FLOW PROPERTIES AT THE EXIT OF A MACH 1.8 NOZZLE

MINI PROJECT FINAL REVIEW

Done By,

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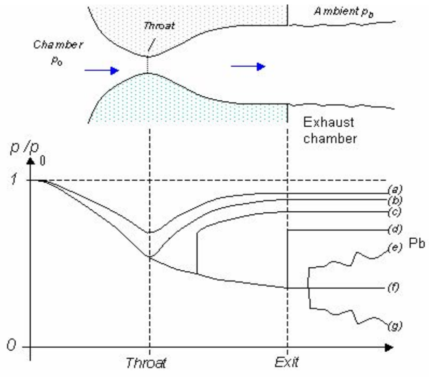
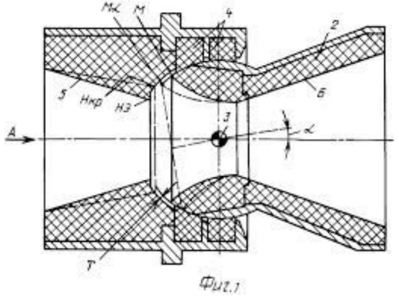
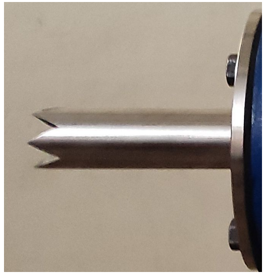
INTRODUCTION:

- Nozzles isentropically expand fluids⇒ subsonic to supersonic
- Work based on the area-mach number relation
- Convergent channel ⇒ subsonic to sonic
- Divergent channel ⇒ sonic to supersonic
- Sonic at throat
- Used as the main propulsive systems for air breathing engines & rockets





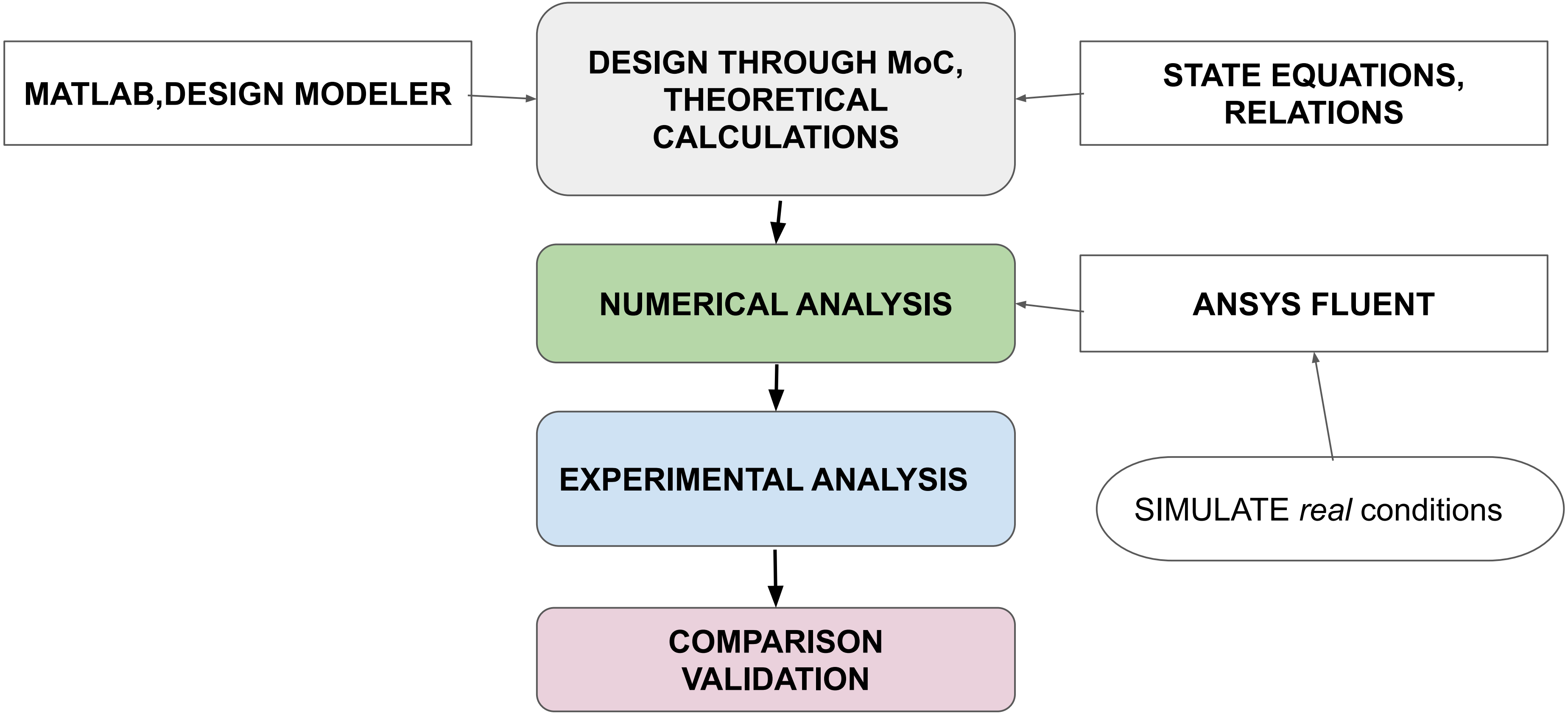


$$\frac{dA}{A} = \frac{dV}{V}(M^2 - 1)$$

WORKING PROCEDURE:

- To determine the properties at exit of a M = 1.8 nozzle
- To simulate numerically and validate experimentally
- To compare the properties between numerical and experimental model by comparing respective values
- To simulate an overexpansion case

METHODOLOGY:



THEORETICAL CALCULATIONS:

- Equations of state relating state variables as a function of M are employed
- A* denotes the throat area, fixed in accordance to design constraints
- P0/P ⇒ **NPR**
- Area ratio for M=1.8 is *1.4376*

NPR for two cases are found out,

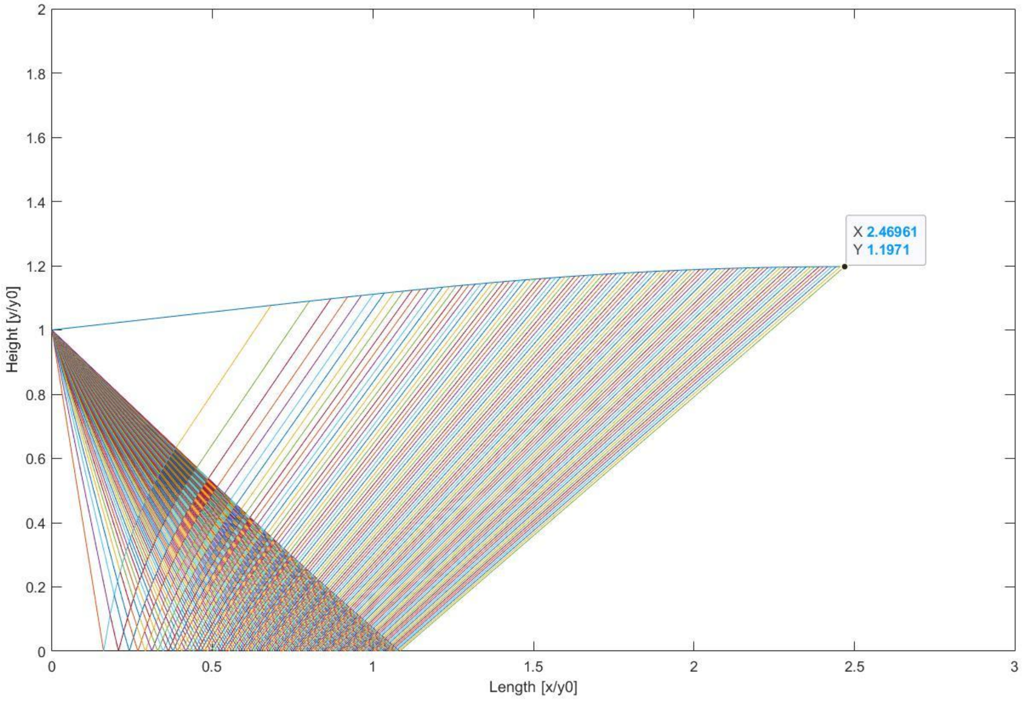
- Ideal ⇒ 5.74 , M = 1.8
- Overexpansion ⇒ 3.74 , M = 1.69

$$\frac{P0}{P} = \left(1 + \frac{\gamma-1}{2} M^2\right)^{\frac{\gamma}{\gamma-1}}$$

$$\frac{A}{A*} = \left(\frac{1+\frac{\gamma-1}{2}M^2}{\frac{\gamma+1}{2}M}\right)^{\frac{\gamma+1}{2(\gamma-1)}}$$

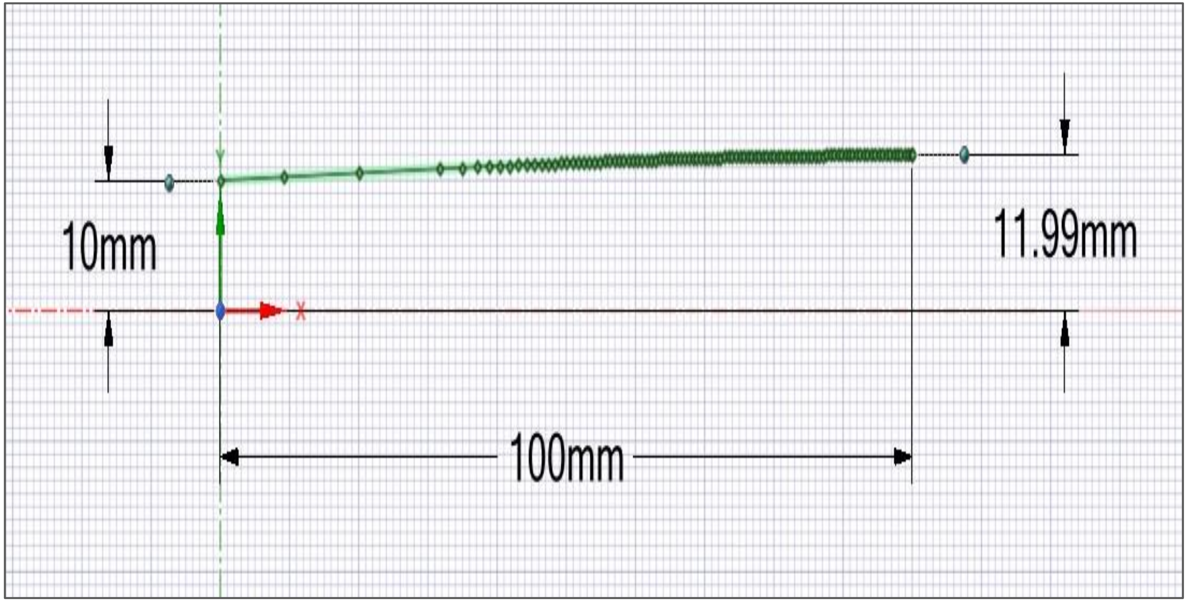
CONTOUR DESIGN

- MoC implemented via a MATLAB code
- 100 characteristic lines are used, 100 wall points are obtained
- Changed to software readable format and imported to DesignModeler



Model specifications - nozzle

Throat radius	10 mm
Exit radius	11.99 mm
Diverging section length	100 mm
Convergent section length	50 mm



*100 contour points are used

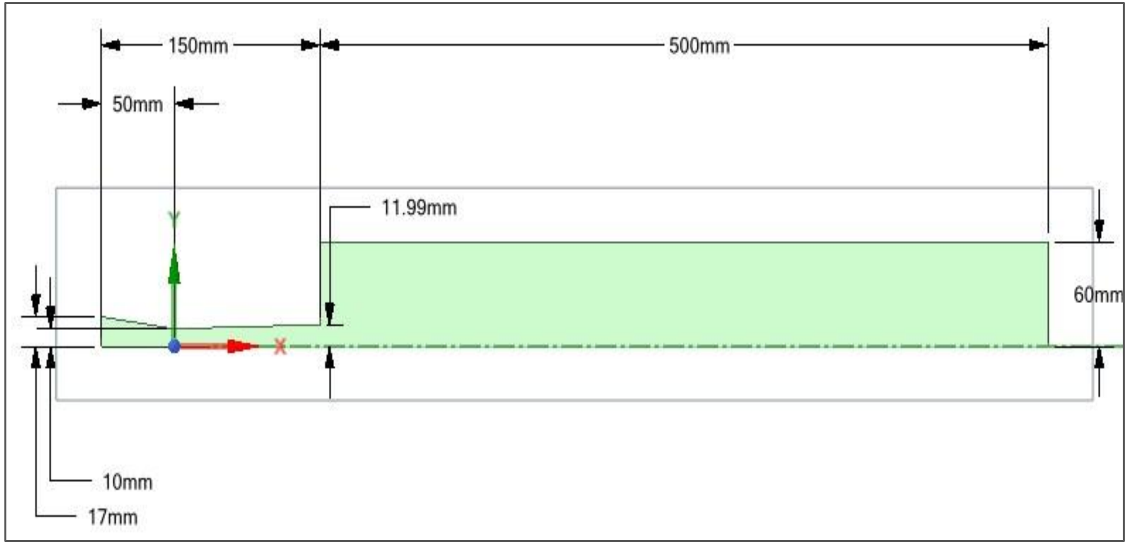
Numerical Domain:

Pressure chamber specifications:

- **Length** ⇒3 times of nozzle length
  - **(500mm).**
- **Width** ⇒5 times of exit width
  - **(60mm)**

⇒ allowance for free expansion of flow.

⇒rotated by 90º about x-axis



*Used for ***visualizing*** fluid flow (shock cells, supersonic jet) <u>downstream</u> of the nozzle.

Meshing details

3 methods in meshing used:

- Multizone
- Body sizing
- Inflation

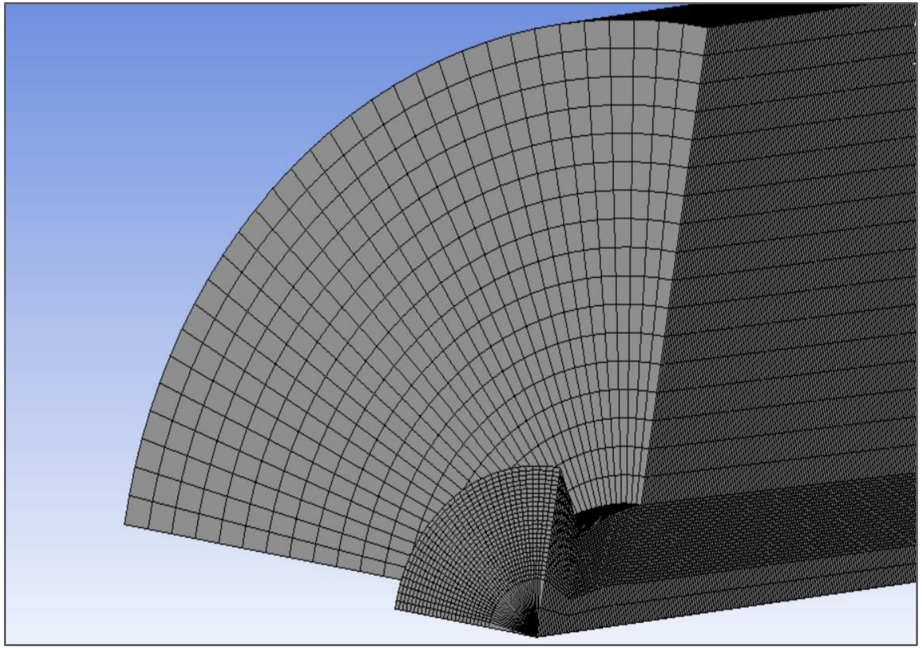
  ⇒radial,quadrilateral dominant mesh used.

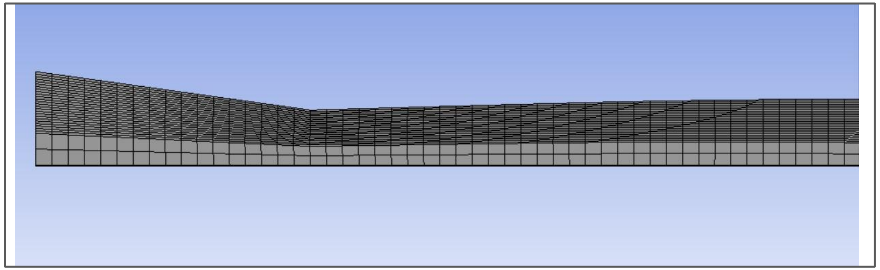
No of elements= 0.279 million

Element size ⇒ 3 mm

Boundary meshing ⇒ inflation (1.2 , FLT)

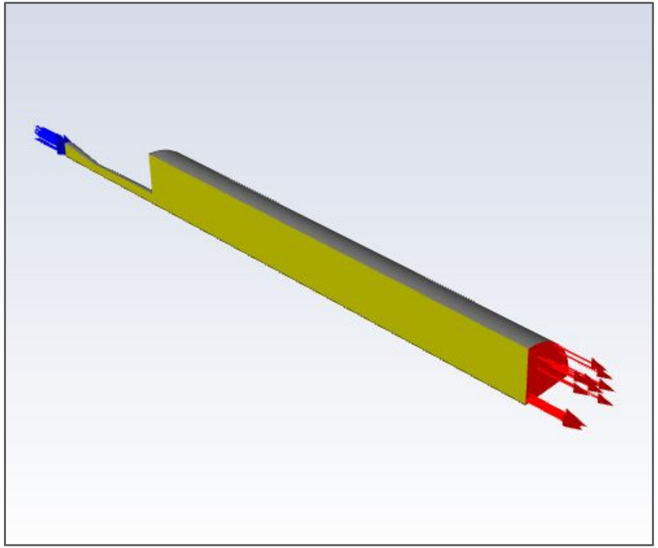
Faces are named.





Numerical solutions - fluent analysis

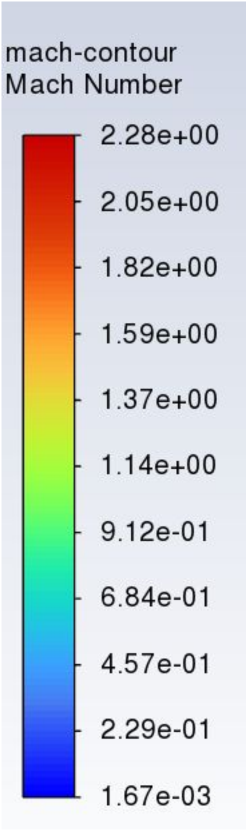
- Solver : type**(density based),**velocity formulation(absolute),time(steady)
- Model: **energy-on , viscous-sst k-omega**
- Materials: fluid(air), solid(aluminium)
- Inlet boundary conditions: (**P0=5.8232,3.7895**bar, **P=5.5,3.5**bar, **TI=3%**)
- Outlet boundary conditions: (**P=1.01325**bar,**BTI=3%**)
- Around **100000 iterations** carried out.
- Courant number is changed.
- Courant number ranges from 0.25,0.5,0.75 to 1.



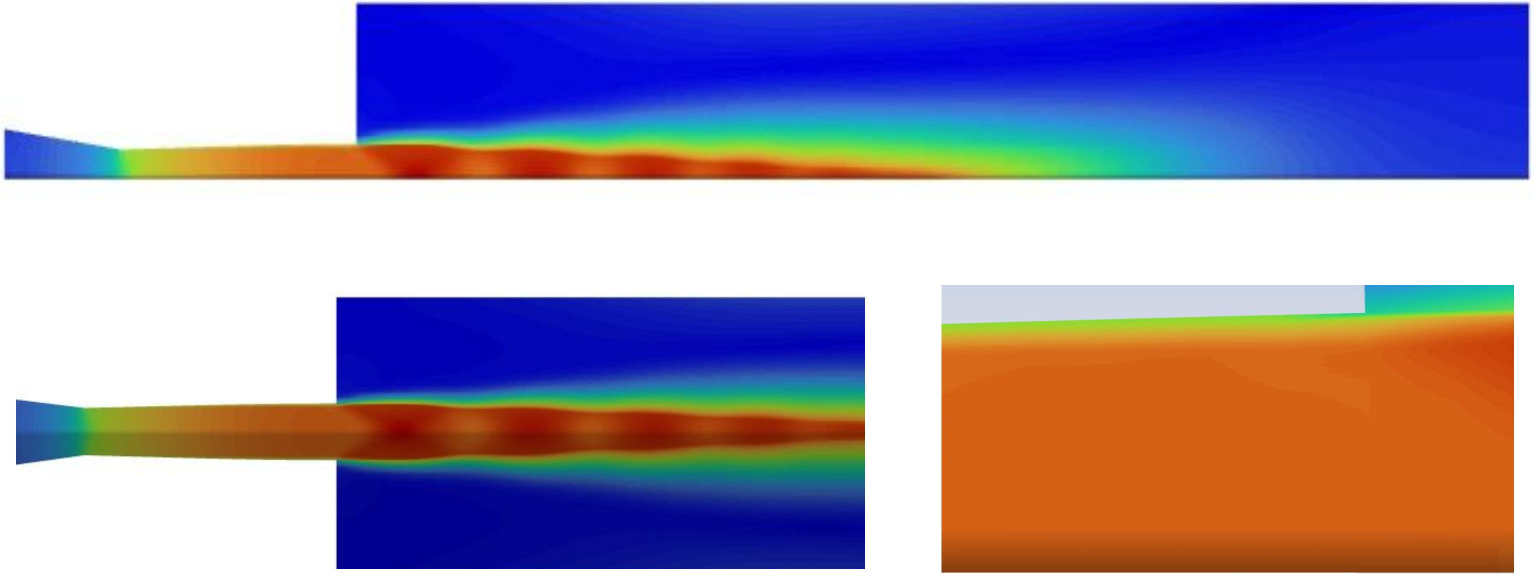
Solver	Density based
Energy Equation	ON
Viscous	k-ω SST
Material	Fluid, air
Density	Ideal gas
Viscosity	Sutherland model
Turbulence index	3%

Total pressure	5.74; 3.74 atm
Static pressure	5.70; 3.70 atm
Temperature	300 K
Outlet pressure	1 atm.
Flux	AUSM
Courant no	0.1, 0.25, 0.5, 0.75, 1

MACH CONTOUR NPR 5.74 (design)

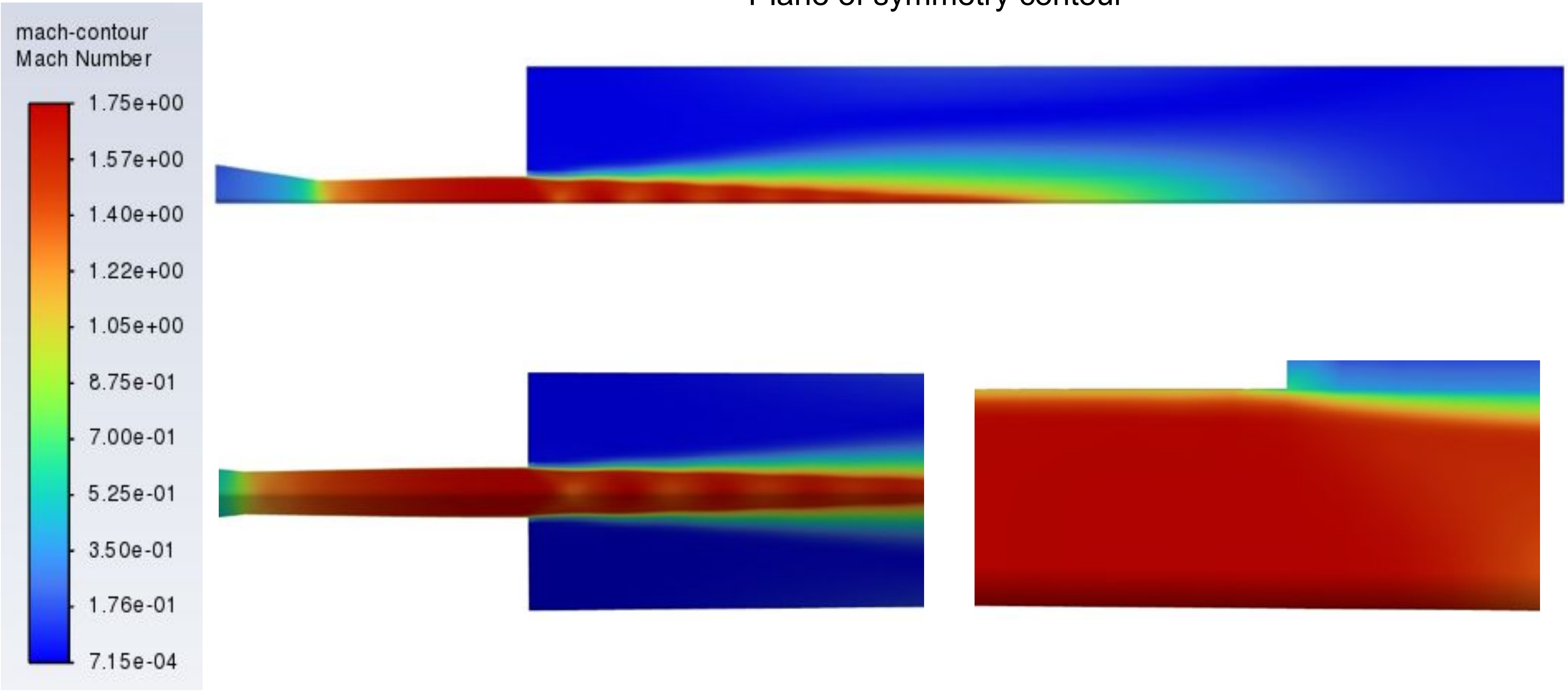


Plane of symmetry contour



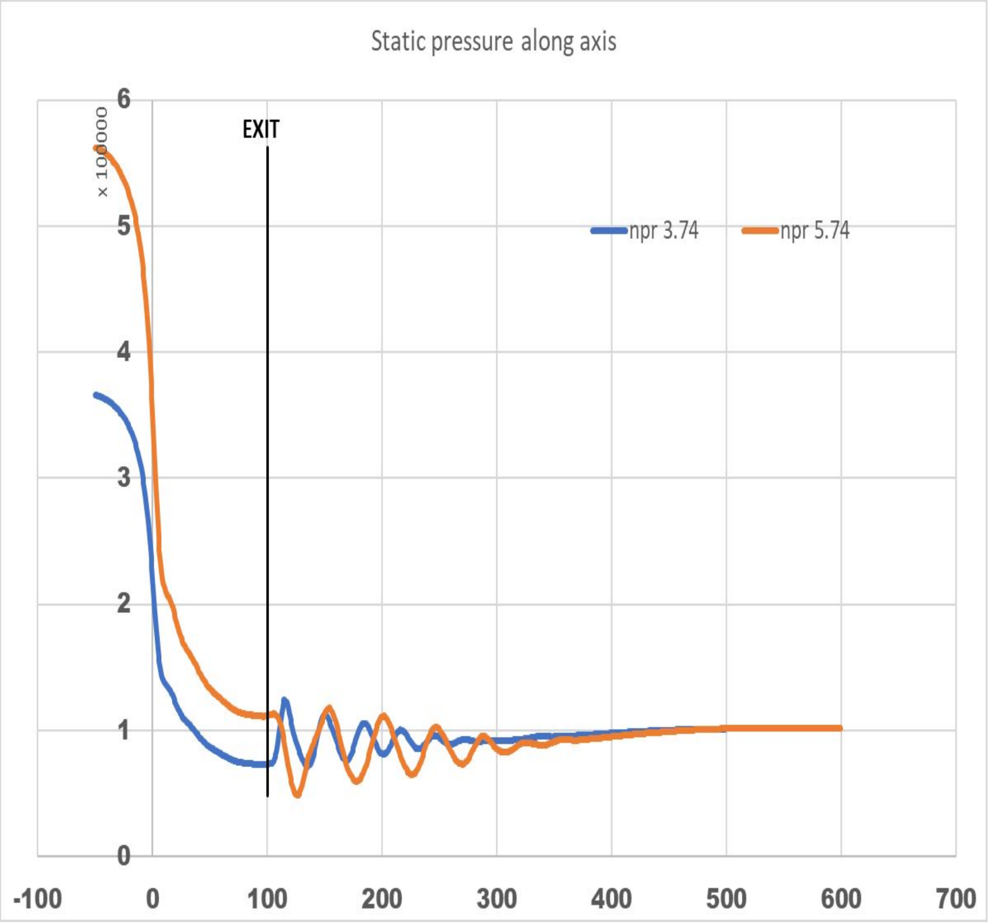
MACH CONTOUR NPR 3.74 (over-expansion)

Plane of symmetry contour



Existence of shockwaves can be quantitatively verified using the static pressure plots along the jet axis.

- For NPR 5.74, static pressure drop is observed just after the exit⇒ ***expansion waves***
- For NPR 3.74, static pressure rise is seen, indicating an oblique shock at the exit
- Further expansion and compression of the flow in numerous shock cells can also be seen as a series of ‘fluctuations’ in the static pressure.



INFERENCES - CFD :

- Exit supersonic jet is made visible, mirrored along the plane of symmetry
- Iso-velocity (potential flow core), transition regions are seen
- Shear layer profile is also visualized, seen as a region of low Mach number
- Effect of the wall, Shear layer on the overall flow at the exit is observed.
- Mach number at the exit (from y=0 to y=11.99 mm) are plotted

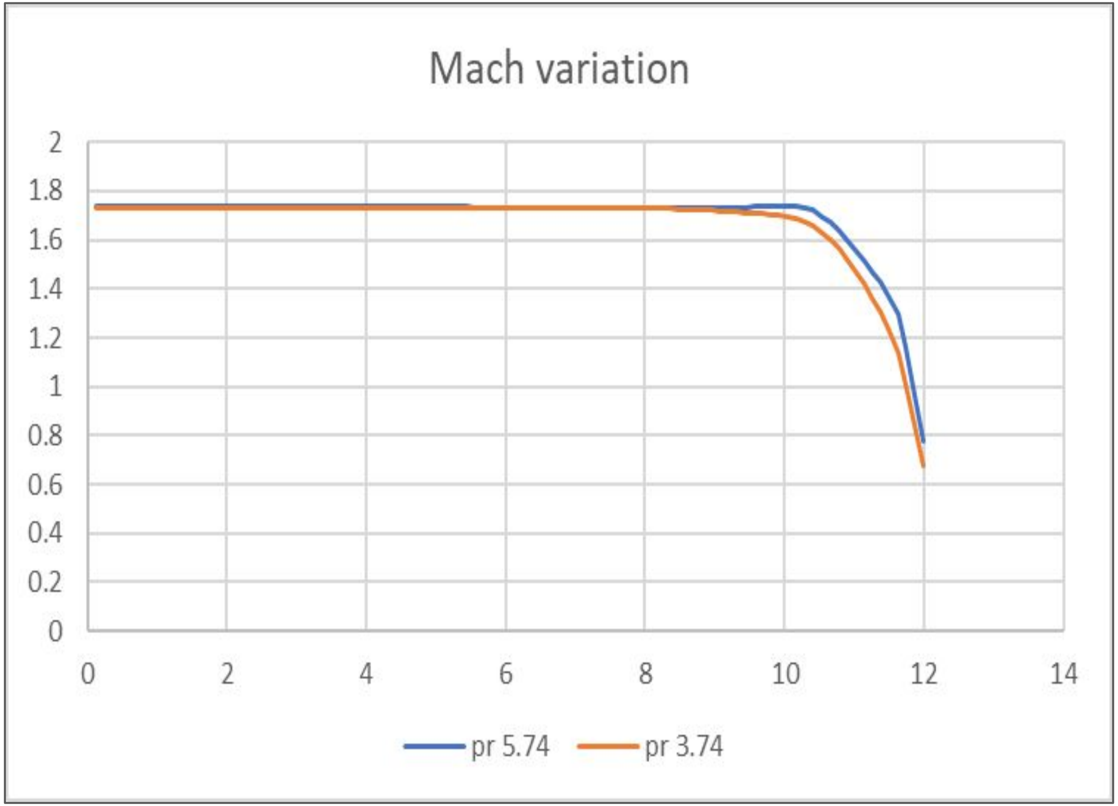
Data @ exit :

⇒ **M at exit** is plotted for both tested NPR

(surface split - rake , 100 points)

Viscous effects cause a **drop in M (0.79 & 0.66 at wall)**

Taken along plane of symmetry



EXPERIMENTAL SETUP

- Blowdown wind tunnel facility is used
- Mach 1.8 base nozzle is operated at NPR 5.74 and 3.74
- Data sampling is done at the exit
  - @ points 5mm from the axis horizontally and vertically
- Long cone and pitot probes are used to measure pressure
- Calibrating M ⇒ Rayleigh Pitot formula
- MATLAB implementation for ease of computation

$$\frac{P02}{P1} = \left(\frac{(\gamma+1)^2 M^2}{4\gamma M^2 - 2(\gamma-1)}\right)^{\frac{\gamma}{\gamma-1}} * \frac{1-\gamma+2\gamma M^2}{\gamma+1}$$

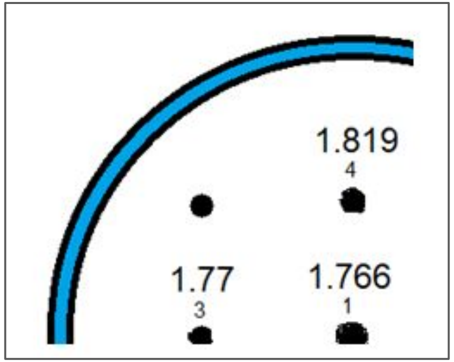
Experimental analysis → Results:

⇒ M 1.8 nozzle calibrated and operated at

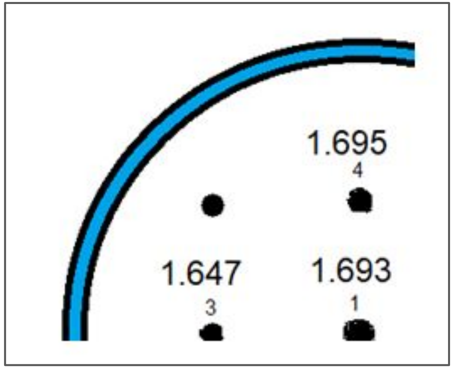
NPR 5.74 bar & NPR 3.74 bar

⇒ Quadrant sections are analysed (CFD done for only a quadrant of 3D model)

⇒ Data values at design NPR are collected , averaged and checked with rayleigh Pitot formula ; implementation of *MATLAB code*



NPR 5.74



NPR 3.74

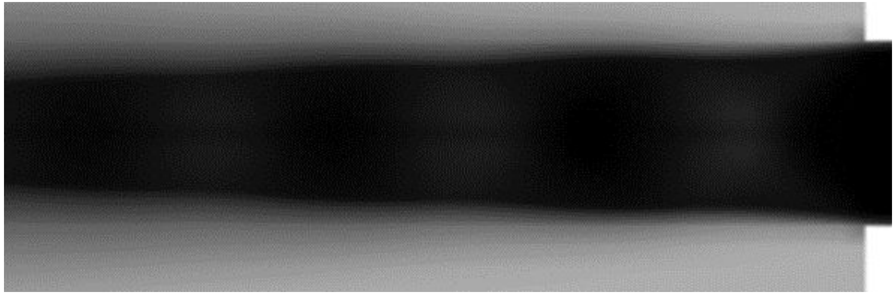
Data sampling points in nozzle , each point at 5 mm distance

RESULTS

x	y	NPR5.74 computed	NPR5.74 experimental	NPR3.74 computed	NPR3.74 experimental
0	0	1.739	1.766	1.733	1.693
0	5	1.735	1.819	1.733	1.695
5	0	1.735	1.77	1.733	1.647

OVEREXPANSION - CASE STUDY

- Shadowgraph for NPR 3.74 compared with computational results
- Shear layer profiles are nearly the same
- Shock structure is not sharp, but are represented as dark black and grey bands



FURTHER WORK:

- To better visualize shock patterns employing a post-processing software
- To simulate other NPR’s numerically

Conclusions

- Variation of mach number at the exit ⇒ **viscous effects dominate**
  - Causes M to reduce as distance from axis approaches the wall
- Significant difference is observed between numerical and experimental values
  - Simulation conditions, unpredictable nature of flow
  - Necessity to carry out simulation further for more accurate results.
- Values in results are not symmetric, wall shear and a minute degree of rotation in the overall nozzle flow.

Experimental values show a slight deviation from the predicted theoretical value at the exit. Computed values differ significantly from the experimental and theoretical values

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