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Design and Analysis of a Fuel Injector of a Liquid Rocket Engine

M. Thirupathi, N. Madhavi, K. Simhachalam Naidu

ABSTRACT- the performance and stability of liquid rocket engines is determined to a large degree by atomization, mixing and combustion process. Control over these processes is exerted through the design of the injector. Injectors in Liquid Rocket Engines (LREs) are called upon to perform many functions. They must first of all mix the propellants to provide suitable performance in the shortest possible length. Suitable atomization and mixing must be followed, so that the size and weight of pressure vessels can be minimized. The injector implementation in Liquid Rockets determines the percentage of the theoretical performance of the nozzle that can be achieved. A poor injector performance causes unburnt propellant to leave the engine, giving unpleasant and poor efficiency. Injectors can be as simple as a number of small diameter holes arranged in carefully constructed patterns through which the fuel and oxidiser travel. The speed of the flow is determined by the square root of the pressure drop across the injectors, the shape of the hole and other details such as the density of the propellant. The performance of an injector can be improved by either using a superior propellant combustion, increasing the mass flow rate or by reducing the size & increasing the number of orifices on the injector plate. In the current project, the last method is applied. The first two methods are not applied due to exceptionally high cost of superior propellants & because the feed system is pressure feed and not pump feed.

I. INTRODUCTION

A. ROCKET ENGINES

A Rocket engine or simply “Rocket” stored propellant mass for forming its high speed propulsive jet. Rocket engines are reaction engines and obtain thrust in accordance with Newton’s third law, since they need no external material to form their jet, rocket engine can be used for space craft propulsion as well as terrestrial uses, such as missiles. Most rocket engines are internal combustion engines, although non-combustion forms also exists Rocket engines as a group have the highest exhaust velocities, are by far the lightest, but are the least propellant efficient (have the lowest specific impulse) of all types of jet engines.

These rocket engines are classified into;

- Chemical rockets are rockets powered by exothermic chemical reactions of the propellant.
- Rocket motor (or solid-propellant rocket motor) is a synonymous term with rocket engine that usually refers to solid rocket engines.

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- Liquid rockets (or liquid-propellant rocket engine) use one or more liquid propellants that are held in tanks prior to burning.
- Hybrid rockets have a solid propellant in the combustion chamber and a second liquid or gas oxidiser or propellant is added to permit it to burn.
- Thermal rockets are rockets where the propellant is inert, but is heated by a power source such as solar or nuclear power or beamed energy.
- Monopropellant rockets are rockets that use only one propellant,

Decomposed by a catalyst. The most common monopropellants are hydrazine and hydrogen peroxide.

The solid motor is used mainly as a booster for launch vehicles. Solid motors are almost never used in space because they are not controllable. The boosters are lit and then they fire until all the propellant has burned. Their main benefits are simplicity, a shell life which can extend to years as in the case of missiles and high reliability

B. LIQUID ROCKET ENGINE

The idea of liquid rocket as understood in the modern context first appears in the book The Exploration of Cosmic Space by Means of Reaction Devices, by the Russian schoolteacher Konstantin Tsiolkovsky. This seminal treatise on astronautics was published in 1903, but was not distributed outside of Russia until years later, and Russian scientists paid little attention to it. During the 19th century, the only known developer of liquid propellant rocket engine experiments was Peruvian scientist Pedro Paulet, who is considered one of the "fathers of aeronautics." However, he did not publish his work. In 1927 he wrote a letter to a newspaper in Lima, claiming he had experimented with a liquid rocket engine while he was a student in Paris three decades earlier. Historians of early rocketry experiments, among them Max Valier and Willy Ley, have given differing amounts of credence to Paulet's report. Paulet described laboratory tests of, but did not claim to have launched a liquid rocket. The first flight of a liquid-propellant rocket took place on March 16, 1926 at Auburn, Massachusetts, when American professor Dr. Robert H. Goddard launched a vehicle using liquid oxygen and gasoline as propellants. The rocket, which was dubbed "Nell", rose just 41 feet during a 2.5-second flight that ended in a cabbage field, but it was an important demonstration that liquid-fuelled rockets were possible. Goddard proposed liquid propellants about fifteen years earlier and began to seriously experiment with them in 1921. After Goddard's success, German engineers and scientists became enthralled with liquid fuel rockets and designed and built rockets, testing them in the early 1930s in a field near Berlin. This amateur rocket group, the VfR, included.

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Wernher von Braun who became the head of the army research station that secretly built the V-2 rocket weapon for the Nazis. The German-Romanian Hermann Oberth published a book in 1922 suggesting the use of liquid propellants. After World War II the American government and military finally seriously considered liquid-propellant rockets as weapons and began to fund work on them. The Soviet Union did likewise and thus begin the Space Race. A liquid-propellant rocket or a liquid rocket is a rocket engine that uses propellants in liquid form. Liquids are desirable because their reasonably high density allows the volume of the propellant tanks to be relatively low, and it is possible to use lightweight centrifugal turbo pumps to pump the propellant from the tanks into the combustion chamber, which means that the propellants can be kept under low pressure. This permits the use of low-mass propellant tanks, resulting in a high mass ratio for the rocket. Liquid rockets have been built as monopropellant rockets using a single type of propellant, bipropellant rockets using two types of propellant, or more exotic tripropellant rockets using three types of propellant. Bipropellant liquid rockets generally use a liquid fuel and a liquid oxidizer, such as liquid hydrogen or a hydrocarbon fuel such as RP-1, and liquid oxygen. The engine may be a cryogenic rocket engine, where the fuel and oxidizer, such as hydrogen and oxygen, are gases which have been liquefied at very low temperatures.

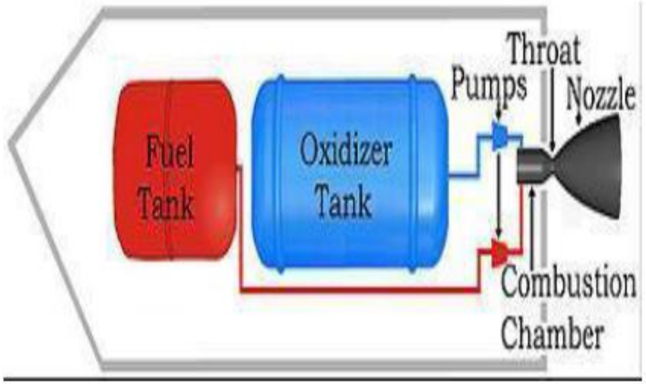

Fig: Schematic diagram of a rocket engine

C. INJECTORS

The injector implementation in liquid rockets determines the percentage of the theoretical performance of the nozzle that can be achieved. A poor injector performance causes unborn propellant to leave the engine, giving extremely poor efficiency. Additionally, injectors are also usually key in reducing thermal loads on the nozzle; by increasing the proportion of fuel around the edge of the chamber, this gives much lower temperatures on the walls of the nozzle.

II. LITERATURE SURVEY

Injectors can be as simple as a number of small diameter holes arranged in carefully constructed patterns through which the fuel and oxidiser travel. The speed of the flow is determined by the square root of the pressure drop across the injectors, the shape of the hole and other details such as the density of the propellant. Injectors today classically consist of a number of small holes which aim jets of fuel and oxidiser so that they collide at a point in space a short distance away from the injector plate. This helps to break the flow up into small droplets that burn more easily.

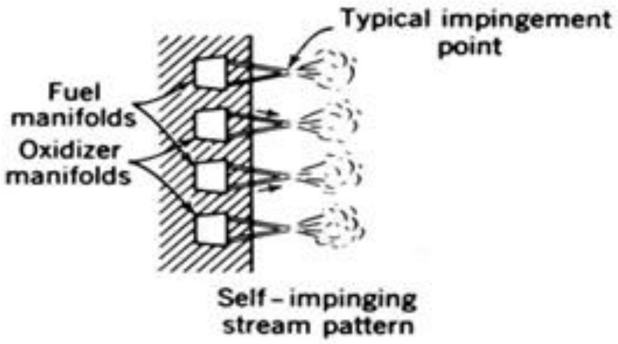

Fig 2: Self-Impinging Doublet Type

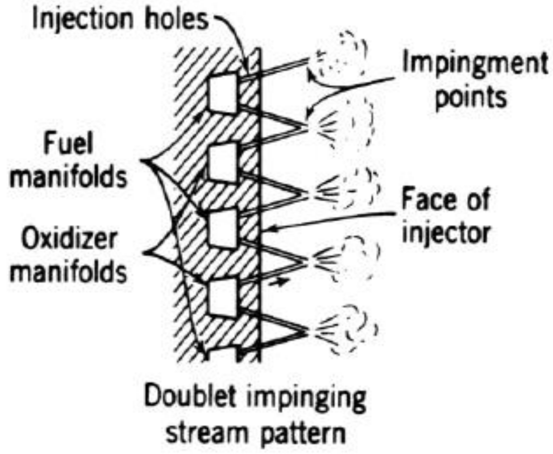

Fig: Cross Impinging Doublet Type

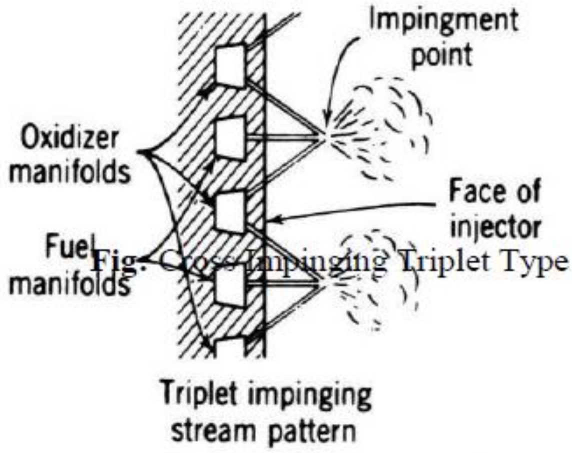

Fig: Cross Impinging Triplet Type

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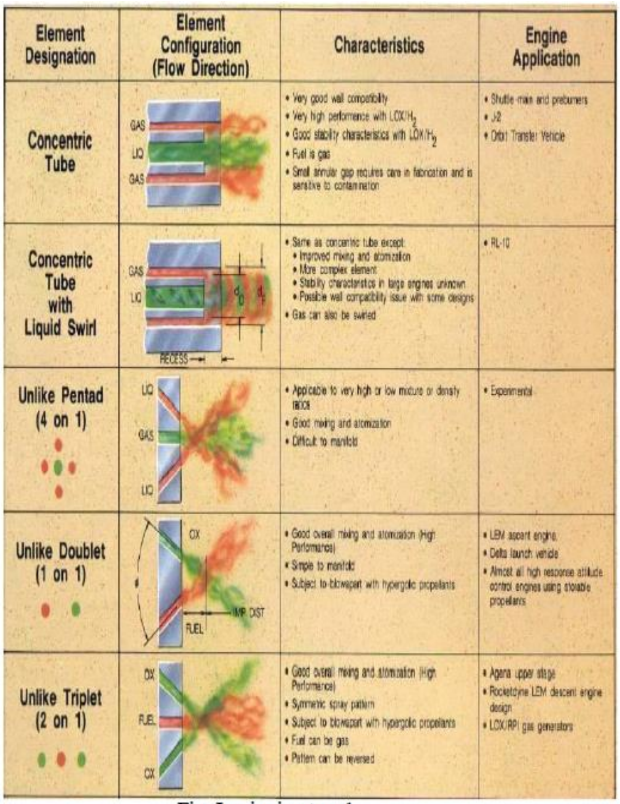
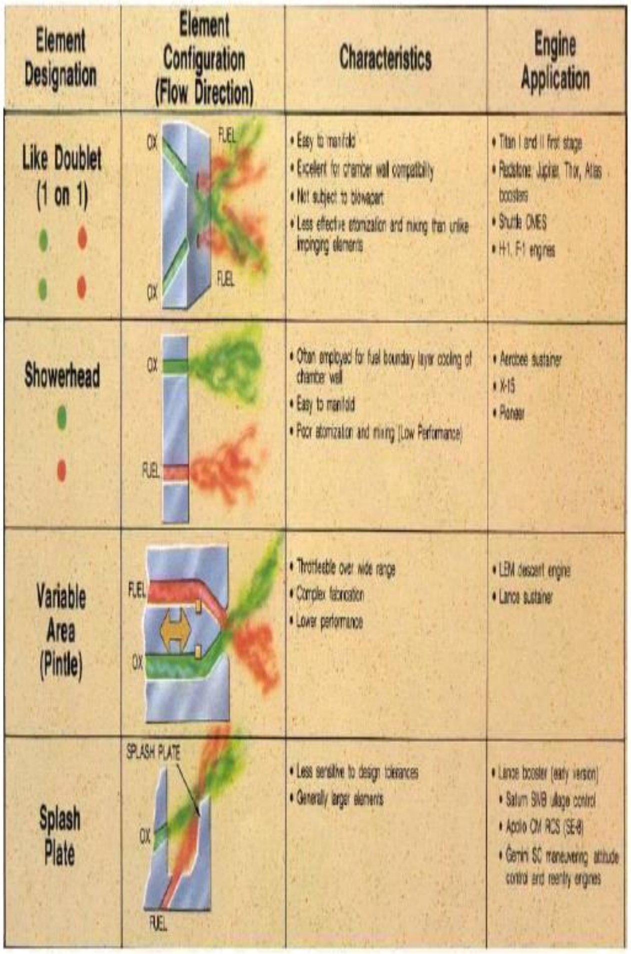


Element Designation	Element Configuration (Flow Direction)	Characteristics	Engine Application
Concentric Tube	GAS, LIQ, GAS	• Very good wall compatibility • Very high performance with LOX/H_2 • Good stability characteristics with LOX/H_2 • Fuel is gas • Small annular gap requires care in fabrication and is sensitive to contamination	• Shuttle main and preburners • J-2 • Orbit Transfer Vehicle
Concentric Tube with Liquid Swirl	GAS, LIQ, d_0, d_1, RECESS	• Same as concentric tube except: • Improved mixing and atomization • More complex element • Stability characteristics in large engines unknown • Possible wall compatibility issue with some designs • Gas can also be swirled	• RL-10
Unlike Pentad (4 on 1)	LIQ, GAS, LIQ	• Applicable to very high or low mixture or density ratios • Good mixing and atomization • Difficult to manifold	• Experimental
Unlike Doublet (1 on 1)	OX, FUEL, IMP DIST	• Good overall mixing and atomization (High Performance) • Simple to manifold • Subject to blowapart with hypergolic propellants	• LEM ascent engine • Delta launch vehicle • Almost all high response attitude control engines using storable propellants
Unlike Triplet (2 on 1)	OX, FUEL, OX	• Good overall mixing and atomization (High Performance) • Symmetric spray pattern • Subject to blowapart with hypergolic propellants • Fuel can be gas • Pattern can be reversed	• Agena upper stage • Rocketdyne LEM descent engine design • LOX/RP1 gas generators

Fig: Impinging type1



Element Designation	Element Configuration (Flow Direction)	Characteristics	Engine Application
Like Doublet (1 on 1)	OX, FUEL, FUEL, OX	• Easy to manifold • Excellent for chamber wall compatibility • Not subject to blowapart • Less effective atomization and mixing than unlike impinging elements	• Titan I and II first stage • Redstone, Jupiter, Thor, Atlas boosters • Shuttle OMES • H-1, F-1 engines
Showerhead	OX, FUEL	• Often employed for fuel boundary layer cooling of chamber wall • Easy to manifold • Poor atomization and mixing (Low Performance)	• Aerobee sustainer • X-15 • Pioneer
Variable Area (Pintle)	FUEL, OX	• Throttleable over wide range • Complex fabrication • Lower performance	• LEM descent engine • Lance sustainer
Splash Plate	SPLASH PLATE, OX, FUEL	• Less sensitive to design tolerances • Generally larger elements	• Lance booster (early version) • Saturn SIVB ullage control • Apollo CM RCS (SE-8) • Gemini SC maneuvering attitude control and reentry engines

Fig: Impinging type2

III. PROPELLANTS

Technically, the word propellant is the general name for chemicals used to create thrust. For vehicles, the term propellant refers only to chemicals that are stored within the vehicle prior to use, and excludes atmospheric gas or other material that may be collected in operation. In rockets, the most common combinations are bipropellants, which use two chemicals, a fuel and an oxidiser. There is the possibility of a tripropellant combination, which takes advantage of the ability of substances with smaller atoms to attain a greater exhaust velocity, and hence propulsive efficiency, at a given temperature.The term liquid propellant embraces all the various liquids used and maybe one of the following:

1. Oxidiser (liquid oxygen, nitric acid, etc.)
2. Fuel (gasoline, alcohol, liquid hydrogen, etc.)
3. Chemical compound or mixture of oxidiser and fuel ingredients, capable of self-decomposition
4. Any of the above, but with a gelling agent

A. TYPES OF PROPELLANTS

The most commonly known forms of liquid propellants are as follows:

A monopropellant contains an oxidizing agent and combustible matter in a single substance. It may be a mixture of several compounds or it may be a homogeneous material, such as hydrogen peroxide or hydrazine. Monopropellants are stable at ordinary atmospheric conditions but decompose and yield hot combustion gases when heated or catalysed.

A bipropellant rocket unit has two separate liquid propellants, an oxidizer and a fuel. They are stored separately and are not mixed outside the combustion chamber. The majority of liquid propellant rockets have been manufactured for bipropellant applications.

A cold gas propellant (e.g., nitrogen) is stored at a very high pressure, gives a low performance, allows a simple system and is usually very reliable. It has been used for roll control and attitude control.

A cryogenic propellant is liquefied gas at low temperature, such as liquid oxygen (-183°C). Provisions for venting the storage tank and minimizing vaporization losses are necessary with this type.

Storable propellants (e.g., nitric acid or gasoline) are liquid at ambient temperatures and can be stored for long periods in sealed tanks. Space storable

Propellants are liquid in the environment of space; this storability depends on the specific tank design, thermal conditions, and tank pressure. An example is ammonia.

A gelled propellant is a thixotropic liquid with a gelling additive. It behaves like jelly or thick paint. It will not spill or leak readily, can flow under pressure, will burn, and is safer in some respects.

B. DINITROGEN TETROXIDE (OXIDISER)

Nitrogentetroxide (or Dinitrogentetroxide) is the chemical compound N2O4. It is a useful reagent in chemical synthesis. It forms an equilibrium mixture with nitrogen dioxide; some call this mixture dinitrogen tetroxide, while some call it nitrogen dioxide. Dinitrogen tetroxide is a powerful oxidizer. N2O4 is hypergolic with various forms of hydrazine, i.e., they burn on contact without a separate ignition source, making them popular bipropellant rocket fuels.

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i. *Production*

Nitrogen dioxide is made by the catalytic oxidation of ammonia: steam is used as a diluent to reduce the combustion temperature. Most of the water is condensed out, and the gases are further cooled; the nitric oxide that was produced is oxidized to nitrogen dioxide, and the remainder of the water is removed as nitric acid. The gas is essentially pure nitrogen tetroxide, which is condensed in a brine-cooled liq

C. ORIFICE

A calibrated orifice is a restriction that is deliberately placed into a system of pipes to set the flow rate through the system. The orifice may be designed to produce proportional flow (as in the jet in a carburettor), or choked flow (as in a filtering bypass in a closed industrial cooling system, which might be designed to pass a particular flow rate through a filter assembly to maintain cleanliness of a closed-loop fluid system). Many pressure gauges also use an orifice (also called a restrictor) to limit the flow into a gauge. Since the pressure is even throughout the system, allowing only a small portion of the flow into the actual gauge allows it to be in parallel with the pressure circuit and still measure accurately. It also prevents or minimizes damage to the gauge during pressure surges at start-up, or due to any spikes in the system pressure.

IV. CALCULATIONS

A.TRIPLETS & DOUBLET IMPINGING INJECTOR

Assumptions:

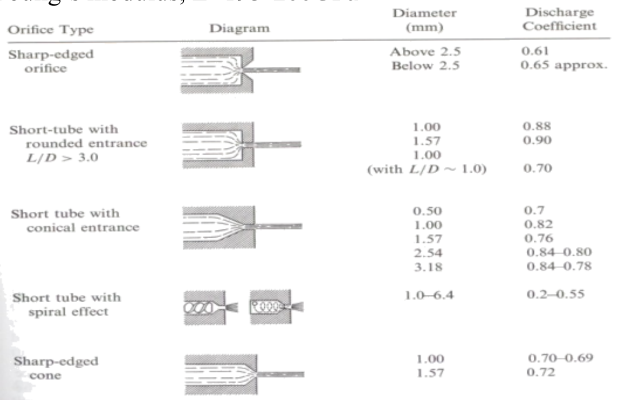
Mass, m=3000Kg
Combustion Chamber Pressure, Pcc=100Kg/cm^2
Number of oxidizer orifice, **no=160 & 80**
Number of fuel orifice**, nf=80**

Given data:

Coefficient of discharge, Cd=0.65
Change in Pressure, ΔP=20Kg/cm^2
Density of oxidizer, ρo=1442.46Kg/m^3
Density of fuel, ρf=790Kg/m^3
Mixture ratio, r=1.98
Specific Impulse, Isp=285sec
Factor of safety, fs=2

Stainless Steel AISI 321:

Tensile strength-Ultimate, Su=6.322*10^7 Kg/m^2 **[OR]** 5.251*10^7 Kg/m^2 Tensile strength-Yield, Sy=2.447*10^7 Kg/m^2 **[OR]** 2.0904*10^7 Kg/m^2
Poisson's ratio=0.27-0.30
Density of Stainless Steel AISI 321=8000Kg/m^3
Young's modulus, E=193-200GPa



Orifice Type	Diagram	Diameter (mm)	Discharge Coefficient
Sharp-edged orifice		Above 2.5 Below 2.5	0.61 0.65 approx.
Short-tube with rounded entrance $L/D > 3.0$		1.00 1.57 1.00 (with $L/D \sim 1.0$)	0.88 0.90 0.70
Short tube with conical entrance		0.50 1.00 1.57 2.54 3.18	0.7 0.82 0.76 0.84–0.80 0.84–0.78
Short tube with spiral effect		1.0–6.4	0.2–0.55
Sharp-edged cone		1.00 1.57	0.70–0.69 0.72

Fig: Discharge Coefficient Chart

Calculations for triplet and doublet

$$\xi = \frac{Acc}{At} = \frac{d^2cc}{d^2t}$$

$$\dot{m} = \frac{F}{Isp} = \frac{3000}{285} = 10.52\ kg/sec$$

$$\sigma max = \frac{6M}{h^2}\quad Where\ M = Pcc\frac{r^2cc}{8}$$

$$r = \frac{\dot{m}o}{\dot{m}f}$$

$$\dot{m}f = Cd\,Af\sqrt{2\,\Delta P\,g\,\rho f}$$

$$Af = \dot{m}f/Cd\sqrt{2\,\Delta P\,g\,\rho f}$$

$$At = \frac{F}{Pcc\,Cf}$$

$$dt = \sqrt{\frac{4At}{\pi}} = 48.113\ mm$$

$$Ao = \dot{m}o/Cd\sqrt{2\,\Delta P\,g\,\rho o}$$

$$\dot{m}o = Cd\,Ao\sqrt{2\,\Delta P\,g\,\rho o}$$

$$Vo = \frac{\dot{m}o}{\rho o\,Ao}$$

$$\sigma max = \frac{Sy}{fs}$$

We also know $$Vf = \frac{\dot{m}f}{\rho f\,Af}$$

σmax

Equating both the values, we get

$$\frac{Sy}{fs} = \frac{3}{4}Pcc\frac{r^2cc}{h^2}$$

$$h = \sqrt{\frac{3}{4}Pcc\frac{r^2cc\,fs}{Sy}}$$

V. Impinging Angels and Design Specifications

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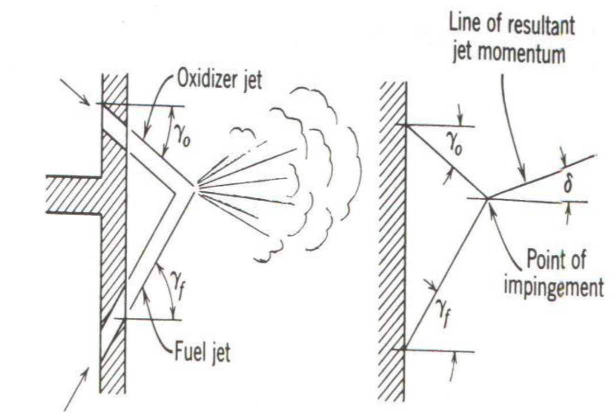

Fig: Impinging Angles

Here γ is replaced with θ for simplicity purpose

- For **θo=73.87°**; **θf=0**

  Then Tanδ=1.0002; **δ=45.006°**

- For **θo=60°**; **θf=0**

  Then Tanδ=0.732; **δ=36.215°**

- For **θo=45°**; **θf=0**

  Then Tanδ=0.508; **δ=26.967°**

- For **θo=30°**; **θf=0**

  Then Tanδ=0.322**; δ=17.893°**

- For **θo=15°**; **θf=0**

  Then Tanδ=0.0156; **δ=8.922°**

- For **θo=0°**; **θf=0**

  Then Tanδ=0; **δ=0°**

i. Triplet Design
ii.

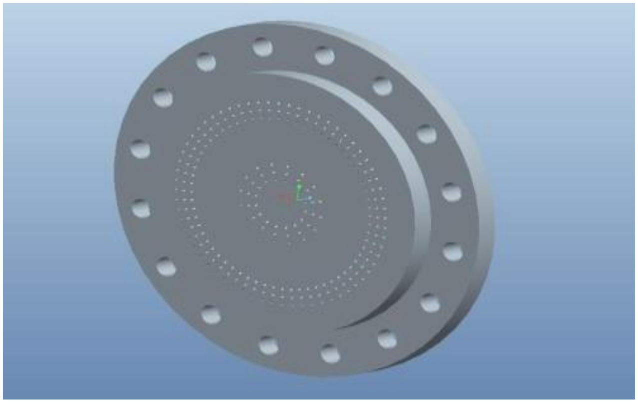

Fig: Triplet Injector Plate

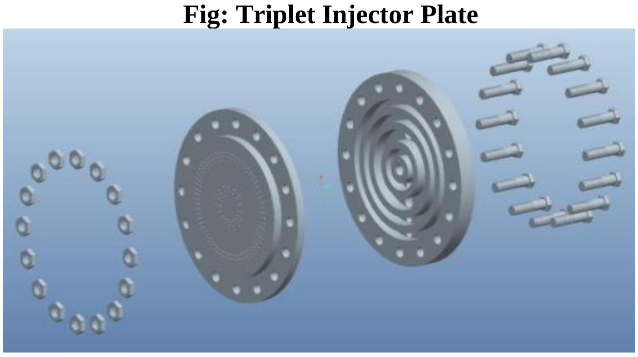

Fig: Injector and Feed Plate Assembly

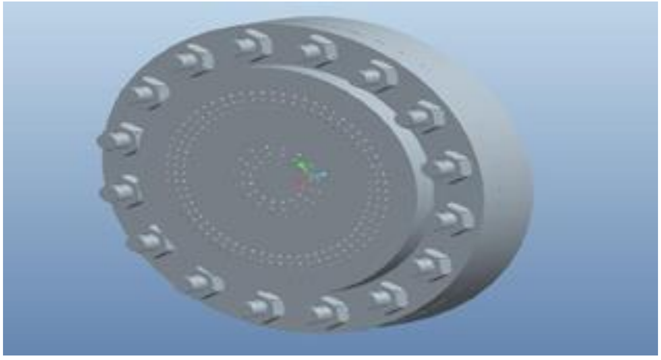

Fig: Assembly of Triplet Impinging Injector

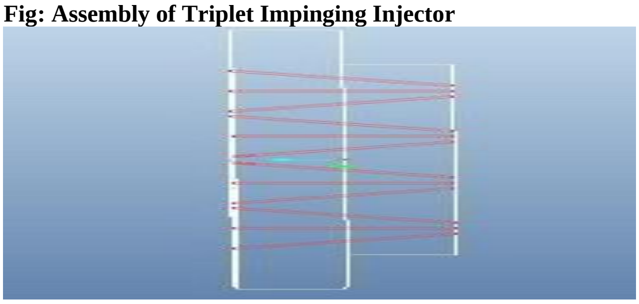

Fig: Triplet Impinging

iii. Doublet Design

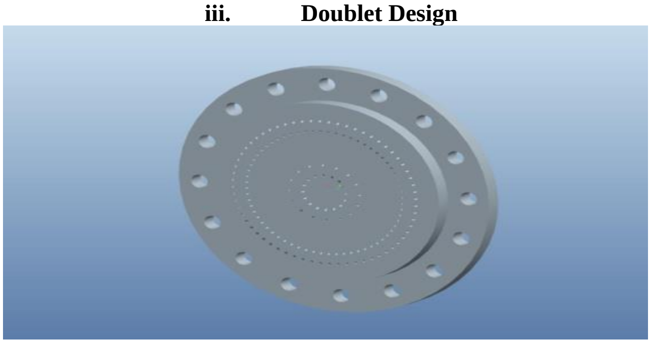

Fig: Doublet Injector Plate – Isometric

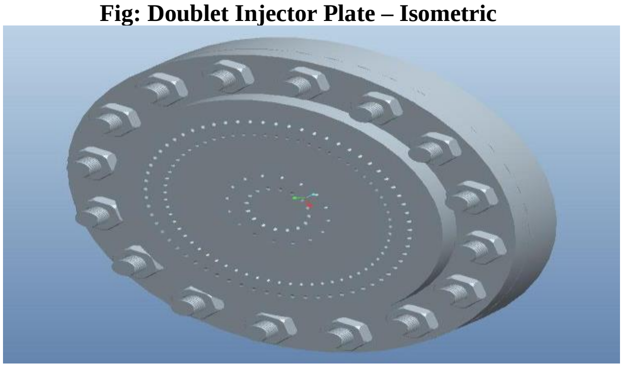

Fig: Assembly of Doublet Impinging Injector

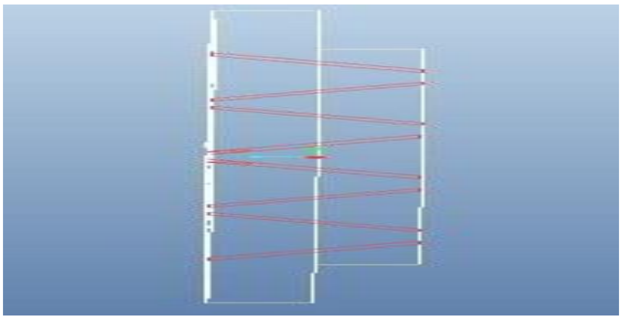

Fig: Doublet Impinging

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A. Triplet Flow and Streamline Analysis

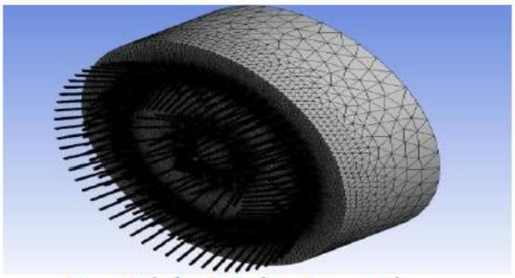

Fig: Triplet Mesh – Isometric

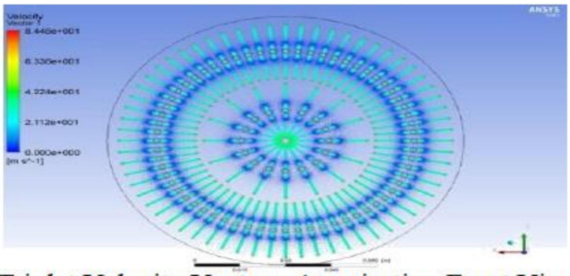

Fig: Triplet Velocity Vector - Atomisation Front View

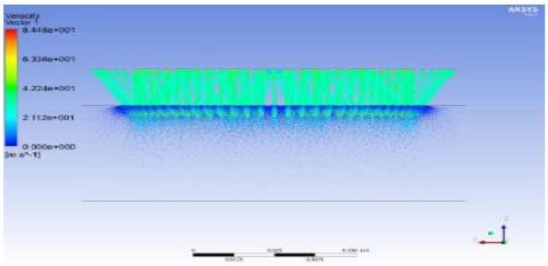

Fig: Triplet Velocity Vector - Atomisation Side View

VI. FLOW ANALYSIS AND STREAMLINES

B.Doublet Flow and Streamline Analysis

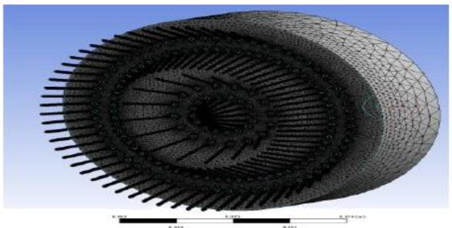

Fig: Doublet Mesh- Isometric

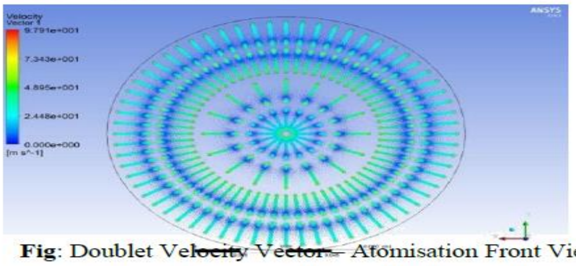

Fig: Doublet Velocity Vector – Atomisation Front Vie

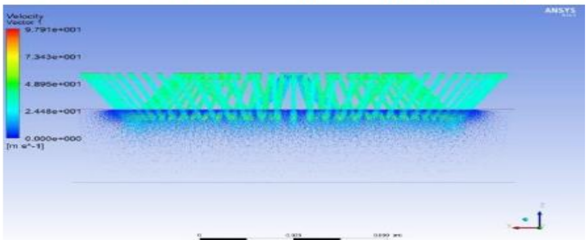

Fig: Doublet velocity vector- Atomisation side view

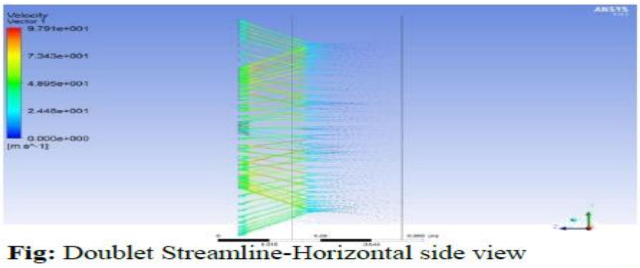

Fig: Doublet Streamline-Horizontal side view

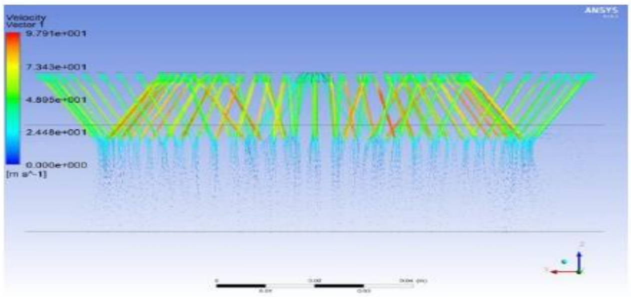

Fig: Doublet Streamline- Vertical Side View

VII. CONCLUSION

- The triplet impinging injector proved to be more efficient when compared to doublet impinging injector, as the atomization is more dense as well as the number of droplets have increased.
- It is also observed that the streamline pattern for both triplet impinging inector and doublet impinging injector, the impinging angle is taken same i.e.; 30 degree between oxidiser and horizontal axis as well as fuel and horizontal axis.
- The **unlike triplet** uses different fuel and oxidizer densities and velocities, thus being more efficient than doublet impinging injector.

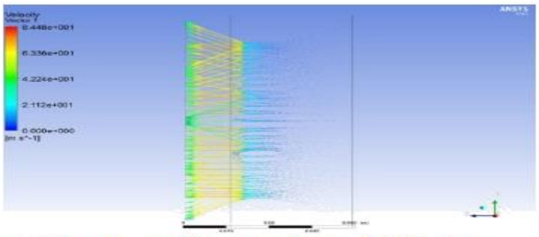

Fig: Triplet Stream line- Horizontal side view

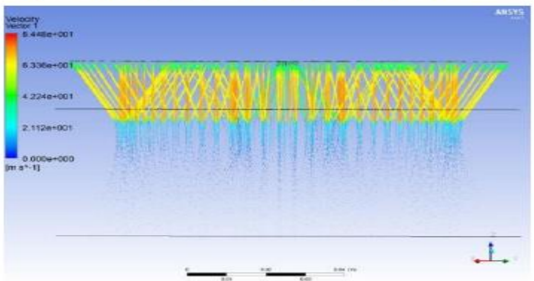

Fig: Triplet Streamline – Vertical Side View

- The **unlike doublet** uses different fuel and oxidizer densities and velocities, thus being less efficient than triplet impinging injector.
- The **like triplet** uses same fuel and oxidizer densities and velocities, thus being less efficient than doublet impinging injector.

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- The **like doublet** uses same fuel and oxidizer densities anvelocities, thus being more efficient than triplet impinging injector.
- The **oxidizer-fuel-oxidizer (Triplet injector)** orifices have been arranged in two girds of concentric circles to create a uniform combustion and also to keep the minimum distance between two holes under safe limits. The outer circular grid has 64 fuel and 128 oxidizer holes. The inner grid has 16 fuel and 32 oxidizer holes. So there are total of **80 fuel** and **160 oxidizer** holes.
- The **oxidizer-fuel (Doublet injector)** orifices have been arranged in two girds of concentric circles to create a uniform combustion and also to keep the minimum distance between two holes under safe limits. The outer circular grid has 64 fuel and 64 oxidizer holes. The inner grid has 16 fuel and 16 oxidizer holes. So there are total of **80 fuel** and **80 oxidizer** holes.

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