm X=10mm X=20mm X=30mm X=40mm

At injection pressure p_{inj}= 8.3 bar, momentum flux ratio j=7.7

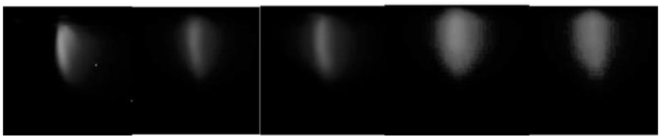


X=0mm X=10mm X=20mm X=30mm X=40mm

At injection pressure P_{inj} = 12bar, momentum flux ratio j=11.6

X=0mm X=10mm X=20mm X=30mm X=40mm

At injection pressure P_{inj} =16.2 bar, momentum flux ratio j=15.3



X=0mm X=10mm X=20mm X=30mm X=40mm

8. PLUME SPREAD AREA

For every fuel injection image at different positions capturing them at various fuel injection pressures, the area of the plume will vary accordingly. The area of the plume is calculated using MATLAB and it is given in the form of pixels. We have taken a reference area of known dimension and the number of pixels of that reference area are found and divided, which gives the no. of pixels per mm^2.

1mm^2 of area = 3672 pixels

For J=3.7 - Initial position

The area calculated = 3.885862e+04 pixels
1 mm^2 = 3672 pixels

Area of the plume = 3.885862e+04 / 3672 = 10.5825mm^2

8.1 AREA OF PLUME AT VARIOUS POSITIONS ACCORDING TO MOMENTUM FLUX RATIOS

For momentum flux ratio J=3.7

Position	1	2	3	4	5
Area of plume (mm^2)	10.5825	38.9869	49.91	72.25	85.4085

For momentum flux ratio J=7.7

Position	1	2	3	4	5
Area of plume (mm^2)	18.2498	51.43	76.55	80.25	113.3

For momentum flux ratio J=11.6

Position	1	2	3	4	5
Area of plume (mm^2)	18.616	66.69	81.31	107.184	124.87

For momentum flux ratio J=15.3

Position	1	2	3	4	5
Area of plume (mm^2)	18.78	73.1	95.25	123.66	127.04

8.2 HEIGHT OF PENETRATIONS AT VARIOUS POSITIONS ACCORDING TO MOMENTUM FLUX RATIOS

For momentum flux ratio J=3.7

Position	1	2	3	4	5
Height of penetration (mm)	5	8.80	9.75	11.50	12.413

For momentum flux ratio J=7.7

Position	1	2	3	4	5
Height of penetration (mm)	6.38	12	12.061	13.53	15.040

For momentum flux ratio J=11.6

Position	1	2	3	4	5
Height of penetration (mm)	7.73	14.57	14.69	16.30	17.05

For momentum flux ratio J=15.3

Position	1	2	3	4	5
Height of penetration (mm)	9.43	16.34	17.52	19.33	19.78

9. ANALYSIS

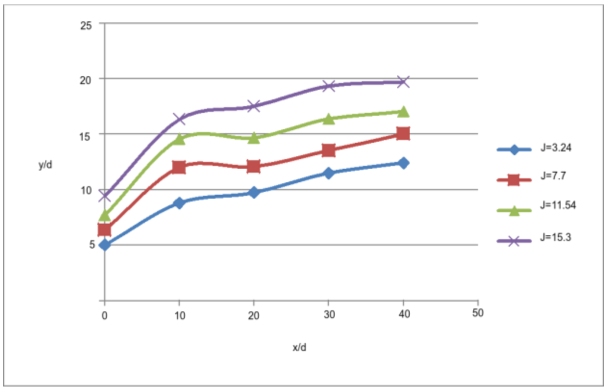


Fig-3: Downstream distance Vs Fuel penetration

The x/d vs. y/d graph for different momentum flux ratios (J ratios) is plotted. It can be concluded that, as the J ratio increases, the penetration increases

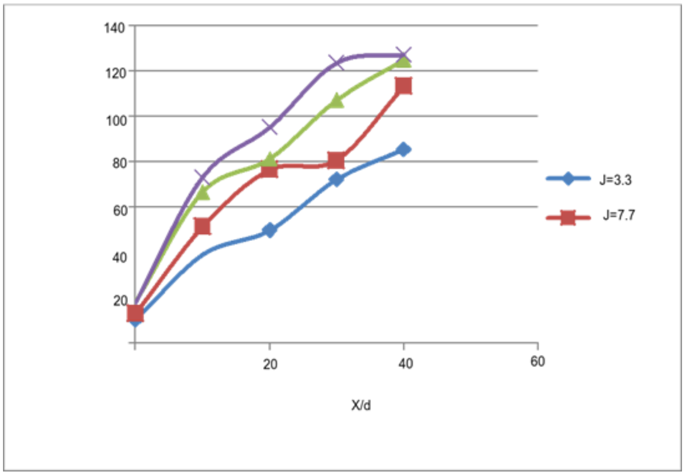


Fig-4: Downstream distance Vs Fuel dispersion

The x/d vs. A/d² graph is plotted for different J ratios. As the J ratio keeps increasing, the "Area of Penetration" (A) keeps increasing. This is analysed at different positions, starting at the injector position. The diameter of the orifice is given as (d).

It was observed that as the momentum flux ratio increased, the spread of the fuel increased. The trend remained the same along the downstream, i.e., the spread increased. It was observed that increase in spread with increase in J ratio is not significant at the injection point.

The experimentally measured penetration values were compared with theoretical values obtained using empirical formulae to check for the validity of the experiment. Empirical formulas for finding penetration is

$$y/d_e = 3.8*(x/d_e)^{0.25}*J^{0.4}$$

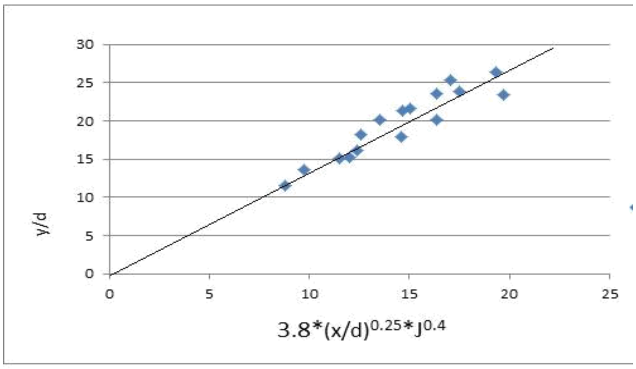


Fig-5: Theoretical Vs Experimental Penetration Values

10. CONCLUSIONS

For effective combustion of fuel in a scramjet application, it is important to consider the parameters like mixing of fuel. A comprehensive series of experiments for kerosene injected into supersonic cross flow at M = 2 were carried out.

The following conclusions were made from the series of experiments carried out in the investigation.

- Jet penetration and fuel spread into the crossflow was found to be proportional to momentum flux ratio of the fuel jet to crossing air in the investigated range between momentum flux ratio j=4 and j=16 due to self-explained dependence of penetration on jet velocity.
- Penetration of fuel increases with increase in momentum flux ratio was found to be significant at locations closer to the injection.
- Fuel spread increases with increase in momentum flux ratio along the downstream distance linearly.

The experimental penetration values and the theoretical penetration values are found to increase linearly along the downstream distances.

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REFERENCES

- E. Lubarsky, D. Shcherbik, O. Bibik, Y. Gopala and B. T. Zinn “Fuel Jet in Cross Flow - Experimental Study of Spray Characteristics,” School of Aerospace Engineering, Georgia Institute of Technology.
- Chung-Jen Tam, Susan Cox-Stouffer, Kuo-Cheng Lin, Mark Gruber, and Thomas Jackson. "Gaseous and Liquid Injection into High-speed Crossflows", 43rd AIAA Aerospace Sciences Meeting and Exhibit, Aerospace Sciences Meetings.
- Yates, C. L “Liquid Injection Into a Supersonic Stream” AFAPL-TR-71-97, Vol 1, 1972 [14] Raymond Fuller, Pei-Kuan Wu, Kevin Kirkendall, Abdollah Nejad, Raymond Fuller, PeiKuan Wu, Kevin Kirkendall, and Abdollah Nejad. "Effects of Injection Angle on the Breakup Processes of Liquid jets in Subsonic Crossflows", 33rd Joint Propulsion Conference and Exhibit, Joint Propulsion Conferences
- Rogers, C. R., Capriotti, D. P., and Guy, W. R., “Experimental Supersonic Combustion Research at NASA Langley,” AIAA Paper 1998-2506, 1998.
- Raymond P. Fuller,* Pei-Kuan Wu,f and Kevin A. Kirkendallt Taitech,Inc., Dayton, Ohio 45431 and Abdollah S. Nejad “Effects of InjectionAngle on the Breakup Processes of Liquid Jets in Subsonic Crossflows” Wright Laboratory, Wright-Patterson Air Force Base, Ohio 45433.
- K.M.Pandey, Member IACSIT and T.Sivasakthivel” Recent Advances in Scramjet Fuel Injection” International Journal of Chemical Engineering and Applications, Vol. 1, No. 4, December 2010 ISSN: 2010-0221.
- Lin, K-C., Kennedy, P.J., and Jackson, T.A., “Structures of Water Jet in Mach 1.94 Supersonic Cross flow”, AIAA Paper 2004-0971,2004.
- S.M.Yaya “Fundamentals of compressible flow for aircraft and rocket propulsion” sixth edition, published by New Age Science.
- P.K.Nag “Engineering Thermodynamics”, sixth edition, McGraw Hill Publications.