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COMPARISON OF NOZZLE PRESSURE RATIOS

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Abstract - *A nozzle is a relatively simple device, just a specially shaped tube through which hot gases flow. However, the mathematics which describes the operation of the nozzle takes some careful though, nozzles come in a variety of shapes and sizes depending on the mission of the aircraft. Simple turbojets, and turboprops, often have a fixed geometry convergent nozzle as shown on the left of the figure. Turbofan engines often employ a co-annular nozzle as shown at the top left. The core flow exits the center nozzle while the fan flow exits the annular nozzle. Mixing of the two flows provides some thrust enhancement and these nozzles also tend to be quieter than convergent nozzles. Afterburning turbojets and turbofans require a variable geometry convergent-divergent - CD nozzle. In this nozzle, the flow first converges down to the minimum area or throat, and then is expanded through the divergent section to the exit at the right. The flow is subsonic upstream of the throat, but supersonic downstream of the throat. The variable geometry causes these nozzles to be heavier than a fixed geometry nozzle, but variable geometry provides efficient engine operation over a wider airflow range than a simple fixed nozzle.*

Key Words: ANALYSIS, COMPARISONS, NOZZLE PRESSURE RATIOS, RAMP ANGLE, CONVERGENT-DIVERGENT (CD) NOZZLE

1. INTRODUCTION

The convergent-divergent (CD) nozzle was introduced in the l950's in an effort to further increase the Mach number capability of military fighter aircraft. The addition of a divergent section to a convergent nozzle provided further expansion of the flow to supersonic conditions at the nozzle exit; this resulted in an increase in momentum thrust. Convergent divergent nozzles often incorporate variable geometry to maintain high performance over a wide range of flight conditions. The F-4 represented the first proof of concept for the CD nozzle; now CD nozzles are utilized in most supersonic military aircraft. Nozzle design improvements continued throughout the 1960's and 1970's with an emphasis on increased installed thrust. The non-axis-symmetric convergent-divergent nozzle was envisioned late in this period, with prospects of installed performance gains over the axis-symmetric nozzles employed in aircraft such as the F-14 and F-15. As a result of improved nozzle integration with the airframe, the non-axis-symmetric nozzle offers performance gains from a reduction in aft-end drag. Non-axis-symmetric designs also offer the designer additional freedom to integrate vectoring and reversing hardware into the nozzle.

1.1 Motivation of the work

The convergent divergent nozzle at various operating condition (i.e. over expanded conditions) causes the various flow separations occurred in the nozzle. The analysis of the various single expansion ramp nozzles can be carried out to examine the flow behavior.

1.2 Objective

- The main objective of this work is to understand the flow by optimizing the geometry of the single expansion ramp nozzles.
- To investigate the basic flow features inside the nozzle.
- To investigate the Mach number variation at different NPRs.
- To investigate the flow separation phenomena in different nozzle configuration and at different NPRs.
- To identify the efficient operating conditions with respect to the nozzle pressure conditions and the effect of the initial ramp angle.

2. METHODOLOGY

The objective of this work is to analyze the flow through three different SERN nozzles having different initial ramp angle at different NPRs. In addition, it also compares the performance parameters like actual to ideal thrust ratio, total pressure loss and nozzle efficiency. Furthermore, it also analyzes the effect of initial ramp angle on the pressure plot.

2.1 project methodology

- Single Expansion Ramp Nozzle (SERN) has been chosen for computing the flow through the nozzle.
- Three different SERN nozzles having different initial ramp angle has been considered for analysis.
- These different nozzle configurations are named as AP1, BP1and CP1.
- 10 NPR cases are considered for the AP1 nozzle.
- There are 11 cases are considered for the BP1 nozzle.

- There are 10 NPR cases are considered for the CP1 nozzles.
- For the two types of nozzles various boundary conditions are calculated based on different NPR conditions.
- Model type used here is 2D.
- 2D model has been generated using the Gambit software.
- ANSYS FLUENT commercial code has been used for computation
- For generating the grid different Y values are calculated for different cases.
- Based on different NPR conditions various types of pressure and Reynolds number are calculated with the help of the gas tables.
- Three locations were investigated using the calculations for generating the grid.
  1. Inlet
  2. Throat
  3. Outlet
- The mesh has been generated in three different nozzles by using Gambit commercial preprocessor code.
- The meshed nozzles have been simulated for the given boundary conditions at different NPRs by using ANSYS FLUENT.
- Three points are created through the center of the AP1, BP1 and CP1nozzles.
- Then variation of the centerline Mach plot was done for the three types of nozzles with different NPR cases.
- In order to find out the flow separation analyzing of the wall shear stress for AP1, BP1 and CP1 nozzles with different cases are done.
- Comparison of three nozzles with numerical calculations and experimental results are done.
- Thrust variation occurred for the three types of nozzles AP1, BP1 and CP1 are calculated and then compared with the experimental results.
- Effect of the initial ramp angle also identified for the three cases.

The single expansion ramp nozzles with various NPR conditions are considered. The investigations are done in the inlet, throat and at the outlet. The various analyses of the nozzles with pressure, velocity, Mach number and mass flow rates are considered. The investigations on various ramp surfaces were also considered in the methodology. The model development and the meshing of two types of nozzles with different NPR conditions are done. Analyzing of the nozzles based on the various NPR conditions and the effect of initial ramp angle for the three cases are done.

3 ANALYLSIS PARAMETER

3.1 MESHING

In this project, Geometry and meshing has been carried out for three different single expanded ramp nozzles (AP1, BP1 and CP1). Depending upon the values of NPRs, fine grid has been generated near the boundary based on the value of y+ (y+ =5). The three different geometry (AP1, BP1 and CP1) has been meshed for ten, eleven and ten different NPRs respectively. In all the cases, quad mesh has been generated. By considering the value of y plus at different NPR conditions in all three geometries, quad mesh has been generated using GAMBIT. y+ has been taken as 5. The calculation of first grid size from the boundary (y) are explained as follows

R= 287.3 Density, $\rho = \frac{P}{RT}$

Nozzle Pressure Ratio NPR = Po/Pe, Pe =101325 pa
Ai/A*=2.68, Pi/Po = 0.97112, Ti/To=0.994682,To=500k
From the gas table

By considering the Reynolds number, velocity, and the universal velocity profile meshing of the AP1, BP1 and CP1 nozzles with respect to the nozzle pressure ratio conditions. Here by considering the pressure inlet, the pressure outlet, top wall, and the bottom wall the meshing is done. Fluid used for the meshing is air. The y values should be calculated for the each case .Meshing is done for the each case with respect to the y values.

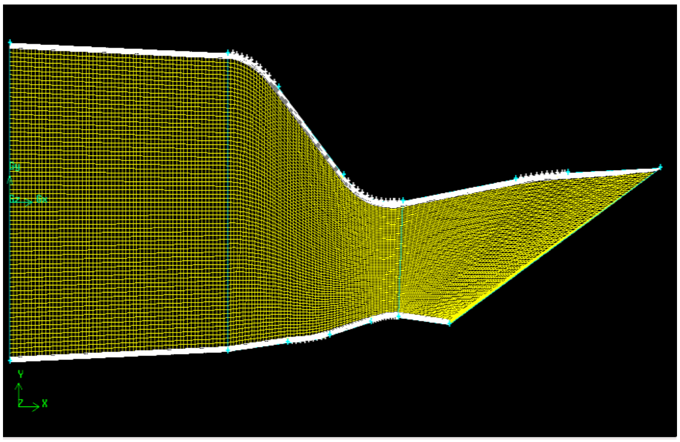

Fig-1: Meshing model for AP1 nozzle

AP1 NOZZLE

In the case of the AP1 nozzles y value is calculated for the ten cases of the nozzle pressure ratio conditions. So that the meshing is done for the each ten cases of nozzle pressure ratio conditions

Case 1 NPR =2.003	**Case 2 NPR = 2.505**
INLET $\rho = 1.38\ kg/m^3$ $V = 71.52\ m/sec$ $\mu_i=2.4688*10^{-5} kgm/sec$ $Re =0.95 * 10^5$ **THROAT** $\rho = 0.93\ kgm/sec$ $V = 427.35\ m/sec$ $\mu_t = 2.4763 * 10^{-5} kgm/sec$ $Re = 4.11 * 10^5$ $C_f = 0.0055$ $\nu = 2.66 * 10^{-5} m^2/sec$ $\sqrt{\tau w/\rho} = 22.41$ $y =0.0059\ mm$	**INLET** $\rho = 1.726 kg/m^3$ $V = 71.52\ m/sec$ $\mu_i= 2.4688 * 10^{-5} kgm/sec$ $Re =1.19 * 10^5$ **THROAT** $\rho = 1.098\ kg/m^3$ $V = 427.35\ m/sec$ $\mu_t = 2.4763 * 10^{-5} kgm/sec$ $Re = 4.850 * 10^5$ $C_f = 0.0053$ $\nu = 2.255 * 10^{-5} m^2/sec$ $\sqrt{\tau w/\rho} = 21.99$ $y =0.0051\ mm$

BP1 NOZZLE and CP1 NOZZLE are same as the AP1 nozzle reading and calculations done. In this project there is three types of nozzles those have been meshed using GAMBIT at different NPR conditions. The meshed type used here is structured quad mesh. This type of mesh is more accurate than other type of mesh.

COMPUTATIONAL FLUID DYNAMICS

Computational fluid dynamics (CFD) is the branch of fluid dynamics providing a cost effective means of simulating real flow by solving the governing equations of fluid flow. The governing equations for Newtonian fluid dynamics are Navier-Stokes equations. It is still active in the area of research in particular for the turbulent problem.

$$\frac{\partial \rho}{\partial t} + \left[\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z}\right] = 0$$

BOUNDARY CONDITIONS

Boundary conditions have been applied at different boundaries for analyzing these nozzles (AP1, BP1and CP1) at different NPRs. Since total pressure at the inlet is calculated based on the value of NPR, boundary condition at inlet varies with NPRs. However, the boundary condition at outlet and wall are same for all the cases Outlet Boundary Condition
Pe =101325 pa
Wall Boundary Condition: Adiabatic, no slip wall.

Table-1: Inlet Boundary conditions for AP1 nozzle

Cases	NPR	Inlet pressure(pa)	Total pressure(pa)
1	2.003	197093.07	202953.975
2	2.505	246488.82	253819.125
3	3.010	296180.79	304988.250
4	3.407	335244.48	345214.275
5	4.010	394579.73	406313.250
6	5.015	493470.66	508144.875
7	6.021	592459.99	610077.825
8	7.492	737204.83	759126.9
9	8.605	846722.84	871901.625
10	10.037	987630.12	1016999.025

SST k-ω models have been used to capture the turbulent quantities in the present work. This model primarily captures the flow phenomena throughout the boundary layer, provided the near wall mesh resolution is sufficient this is an empirical model based on model transport equations for the turbulence kinetic energy (k) and the specific dissipation rate (ω), which can also be thought of as a ratio of ε and k. In this model, the turbulent viscosity is modified to account for the transport of the principal turbulent shear stress. It is this feature that gives this model advantage in terms of performance over both the standard k-ε model and the standard k-ω model. In addition to this, a cross diffusion term in the equation

RESULTS AND DISCUSSION

AP1, CP1 nozzles are analyzed with ten NPR cases and the BP1 nozzle is analyzed with the eleven NPR cases. First grid size near the boundary has been calculated by considering y plus=5 for all the three configuration and at each NPR (31 cases). Separate boundary layer grid has been generated for each cases. Hexahedral grid has been generated in the whole domain in each cases. The flow has been simulated with ANSYS FLUENT commercial code. The converged solutions obtained from the FLUENT are briefed below. The converged solutions captured the basic flow features like subsonic flow in the convergent region, sonic flow at throat and supersonic flow with or without separation depending upon the values of NPR. Fig- 6.2.1 shows Mach number contours of some of the cases where change in Mach number can be easily seen. In general, flow separation has been found in the range 2<NPR<7.4 as shown in X wall shear stress plot in Fig- 6.2.2 However, flow is not separated for higher NPRs. The negative value of X wall shear stress indicates the separation of flow.

3. CONCLUSIONS

The analysis of different nozzles can be done for the internal and static performance with respect to the various nozzle pressure conditions. The operating conditions for different nozzles can be examined by the various analysis of the flow separation and various effects of the ramp length in the single expansion ramp nozzles. The analyzing of the single expansion ramp nozzle is done by examining the flow separation and the variation in the Mach number with respect to the different nozzle pressure ratio conditions. There is flow separation occurred in the several cases of the nozzle pressure ratio conditions. In some of the cases the flow separations are not occurred this shows that at these operate conditions thrust performance is efficient. If the x wall shear stress is negative which shows that there is flow separation occurred. The comparison of the computational and the experimental results for the ideal thrust variation has been done with respect to the nozzle pressure ratio conditions. For the AP1 NPR cases 8, 9 and 10 shows good performance which means at the last three cases flow separation is low and which results in the good thrust performance. In the BP1 nozzles NPR cases 8,9,10 and 11 flow separation does not occur at these cases the shockwaves are reduced. From the BP1, AP1andCP1nozzles the thrust variation is less. These results shows that high NPR conditions the performance is efficient when compared to the lower cases. There are high increasing of Mach number and the velocity with respect to the increasing of nozzle pressure conditions.

FUTURE WORK

Detailed study can be done in the various cases of the different types of nozzles. In the cases of the non-axis symmetric single expansion ramp nozzles various flow analyses can be done by the additional adaption of the various dynamic pressure conditions without changing the nozzle parameters.

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