AERODYNAMIC DESIGN AND PRESENTATION OF NOZZLES WITH DIFFERENT MACH NUMBERS USING CFD ANALYSIS

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Abstract - **The design of an exhaust nozzle system for an aircraft having a supersonic cruise mission is typically optimized for a cruise condition and also must provide sufficient thrust performance at other important operating points such as takeoff and transonic conditions. In contrast, the exhaust nozzle system for a vehicle with an accelerating mission must provide optimal performance across the flight envelop as there is not a fixed cruise point where the aircraft operates the majority of the time.**

The aerodynamic design and performance analysis of two exhaust nozzles considered for use on a vehicle following an accelerating flight profile to a maximum flight speed corresponding to different Mach numbers will be analyzed using CFD analysis.

3D models will be done in UX and CFD analysis will be done in ANSYS. Theoretical calculations will also be done to compare with that of analytical results

1. IntroductionNozzle

When selecting a nozzle, make sure you fully understand its capabilities with your current system. Whether it's a nozzle you've had for 15 years or a new nozzle someone is trying to sell you, put the nozzle on your standard hose load and, with a digital gpm gauge, perform flow testing to ensure you get adequate water. Also consider reach, penetration and reaction force on the firefighter. The only way to truly know what you're getting with a nozzle is to do formalize testing. When using any nozzle to extinguish a fire, keep in mind that actual flow may be affected by many variables, such as differences in piping from the pump to the discharge point, increasing friction loss, variances in those types and their individual friction loss, kinks in the hose, different pump pressures, water supply issues and debrispassing through the water system. Today's nozzles offer a wide variety of features, characteristics and uses. The key is determining which nozzle is right for your needs. To help you make that determination, here's a breakdown of some of the basic nozzle types,

And the pros and cons of each. The smooth-bore nozzle, which has been around for many years, could be considered the staple of the American fire service. Typically, the smooth-bore nozzle produces the greatest reach/gpm combination of all nozzles while at the same time using the lowest engine pump pressures.

The smooth-bore will also maintain the same water pattern to reach the seat of the fire, keeping the pattern compact and getting large amounts of water at the seat of the fire. One drawback is that unless the water pattern is broken up, the water from a smooth-bore won't absorb as much heat as its broken or fog-streamcounterparts.

1.1 Factors affecting spray- All the data relating to nozzles contained in this catalog are based on spraying water at standard temperatures. When spraying liquids other than water, performance is likely to be different. The following presentation describes how various liquid properties andoperating conditions affect performance.

1.2 Capacity - A nozzle's flow rate capacity is primarily dependent of the operating pressure. For hydraulic nozzles, this relationship is straightforward. Capacity C increases in direct proportionality to the square root of the operating pressure P; that is C ~ P1/2. For air assisted nozzles, in which both air pressure and liquid pressure play a role, this simple relationship does not generally hold althoughthe trend of increasing capacity with pressure does.

2. Literature Review

2.1 Aerodynamic Design and Analysis of High Performance Nozzles for Mach 4 Accelerator Vehiclesby Nicholas J. Georgiadis, Teryn W. DalBello, Charles J. Trefny, and Albert L. Johns,NASA Glenn Research Center, Cleveland, OH 44135,44th AIAA Aerospace Sciences Meeting and Exhibit9 - 12 January 2006, Reno, Nevada

2.2 Design and experimental consideration for gas dynamics ofMems based micro supersonic nozzle By TomoakiFujii, Shuichi Furuya, Hideaki Tsukahara, Hiroshi Kawabata,Naoki Takano and Toshiyuki Toriyama

2.3 Numerical simulation and optimization of high performance supersonic nozzle at different conical anglesByA.ShanthiSwaroopini, M.Ganesh Kumar, T.Naveen Kumar,IJRET: International Journal of Research in Engineering and Technology eISSN: 2319-1163| pISSN: 2321-7308

2.4CFD Analysis of a Highly Loaded Gas Turbine StageByPrathapanayaka R, AgnimitraSunkara SN, Balamurugan M, Kishor Kumar4,17th Annual CFD Symposium, August 11-12, 2015, Bangalore

2.5CFD Analysis of Complex Flow through Multiple Nozzle DrivenAerodynamic Laser Cavity ByS. D. Ravi, N. K. S. Rajan, P.S.Kulkarni, National Conference on Recent Trends in Mechanical Engineering Science RTIMES-2007,November 15-16, 2007

2.6 Modelling and Simulation of Supersonic Nozzle Using Computational Fluid DynamicsByVenkatesh .V, C Jaya pal Reddy, International Journal of Novel Research in Interdisciplinary Studies Vol. 2, Issue 6, pp: (16-27), Month: November-December 2015.

2.7 Calculation and design of supersonic nozzles for cold gas dynamic spraying using matlab and ansys fluentBy Jean-Baptiste Mulumba Mbuyamba

3. Problem statement

In this thesis, the performances of the convergent and convergent – divergent nozzles at different Mach numbers and also by changing the lengths of the nozzle are investigated. The investigations are carried out in order to determine pressure distribution, velocities, Reynolds number and mass flow rates in the nozzle. The above results are investigated to determine better flow condition and nozzle length.

4.Introduction to Unigraphics

NX was originally called Unigraphics. The Unigraphics software was developed by the United Computing. In 1977 Mc Donnell Douglas acquired United Computing and subsequently formed the McDonnell Douglas Automation Unigraphics Group. EDS acquired the business in 1991. When EDS acquired Structural Dynamics Research Corporation(SDRC) in 2001, Unigraphics was combined with SDRC's I-DEAS CAD product. The gradual addition of I-DEAS functionality into the Unigraphics code base was the basis for the current NX product line.

4.1 Convergent Model

4.1.1 Surface object (Length 101.6 mm)

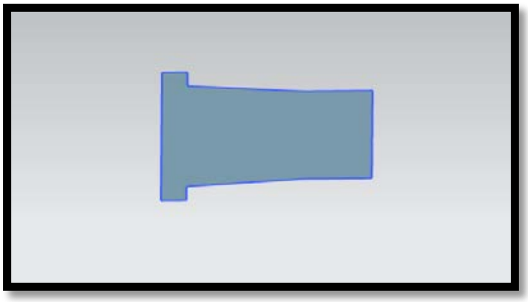


Figure-1 1st Model image of Convergent in Unigraphics

4.1.2 Surface object (Length 110.236 mm)

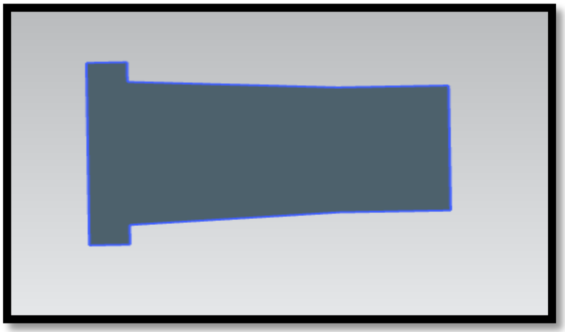


Figure-2 2nd Model imageof Convergent in Unigraphics

4.1.3 Surface object (Length 127 mm)

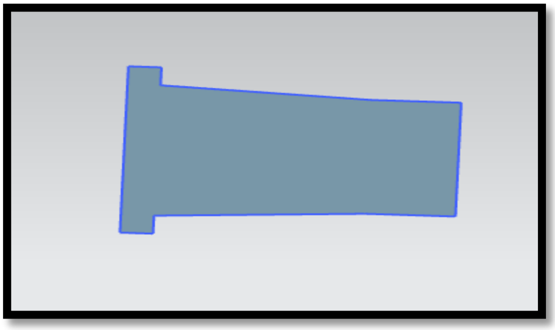


Figure-3 3rdModel image of Convergent in Unigraphics

4.1.4 Surface object (Length 135.66 mm)

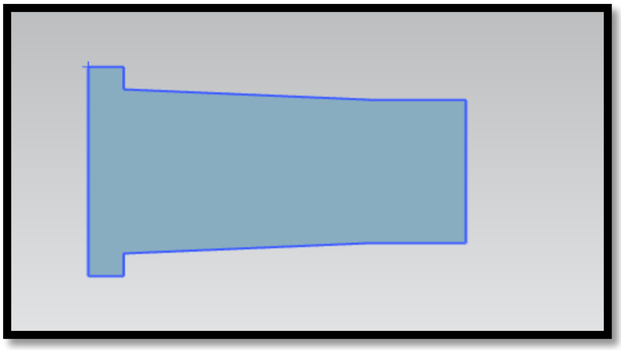


Figure-44th Model image of Convergent in Unigraphics

4.2. Convergent-Divergent model

4.2.1 Surface object (Length 152.4 mm)

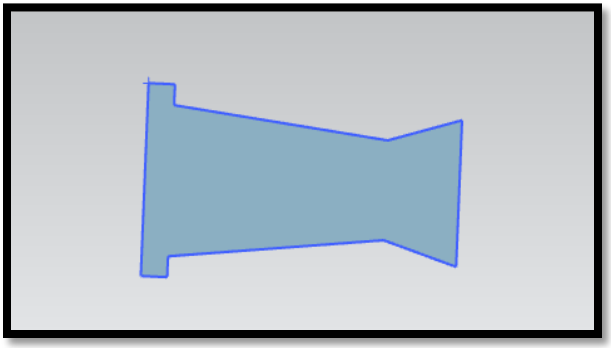


Figure-51st Model image of Convergent-Divergent in Unigraphics

4.2.2 Surface object (Length 162.824 mm)

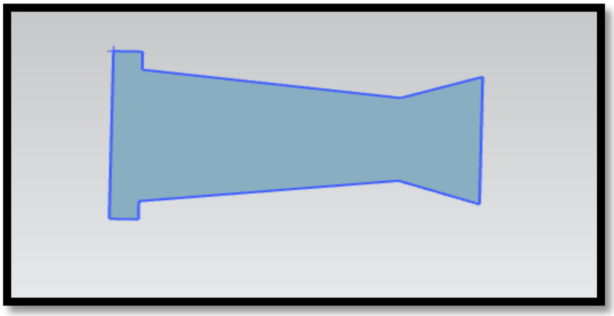


Figure-62nd Model image of Divergent in Unigraphics

4.2.3 Surface object (Length 177.8 mm)

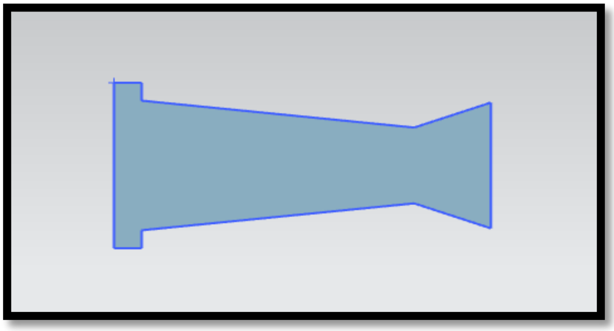


Figure-73rd Model image of Divergent in Unigraphics

4.2.4 Surface object (Length 188.214 mm)

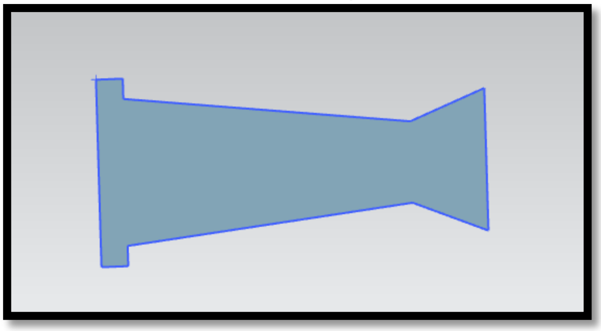


Figure-84th Model image of Divergent in Unigraphics

5. Introduction to ANSYS

ANSYS is general-purpose finite element analysis (FEA) software package. Finite Element Analysis is a numerical method of deconstructing a complex system into very small pieces (of user-designated size) called elements

5.1 Introduction to CFD

Computational fluid dynamics, usually abbreviated as CFD, is a branch of fluid mechanics that uses numerical methods and algorithms to solve and analyze problems that involve fluid flows. Computers are used to perform the calculations required to simulate the interaction of liquids and gases with surfaces defined by boundary conditions. With high-speed supercomputers, better solutions can be achieved. Ongoing research yields software that improves the accuracy and speed of complex simulation scenarios such as transonic or turbulent flows. Initial experimental validation of such software is performed using a wind tunnel with the final validation coming in full-scale testing, e.g. flight tests.

6. CFD Analysis for aerodynamic nozzle convergent model

6.1 Fluid –Nitrogen

Model length - 101.6mm

6.1.1 Pressure:

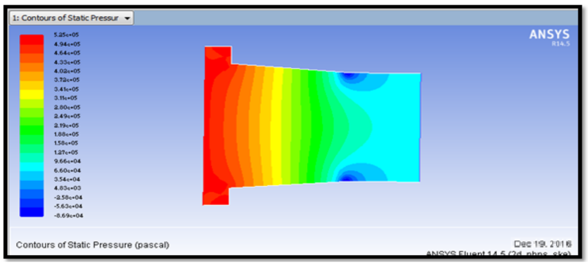


Figure-9Pressure result of Convergent in ANSYS CFD

6.1.2 Velocity

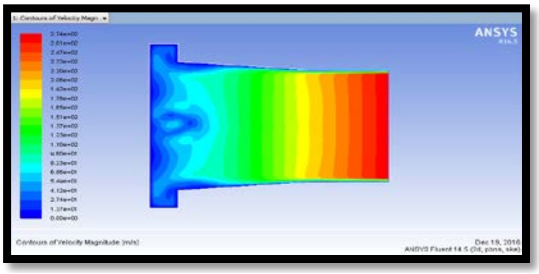


Figure-10Velocity result of Convergent in ANSYS CFD

6.1.3 Reynolds number

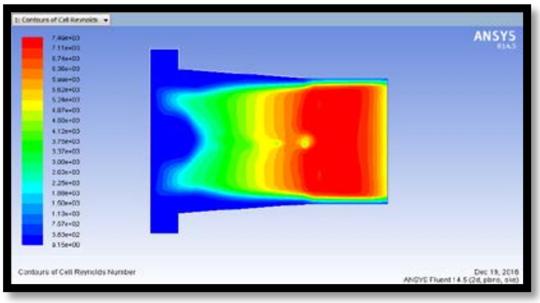


Figure-11Reynolds number result of Convergent in ANSYS CFD

6.1.4 Temperature

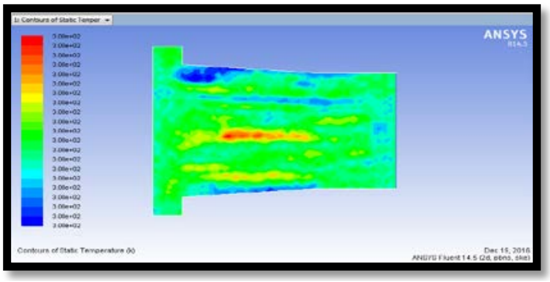
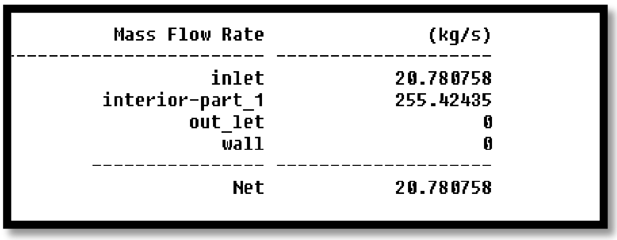


Figure-12Temperatureresult of Convergent in ANSYS CFD

6.1.5 Mass flow rate



```
            Mass Flow Rate                  (kg/s)
-------------------------- --------------------
                     inlet            20.780758
           interior-part_1            255.42435
                   out_let                    0
                      wall                    0
           ---------------- --------------------
                       Net            20.780758
```

Figure-13Mass flow rateresult of Convergent in ANSYS CFD

6.1.6 Heat transfer rate

Figure-14Heat transfer rate result of Convergent in ANSYS CFD

6.2 convergent- divergent modal

Fluid –nitrogen

Model length – 152.4 mm

6.2.1 Pressure

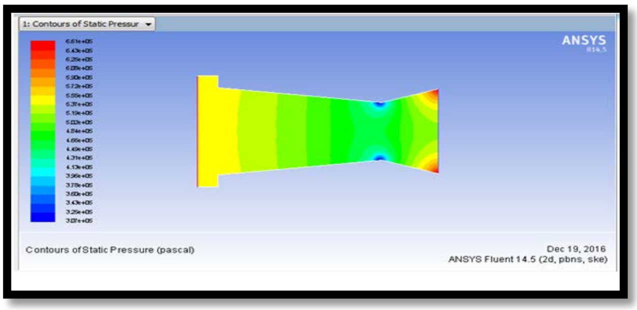


Figure-15Pressure result of Convergent in ANSYS CFD

6.2.2 Velocity

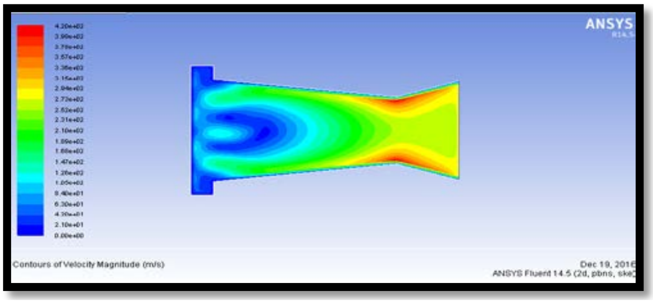


Figure-16Velocity result of Convergent in ANSYS CFD

6.2.3 Reynolds number

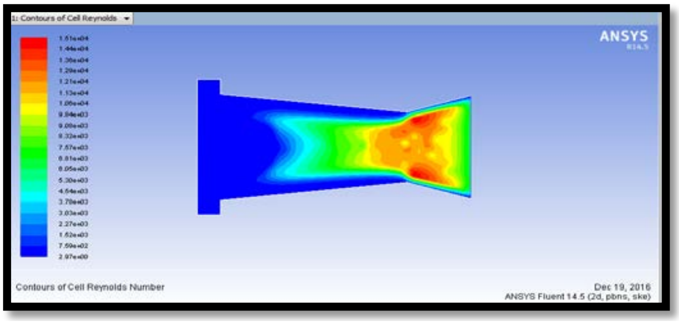


Figure-17Reynolds number result of Convergent in ANSYS CFD

6.2.4 Temperature

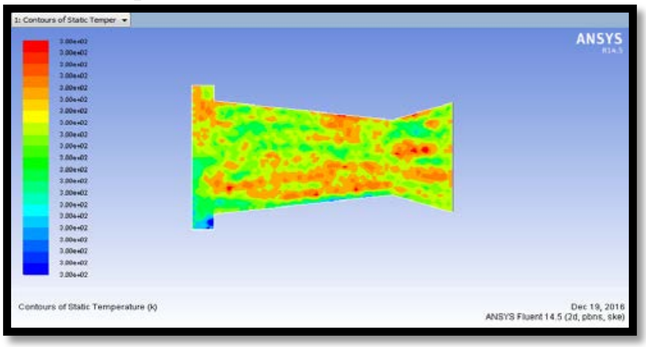


Figure-18Temperatureresult of Convergent in ANSYS CFD

6.2.5 Mass flow rate

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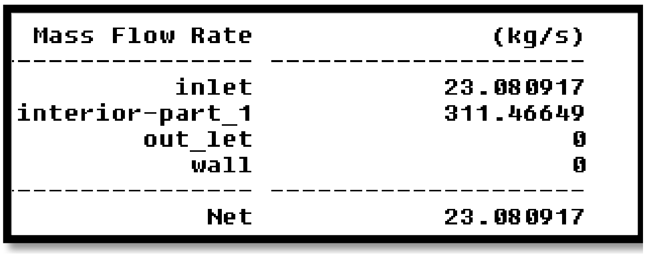
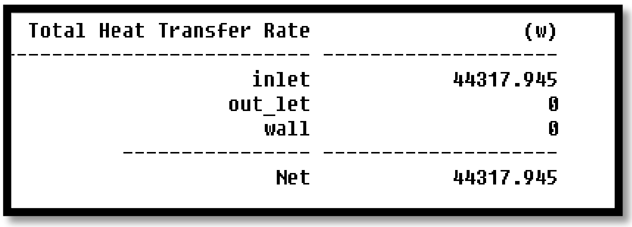


```
 Mass Flow Rate                          (kg/s)
-------------------------------- --------------------
                inlet                 23.080917
interior-part_1                      311.46649
              out_let                          0
                 wall                          0
-------------------------------- --------------------
                  Net                 23.080917
```

Figure-19Mass flow rateresult of Convergent in ANSYS CFD

6.2.6Heat transfer rate



```
 Total Heat Transfer Rate                        (w)
-------------------------------- --------------------
                     inlet              44317.945
                   out_let                      0
                      wall                      0
                ---------------- --------------------
                       Net              44317.945
```

Figure-20 Heat transfer rate result of Convergent in ANSYS CFD

7. Results table

7.1Convergent

7.1.1 Model length = 101.6mm

Mach number	Pressure (Pa)	Velocity (M/s)	Reynolds number	Temperature (K)	Mass flow Rate (kg/s)	Heat transfer rate (w)
0.8	5.25e+05	2.74e+02	7.49e+03	3.00e+02	20.780758	39901.379
1.2	9.25e+05	4.12e+02	1.43e+04	3.00e+02	31.171146	59852.063
5	4.53e+06	1.72e+03	1.38e+05	3.00e+02	129.87976	249383.61

Table -1 Convergent result for modal-1

7.1.2 Model length = 110.236mm

Mach number	Pressure (Pa)	Velocity (M/s)	Reynolds number	Temperature (K)	Mass flow Rate (kg/s)	Heat transfer rate (w)
0.8	4.81e+05	2.79e+02	1.09e+04	3.00e+02	5.722045e-06	0.35546875
1.2	8.81e+05	4.19e+02	2.09e+04	3.00e+02	0.02038765	40.554688
5	4.44e+06	1.75e+03	1.95e+05	3.00e+02	0.038833618	72.34375

Table -2 Convergent result for modal-2

7.1.3 Model length = 127mm

Mach number	Pressure (Pa)	Velocity (M/s)	Reynolds number	Temperature (K)	Mass flow Rate (kg/s)	Heat transfer rate (w)
0.8	4.44e+05	2.78e+02	1.21e+04	3.00e+02	0.001581195	2.34375
1.2	8.24e+05	4.17e+02	2.33e+04	3.00e+02	0.0011749268	2.7382813
5	4.31e+06	1.74e+03	2.14e+05	3.00e+02	0.028411865	54.140625

Table -3 Convergent result for modal-3

7.1.4 Model length = 135.636mm

Mach number	Pressure (Pa)	Velocity (M/s)	Reynolds number	Temperature (K)	Mass flow Rate (kg/s)	Heat transfer rate (w)
0.8	4.61e+05	2.78e+02	1.27e+04	3.00e+02	0.0390625	0.0002117157
1.2	7.81e+05	4.17e+02	2.44e+04	3.00e+02	0.0007648468	2.2203125
5	4.22e+06	1.74e+03	2.16e+05	3.00e+02	0.020019531	34.484375

Table -4 Convergent result for modal-4

7.2Convergent-Divergent

7.2.1 Model length = 152mm

Mach number	Pressure (Pa)	Velocity (M/s)	Reynolds number	Temperature (K)	Mass flow Rate (kg/s)	Heat transfer rate (w)
0.8	6.61e+05	4.20e+02	1.51e+04	3.00e+02	23.080917	44317.945
1.2	1.06e+06	6.30e+02	2.95e+04	3.00e+02	34.621384	66476.906
5	5.52e+06	2.63e+03	2.83e+05	3.00e+02	144.25578	276987.16

Table -5 Convergent-Divergent result for modal-1

7.2.2 Model length = 162.814mm

Mach number	Pressure (Pa)	Velocity (M/s)	Reynolds number	Temperature (K)	Mass flow Rate (kg/s)	Heat transfer rate (w)
0.8	5.88e+05	4.37e+02	1.60e+04	3.00e+02	24.845444	46259.625
1.2	9.5e+05	6.56e+02	3.12e+04	3.00e+02	37.268173	69389.445
5	4.6e+06	2.74e+03	2.95+05	3.00e+02	155.28404	289122.69

Table -6Convergent-Divergent result for modal-2

7.2.3 Model length = 177.8

Mach number	Pressure (Pa)	Velocity (M/s)	Reynolds number	Temperature (K)	Mass flow Rate (kg/s)	Heat transfer rate (w)
0.8	4.92e+05	5.58e+02	2.13e+04	3.00e+02	0.0052032471	8.7734315
1.2	8.42e+05	8.37e+02	4.15e+04	3.00e+02	0.01128006	20.992188
5	4.44e+06	3.49e+03	3.99e+05	3.00e+02	0.04460034	75.65625

Table -7Convergent-Divergent result for modal-3

7.2.4 Model length = 188.214mm

Mach number	Pressure (Pa)	Velocity (M/s)	Reynolds number	Temperature (K)	Mass flow Rate (kg/s)	Heat transfer rate (w)
0.8	4.63e+05	5.85e+02	2.30e+04	3.00e+02	0.0026283264	5.8085938
1.2	7.63e+05	8.78e+02	4.44e+04	3.00e+02	0.004650116	8.71875
5	4.06e+06	3.66e+03	4.21e+05	3.00e+02	0.00079345703	-10.5625

Table -8Convergent-Divergent result for modal-4

8. Conclusion

The aerodynamic design and performance analysis of two exhaust nozzles convergent model and convergent – divergent models by changing the lengths of the nozzle under subsonic, transonic, supersonic flow conditions. The comparisons are made for pressure distribution, velocity and mass flow rates.

3D models are done in NX and CFD analysis is done in Ansys.

By observing the results, the velocity is increasing along with the length of the nozzle. Pressure gradually decreased along the length of the nozzle except a slight rise during the shocking. However, the rise was not significant comparing to the total fall in pressure. According to Bernoulli's equation, pressure decreases as velocity increases. Mass flow rates are increasing by increase of Mach numbers but decreasing due to increase of lengths. The values are increasing by increasing the length of the nozzle. This is due to fact that by increasing the lengths the fluid is compressed inside the nozzle.The pressure distribution, velocities are more under super-sonic flow conditions due to high inlet velocities.

So it can be concluded that increasing Mach numbers and lengths yields to better performance of nozzle.

9. Future scope

In this thesis, only the performances of the convergent and convergent – divergent nozzles are investigated for fluid flow conditions. But also the mechanical, thermal, and structural factors would need to be considered in overall system studies in order to make the optimal selection.

10. References

[1] Deng Qingfeng, ZhengQun , Yue Guoqiang , Zhang Hai , Luo Mingcong, “Using a Pressure Controlled Vortex Design Method to Control Secondary Flow Losses in a Turbine Stage", Chinese Journal of Aeronautics,2013,26(5),pp 1125–1134

[2] John D Denton, "Some Limitations of Turbomachinery CFD”, Proceedings of ASME Turbo Expo 2010: Power for Land, Sea and Air, 2010, PaperGT2010-22540

[3] Prathapanayaka et. al, "Design and Development of 385kW turbine stage for Small Gas Turbine Engine", Project Document,PD-PR/2015/1000, 2015,Propulsion Division, National Aerospace Laboratories, Bangalore.

[4] Hany Moustapha, Mark F.Zelesky, Nicholas C.Baines, David Japikse; Axial and Radial Flow Turbines, Published by Concepts NREC, 2003

[5] NASA SP-290, “Turbine Design and Application”, 1994

[6] Anderson JD, [2001], Fundamentals of Aerodynamics, 3rd Edition, pp.532-537, pp.555-585.

[7] Anderson JD, [1982], Modern Compressible Flow with Historical, pp.268-270, pp.282-286.

[8] Shapiro, AH, [1953], The Dynamics and Thermodynamics of Compressible Fluid Flow, Vol.1, pp. 294-295.

[9] Shapiro, AH, [1953], The Dynamics and Thermodynamics of Compressible Fluid Flow, Vol.2, pp. 694-695.

[10] Farley John M, Campbell Carl E, [1960], Performance of several characteristics exhausts nozzles, NASA Lewis Research center.

[11] Angelino, G., Oct. [1964], "Approximate Method for Plug Nozzle Design", AIAA Journal, Vol. 2, No. 10, pp. 1834-1835.

[12] J.Reid, [1964], An Experiment on Aerodynamics nozzles at Mach 2, Aeronautical research council reports &memoranda, R & M. No 3382.

[13] G T Galesworthy, JB Robert and C Overy [1966], the Performance of conical convergent divergent nozzles of arearatio 2.44 and 2.14 in external flow. Aeronautical Research Council CP No 893.

[14] TV Nguyen and JL Pieper [1996], Nozzle separation prediction techniques and controlling techniques, AIAA paper.

[15] Gerald Hagemann, [1998], Advanced Rocket Nozzles, Journal of Propulsion & Power, Vol.14, and No.5.

[16] Dale, D., Kozak, J., Patru, D., [2006], "Design and Testing of a Small Scale Rocket for Pico- Satellite Launching", Rochester Institute of Technology METEOR Project, Senior Design Project 06006.

[17] Nicholas J Georgiadis, Teryn W DalBello, Charles J Trefny, and Albert L. Johns,[2006],Aerodynamic Design and Analysis of high performance nozzles for Mach 4 Accelerator Vehicles.