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# Design of Nozzles for Supersonic Gas Injector Prototype

Hitesh Chandani[1], Samiran Shanti Mukherjee[2], Ranjana Gangradey[2], Harish S. Choksi[3]

[1]*ME (Jet propulsion & Gas Turbine plant) student, Mechanical department, MSU-Baroda, Gujarat*
[2]*Cryo Pump and Pellet injector division, Institute for Plasma Research, Gandhinagar, Gujarat*
[3]*Associate Professor, Mechanical Department, MSU-Baroda, Gujarat*

***Abstract**: Supersonic Gas Injection (SGI) is an efficient and economical method than conventional Gas puffing and complex Pellet injection methods for a small and medium sized tokamaks. To test SGI there is a need to develop a small scaled prototype where we can study the behaviour of this technique. In this paper SGI prototype is designed for hydrogen gas flow rate of 2.57E+21 molecules per pulse. This pulse flow, ranges from 2 ms to 6 ms time is analysed in the vacuum test chamber. Various Convergent-Divergent (CD) supersonic conical nozzles were studied and analysed with different divergence angles ($7^0$, $12^0$ and $15^0$) to know the best suitable dimensions of nozzle for different test conditions and specified flow parameters. The observed flow velocities are in the range of 350 m/s to 2250 m/s and maximum Mach no. 2.7 can be reached in the test chamber of SGI prototype. The flow properties like Temperature, Velocity, Pressure, Density and Mach number (M) varies with position and flow time in the test chamber and for that analysis comparative results are presented in this paper.*

***Key words**: Tokamak, plasma fuelling, pellet injection, Supersonic nozzles, Mach number*

## I. INTRODUCTION

There are mainly three methods of plasma fuelling used for various tokomaks, Gas Puffing, Pellet injection and Supersonic Molecular Beam injection. Gas puffers produce a diffuse, undirected flow. Due to the low density of the gas, penetration is determined by the single particle mean free path. This results in poor fuelling efficiency, where only 10% or less of the particles penetrate past the plasma edge [1]. Pellet injection system for steady fuelling are complex and expensive, making them ill-suited for medium and small experiments. Furthermore, the pellet system would need to pulse with a frequency that matches the plasma's effective particle confinement time ($\tau$) [1, 2]. Supersonic molecular beam injection has a much larger radial injection speed and a larger injecting molecular flux than GP. It gives high-speed and high-directive gas deeper into the core plasma injection because of higher plenum pressure compared to the conventional gas puffing and it can inject neutral particles [3, 4]. It is economical to develop and to maintain. This method has been tested around the world in many fusion reactor tokamaks by researchers for example, NSTX [3, 4], Tore Supra [5], KSTAR [6], HL-1M [7, 8], ADITYA [9] etc. After many experiments they have concluded that Supersonic molecular beam injection (SMBI) is suitable for small and medium sized tokamaks. This suitability gives the reason to develop more theoretical and experimental base support for SMBI fuelling method to adopt that technology for tokamak fuelling.

## II. BASIC LAYOUT OF PROTOTYPE SUPERSONIC GAS INJECTOR

After studying various research papers and other literatures regarding SMBI method the design idea of prototype is developed to do laboratory experiments on it. Its construction and working is explained conceptually here. It includes A fast solenoidal valve with its controlling devices, fuelling gas supply, Supersonic convergent divergent nozzle, Test Chamber, Turbomolecular pump supported with a rotary pump, Various diagnostic devices can be attached to the test chamber like Pressure gauge, Supersonic pitot tube with pitot adjustments, Fast ionization gauge etc. as shown in figure 1 to measure the gas jet parameter in the test chamber or to view the jet propagation along the length of chamber a very high resolution camera can be fitted across the chamber.

Before the experiment get triggered, high pressurised fuel gas is supplied to the valve inlet and test chamber is maintained at high vacuum by using turbomoleculer pump. A current pulse is supplied to the valve which triggers the plunger and results into valve opening. High pressurised gas pass through the outlet of valve where some stagnation pressure will be lost due to throttling expansion of gas and friction of pipe. Flowing gas will now enter into the Supersonic nozzle's convergent part which increase the velocity of gas and increase flow's Mach no. from subsonic to sonic condition at nozzle's throat. Divergent portion of nozzle will further expand and increase its velocity to get supersonic conditions. At the outlet of nozzle we obtain a supersonic gas jet which enter into the vacuum chamber for further expansion. In this test chamber various properties of gas jet are measured by mentioned diagnostics instruments attached to the vacuum chamber. For an experiment to get performed with this prototype 10 bar absolute pressure at inlet of nozzle and $10^{-6}$ bar absolute pressure at outlet are maintained with 300 Kelvin stagnation temperature.

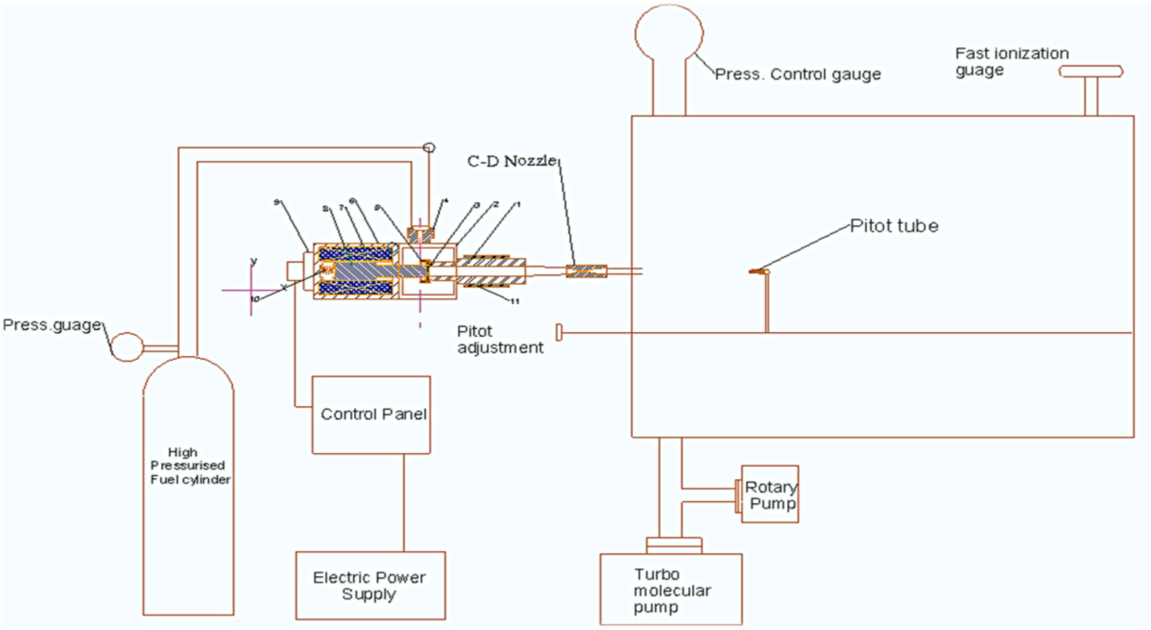
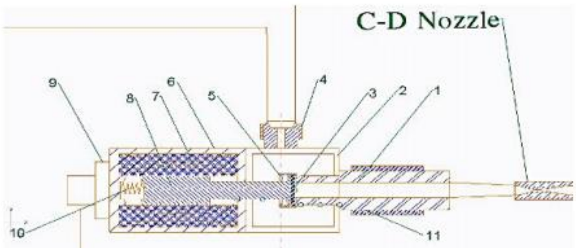



*Figure 1: Layout of SGI Prototype*




*1 – valve output tube, 2 - high pressure chamber, 3 – valve gasket, 4 – input tube, 5 – gasket holder, 6 – electromagnet body, 7 - electromagnet windings, 8 – electromagnet armature, 9 - electrical connector, 10 – spring, 11 – valve seat*

*Figure 2: Solenoidal valve used for SGI Prototype*

## III. DESIGN OF SUPERSONIC NOZZLE

Considering above mentioned parameters supersonic nozzle has to be designed by using various compressible gas dynamics equations. All calculations are made on the basic assumption of isentropic conditions. The maximum flow of fuel gas particles are needed to be injected through the nozzle with a very high velocity to reach to the plasma core in vacuum chamber. This condition makes the design of such supersonic nozzle very critical. If high pressurised fluid is injected at the inlet area $A_{i,}$ as shown in figure 3 it converts the pressure energy into kinetic energy in the convergent portion of nozzle up to throat. Now, divergence portion act as a nozzle or diffuser is depends on the flow condition at the throat of nozzle. If flow is subsonic (M<1) divergent portion increases the pressure energy and decreases flow velocity but if flow reaches to sonic condition (M=1) at throat then further kinetic energy increases and flow becomes supersonic (M>1) in the divergent portion of nozzle. To get Supersonic flow at the outlet of nozzle Pressure ratio ($P_i/P_o$) should be high enough to avoid the shock occurrence in the divergent part of nozzle [10]. Consider the number of gas particles to be fuelled per pulse is same as it is in hydrogen pellet injection method. As the outlet of solenoidal valve available is 4 mm, we have calculated the throat diameter of nozzle 2.2 mm with its inlet and outlet diameter as 4 mm.

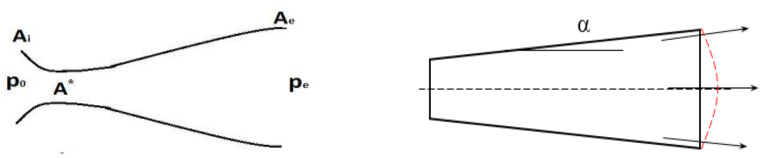



*Figure 3: Convergent-Divergent Nozzle with divergence half angle 'α'*

For lengths of converging part and diverging part of CD nozzle convergence and divergence angles ('α' as shown in figure 3) should be fixed which significantly affects the flow dynamics or flow nature in the CD nozzle. A small angle produces greater thrust, because it maximizes the axial component of exit velocity and produces a high specific impulse, Penalty is longer and heavier nozzle that is more complex to build. At the other extreme, size and weight are minimized by a large nozzle wall angle. Large angles reduce performance at high ambient pressure causes overexpansion and flow separations. So, primary metric of characterization is divergence Loss because high convergence angle does not affects the flow, due to its subsonic conditions. From various literature regarding the nozzle angles we have decided to design 3 nozzles with $7^0$, $12^0$ and $15^0$ divergence half angles (α) and $30^0$ convergence half angle fixed to do fluent analysis on them so we can use the most suitable designed nozzle for our particular conditions of flow requirement.

## IV. CFD -FLUENT ANALYSIS APPROACH

In our prototype testing flow of gas is not continuous, variation in the pulse time supplied to the valve also changes the flow rate at the inlet of nozzle. This time dependent situation can only be dealt by transient analysis. So we have considered three time steps 2 ms, 4 ms and 6 ms for gas flow time at the inlet of nozzle and all three different angled nozzles analysed by focusing on changes in flow properties along the test chamber after each above mentioned time intervals. To check the suitability of this type of fuelling method for different sized tokamaks, we have compared the analysis results of all nozzles at each time intervals by considering different distances of 200 mm, 300 mm, 400 mm and 500 mm along the horizontal axis of chamber. To validate this transient analysis, firstly we have done steady state analysis of these designed nozzles and results obtained from this steady state analysis have been accurately matched with results of all properties of flow calculated by using isentropic gas dynamic equations but it is not discussed in this paper.

## V. RESULTS AND DISCUSSIONS

Here $12^0$ divergence angled nozzle are discussed. Comparison of all flow properties like Temperature, Absolute pressure, density,Velocity and Mach number has been done at different time intervals of 2ms, 4ms and 6ms at each specified distances along the chamber.

### A. Temperature

- At 2 ms time:

Due to expansion of hydrogen gas in the nozzle, temperature decreases and cooling of hydrogen gas particles will be observed which results into cluster formation of hydrogen molecules and it enhances the fuelling efficiency. At 2ms time we get lowest temperature static 140 K in the expansion cone at the outlet of nozzle. In test chamber at 200 mm distance 180 K is observed and it increases as we travel along the test chamber axis and it is shown in figure 4.

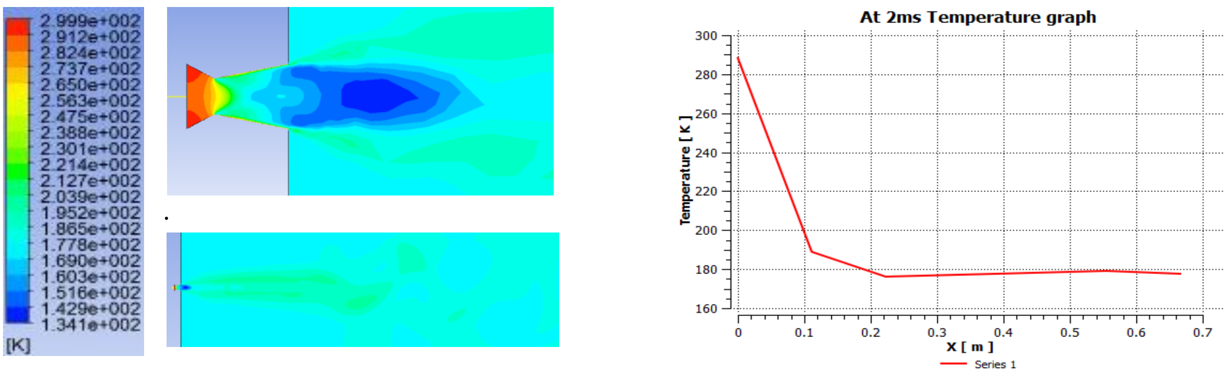



*Figure 4: Temperature contour and Temperature chart for $12^0$ nozzle at 2 ms*

- At 4 ms time:

Development of flow after 4ms decreases the static temperature of gas flow in the test chamber to 80 K at the outlet of nozzle.150 K is observed at 200 mm distance along test chamber axis and it get increases after it due to shock waves as shown in figure 5.

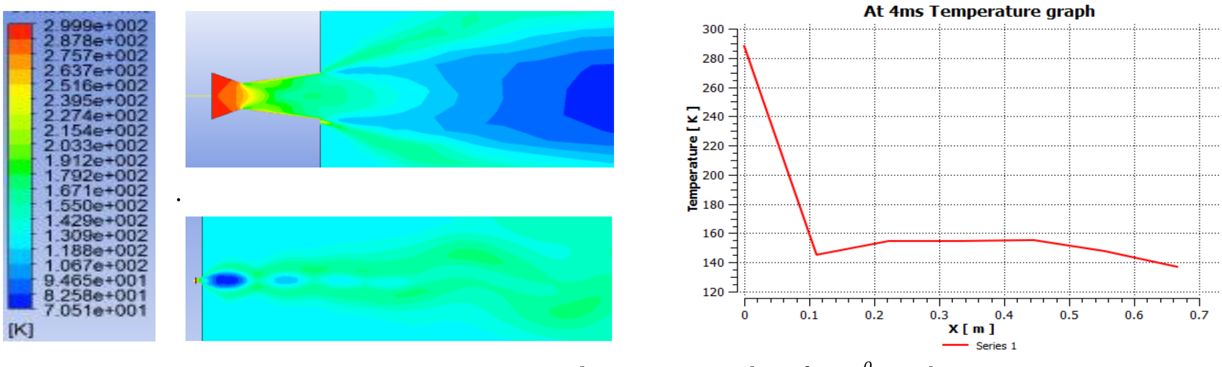



*Figure 5: Temperature contour and Temperature chart for $12^0$ nozzle at 4 ms*

- At 6 ms time:

Further expansion of flow results more cooling of flow due to increase in its development time. At the outlet expansion cone of nozzle we get static temperature below 50 K. At 200 mm distance we get 122 K temperature as it is shown in chart in figure 6.

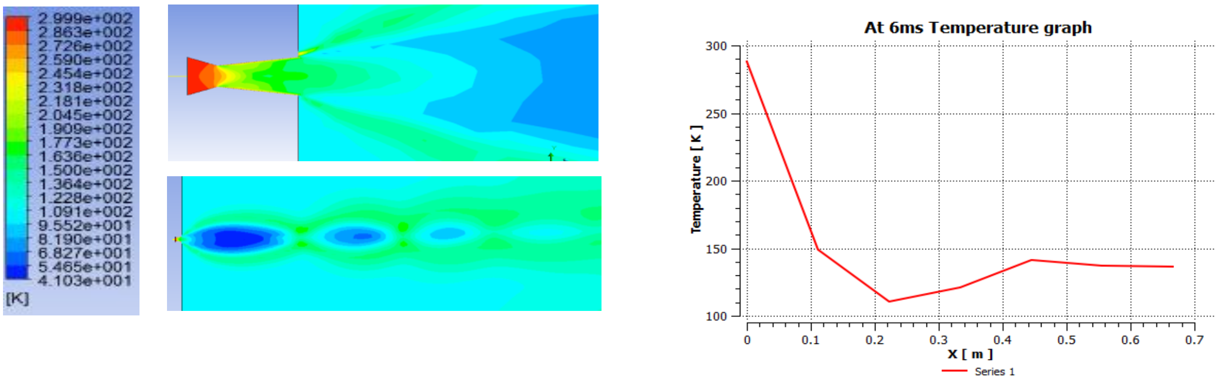



*Figure 6: Temperature contour and Temperature chart for $12^0$ nozzle at 6 ms*

## B. Absolute Pressure

- At 2ms time:

As the divergence angle of nozzle increases expansion of gas flow also increases which results into lower pressure values compared to 2ms flow in $7^0$ nozzle. As shown in figure 7 pressure at 200 mm distance along the nozzle axis is 0.9E+5 Pa which further decreases along the nozzle in the test chamber.

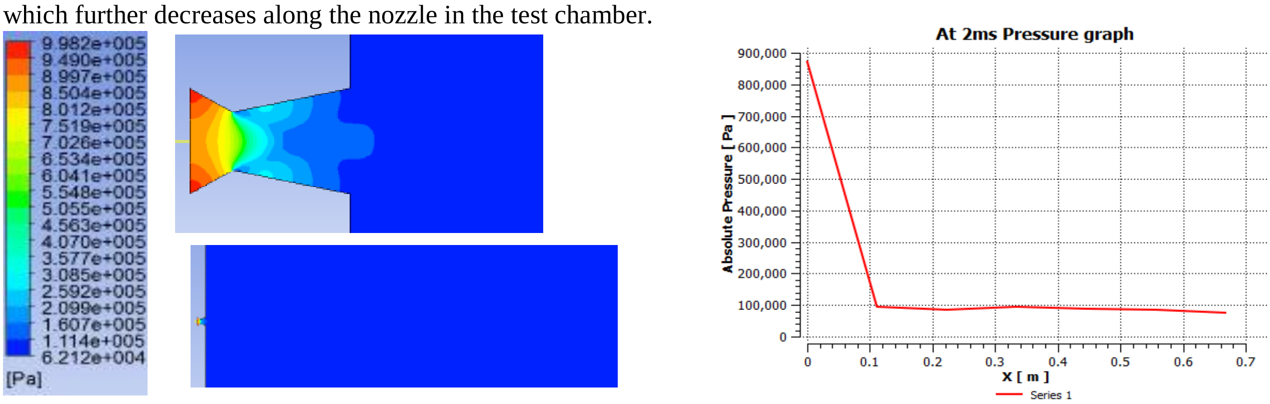



*Figure 7: Pressure contour and Pressure chart for $12^0$ nozzle at 2ms*

- At 4ms time:

Flow develops more as the expansion time increases from 2ms to 4ms and this causes more decrement in the pressure. At 200 mm distance 0.5E+5 Pa pressure is observed along the axis of the test chamber. It further decreases at very slow rate as shown in figure 8.

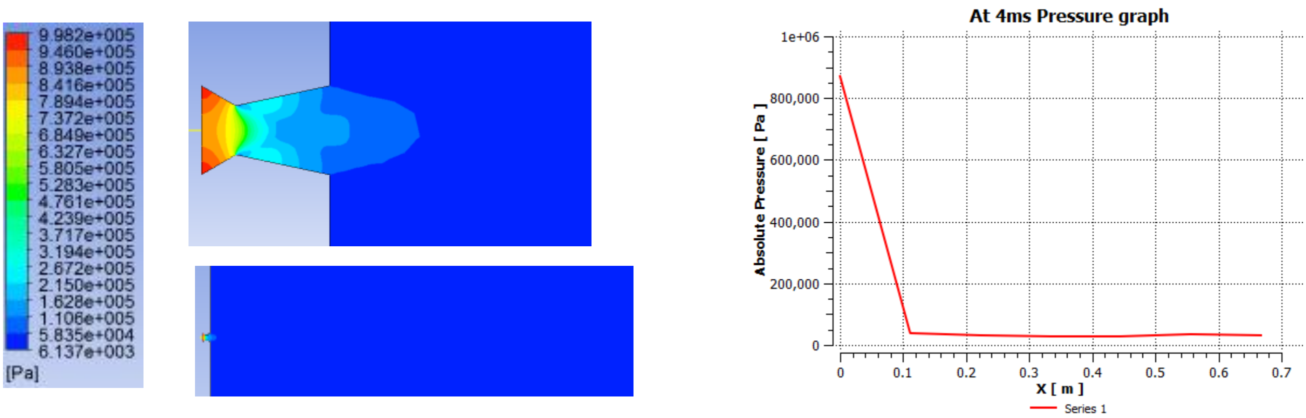



*Figure 8: Pressure contour and Pressure chart for $12^0$ nozzle at 4ms*

- At 6ms time:

For 6ms time under expansion of gas flow occurs such that pressure value from the outlet of nozzle stops decreasing significantly. So, at 200 mm to 500 mm distance along the nozzle axis 0.3E+5 Pa pressure is observed as shown in figure 9.

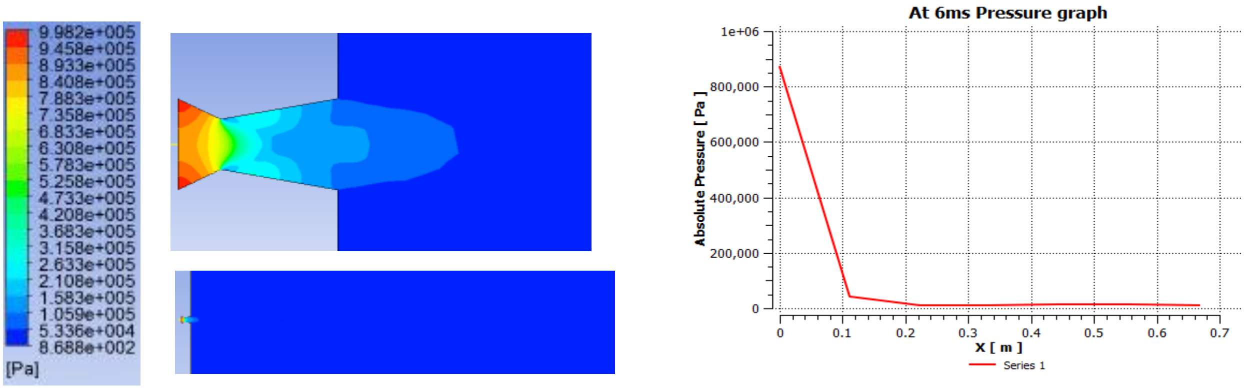



*Figure 9: Pressure contour and Pressure chart for 12$^0$ nozzle at 6ms*

## C. Density

- At 2ms time:

Density is very important property for plasma fuelling purpose. It always get decreases when flow gas gets expanded. So, to supply the hydrogen particles in the form of gas jet, its density should be observed at particular time and distance in the test chamber to maintain sufficient or higher density of gas jet than plasma core. For 2ms time interval density along the distance is approximately 0.1200 Kg/m$^3$ in the test chamber along the axis as it is shown in figure 10.

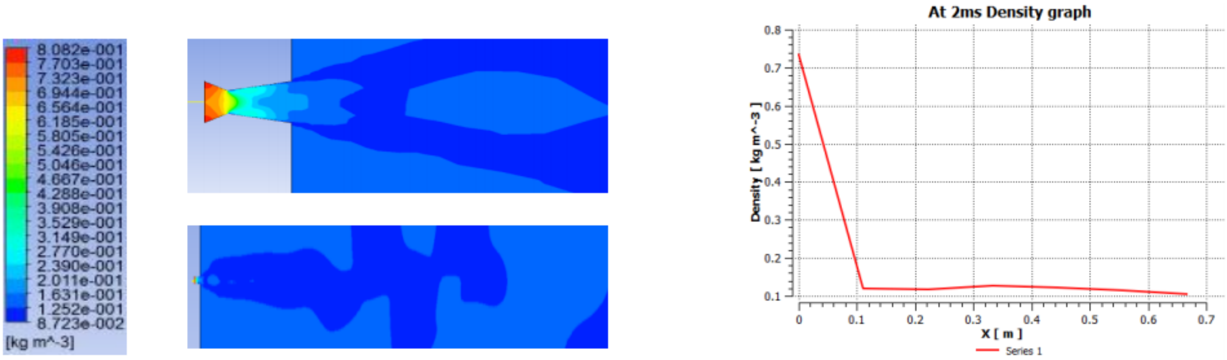



*Figure 10:Density contour and Density chart for 12$^0$ at 2 ms*

- At 4 ms time:

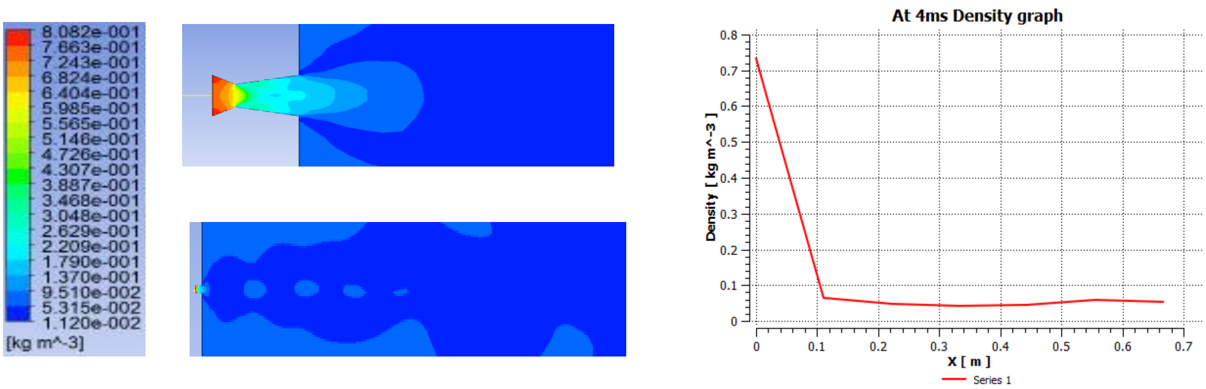



*Figure 11: Density contour and Density chart for 12$^0$ nozzle at 4 ms*

Further expansion of gas due to increase of development time for the flow results into decrement of density of gas jet along the test chamber. So, 0.0450 Kg/$m^3$ density is observed along the axis of test chamber and it is shown in figure 11.

- At 6 ms time:

After 6 ms time flow will expand more in the test chamber and it decreases the density of jet. At 200 mm distance 0.0500 Kg/$m^3$ due to shock wave because it further decreases to 0.0250 Kg/$m^3$ at 300 mm distance along the axis of test chamber as shown in figure 12.

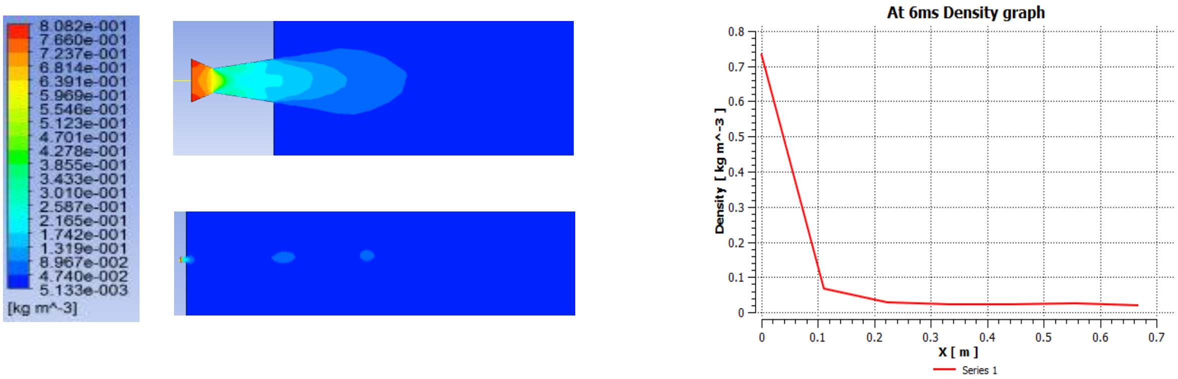



*Figure 12: Density contour and Density chart for $12^0$ nozzle at 4 ms*

## VI. CONCLUSION OF TRANSIENT ANALYSIS RESULTS

In above results of Fluent Analysis we can observe the flow properties, Temperature, Pressure and Densityof fuel gasjet at a particular time, at a particular distance. Velocity and Mach number are decision making criteria for selection of supersonic nozzle so, for $7^0$, $12^0$ and $15^0$ nozzles these properties are compared graphically and conclusion is made as shown below.

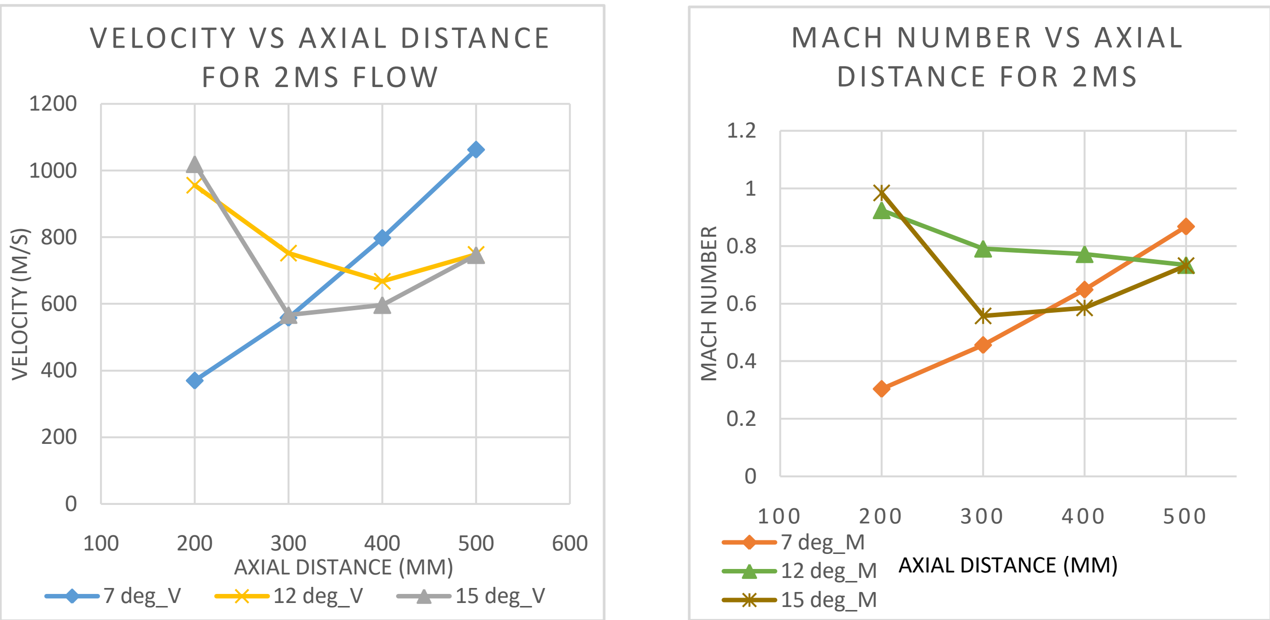



*Figure 13: Comparison of Velocity and Mach number variation in $7^0$, $12^0$ and $15^0$ nozzles for 2ms flow time*

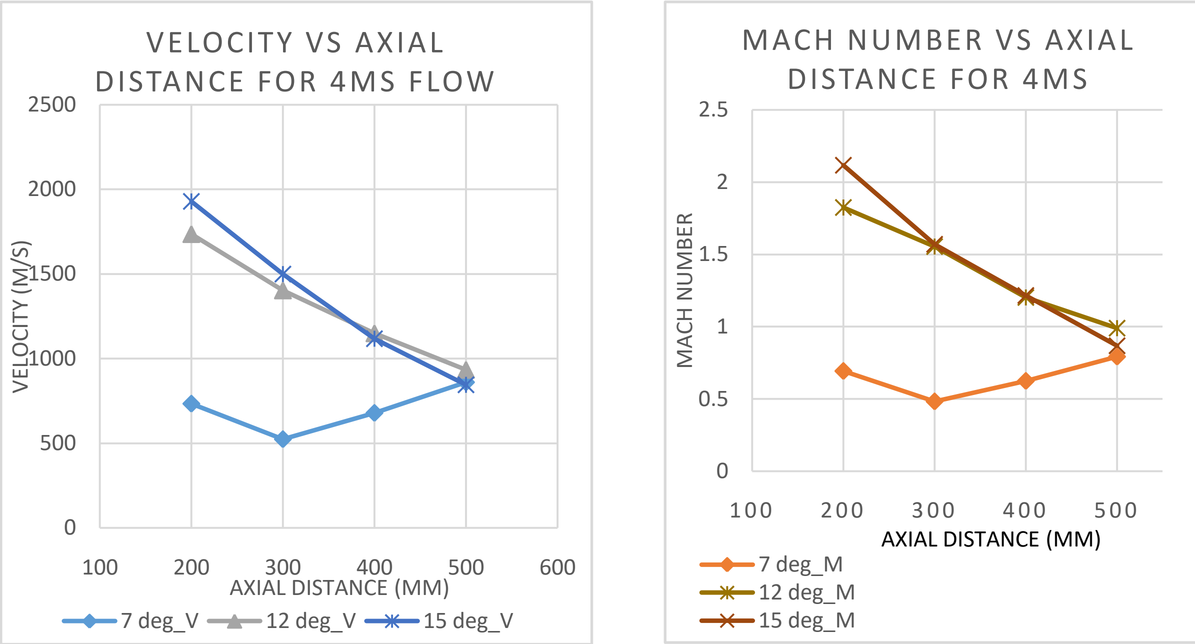



*Figure 14: Comparison of Velocity and Mach number variation in $7^0$, $12^0$ and $15^0$ nozzles for 4ms flow time*

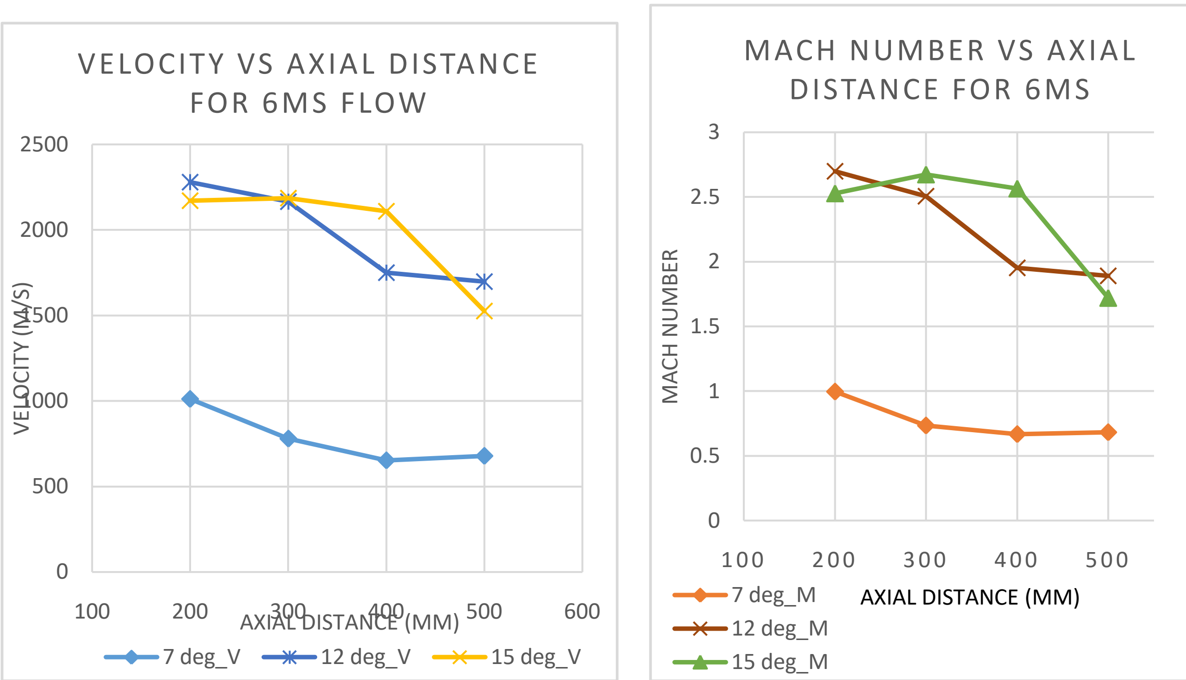



*Figure 15: Comparison of Velocity and Mach number variation in $7^0$, $12^0$ and $15^0$ nozzles for 6ms flow time*

From above shown graphs of comparison we can conclude following points for selection of Supersonic nozzle for specified conditions.

- To get the efficient fuelling for supersonic gas injection mainly velocity of gas jet and density of jet at the point of impact on plasma core are critical. But to get the supersonic flow at required distance Mach number is needed to be observed. For greater density small divergence angle should be preferred mostly but to get a required supersonic velocity of gas jet compromise has to be made.
- For smaller distances like a 200 mm target, flow separation does not play much role in the expansion of gas in the test chamber so, greater the divergence angle, greater the expansion and it results in to high velocity and high Mach number and for $15^0$ nozzle than $7^0$ and $12^0$ nozzle for all time intervals 2 ms, 4 ms and 6 ms .
- For 300 mm distant target at 2 ms, we obtain velocity of 790 m/s for $12^0$ nozzle which is higher than $7^0$ and $15^0$ angled nozzle. At 4 ms and 6 ms time,we have observed higher velocity of 1500 m/s and 2150 m/s respectively for $15^0$ nozzle but Mach number are 1.57 and 2.7 as shown in figure 14 and 15, which

are higher than Mach number for $7^0$ and $12^0$ nozzles. So, $12^0$ nozzle gives better flow properties for this condition at 300 mm.

- Similarly, for 400 mm distance for 2 ms and 4 ms flow time, velocities for $12^0$ nozzle are higher while for 6 ms time interval we observe $15^0$ nozzle gives higher velocity of 2110 m/s and supersonic flow of Mach number 2.55 higher than $7^0$ and $12^0$ nozzles at 400 mm distance in test chamber.
- For far target of 500 mm distance at 4 ms and 6 ms flow time $12^0$ nozzle gives the higher velocity 934 m/s and 1696 m/s and Mach number of 1.8 and 0.86 respectively than other nozzles in the test chamber.

So, for our applied pressure conditions one can choose a best suitable nozzle according to its required flow properties and its test chamber or tokamak size by considering above concluded point.

## VII. ACKNOWLEDGMENT

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