Shockwave and Mach Disk Comparison in Convergent and Convergent-Divergent Nozzles by Analyzing CFD Plots

Sanjay P[1] Sreenivasa T.N[2]
[1,2]Department of Mechanical Engineering
[1,2]AMC Engineering College, Bangalore- 560083

Abstract— A shock wave is a special kind of wave referred to as a steep, finite pressure wave. The change in the flow properties across such a wave are abrupt, in some situations, shocks are undesirable because they interfere with the normal flow behavior. Shock waves cause energy losses in relation to their intensity. At even higher pressure ratios, a Mach disc which is a straight shock front in the center of the jet with specifically high losses is formed [1]. Mach disk is a shock wave that is perpendicular to the direction of the flow which is called a normal shock wave. A normal shock can be seen when the flow turns parallel to the centerline. This normal shock creates a Mach disk in the exhaust flow. The compression waves force the flow to turn back inward and increase in pressure. If the compression waves are strong enough, they will merge into an oblique shock wave and form a new Mach disk [2] In the present investigation, an attempt was made to analyze and compare shockwave and Mach disk for Convergent nozzle (C nozzle) and Convergent- Divergent nozzle (CD nozzle) by considering the various CFD (Computational Fluid Dynamics) plots such as pressure plots and velocity vector plots. The pressure plot shows the pressure variation and the velocity vector plot shows presence of shockwaves across the nozzle. Fluent Software has been used for modeling, computation, simulation and to obtain the plots.

Key words: Shock Waves, Mach Disk, C Nozzle, CD Nozzle, CFD Plots

I. Introduction

A. *Shock Waves:*

When the change in flow variables is small and gradual, isentropic flow will occur. A supersonic flow that is turned while there is an increase in flow area is also isentropic. Since there is an increase in area, this is an isentropic expansion. If a supersonic flow is turned abruptly and the flow area decreases, the flow is irreversible due to the generation of shock waves. The operating pressure ratio determines the location and strength of the shock [3]

Pressure Distribution along a Converging-Diverging Duct: [4]

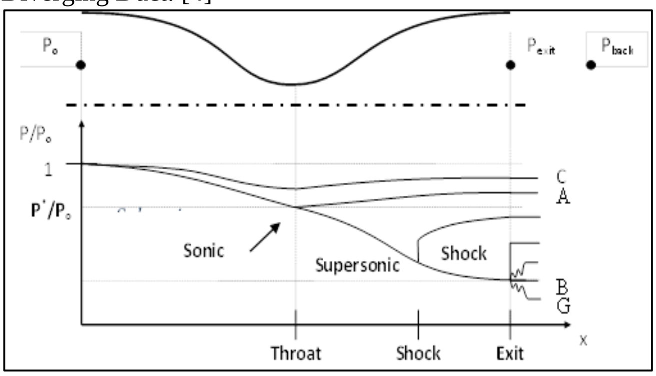

Fig. 1: Pressure Distribution along a Converging-Diverging Duct: [4]

Depends on the back pressure (Pback), we will have one of the following curves:

Curve A:	isentropic subsonic flow	Pexit = Pback
Curve B:	isentropic supersonic flow	
Curve C:	isentropic subsonic flow (Athroat ≠A*)	
Curve D:	normal shock within the nozzle	
Curve E:	normal shock at the nozzle exit	
Curve F:	2D oblique shock outside nozzle	(Pexit < Pback)
Curve G:	2D expansion wave outside nozzle	(Pexit > Pback)

B. *Mach Disk*

The phenomena known as Mach disks are high pressure regions in the exhaust from the exit of a nozzle. These regions are formed through a repeating, and decaying, series of shocks and expansions caused by the difference between the exit pressure around the nozzle and the atmospheric pressure. [5]

Mach disks (also called as Shock diamonds, Mach rings, or thrust diamonds) are a formation of standing wave patterns that appears in the supersonic of nozzle when it is operated in an atmosphere. The diamonds are formed from a complex flow field and are visible due to the abrupt changes in local density and pressure caused by standing shock waves. Shock diamonds form when the supersonic exhaust from a propelling nozzle is slightly over-expanded, meaning that the static pressure of the gases exiting the nozzle is less than the ambient air pressure. This pressure increase in the exhaust gas stream is isothermal, [6]

Figure-2 shows a sketch of a moderately under-expanded single get flow exiting from a straight converging nozzle. Inside the shock 'diamonds', strong fluctuation of flow and gas properties occurs. Here the velocity of the gas decreases and its behavior can be described as that of turbulent jet. The expansion waves are reflected at free jet boundaries as compression waves and coalesce at a point to a common straight shock front which is called 'Mach disk' or 'Mach shock'. [1]

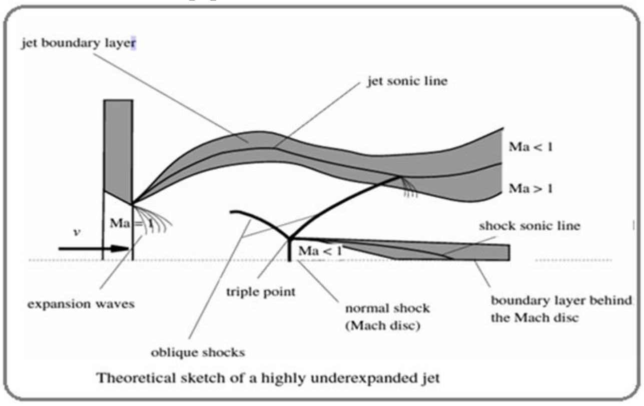

Fig. 2: Highly under expanded jet and Mack disk

II. DETAILS OF THE PRESENT INVESTIGATION

The geometric configuration and process parameters used for CD nozzle and C nozzle for shock wave and Mach disc analysis are described as follows:

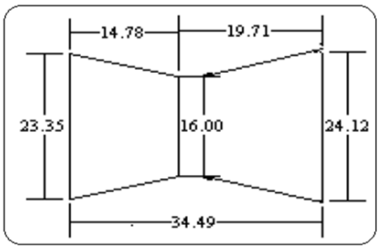

Fig. 3: CD Nozzle dimensions

Serial No	Nozzle Parameters	Values
1	Inlet Diameter	23.35 mm
2	Outlet Diameter	24.12 mm
3	Throat Diameter	16.00 mm
4	Distance between Inlet and nozzle throat	14.78 mm
5	Distance between nozzle throat and outlet	19.71 mm
6	Inlet Pressure	3 Bar
7	Gauge Pressure	1 Bar
8	Exit mach	2.4 Mach
9	Temperature of the gas at inlet	300 K
10	Boundary condition applied at inlet	PRESSUE_INLET
11	Boundary condition applied at outlet	PRESSURE_OUTLET
12	Boundary condition applied for chamber design	PRESSURE_OUTLET
13	Boundary condition applied at axis	SYMMETRY
14	Boundary condition applied at the nozzle wall	WALL
15	Boundary condition applied for MDT	WALL
16	Atomizing gas used	Nitrogen
17	Courant number used – Radial measurement	5 CFL
18	Courant number used – Axial measurement	0.1 CFL

Table 1: CD Nozzle dimensions and process parameters.

For C nozzle, convergent portion of the CD nozzle dimensions (geometric configuration) was considered and dimensions & process parameters remain same as that of CD nozzle.

III. CFD RESULTS/PLOTS FOR THE SHOCKWAVE ANALYSIS IN NOZZLES

A. *CFD Trials Set-Up using Fluent*

Geometric modeling and meshing of the nozzle were carried out and results were plotted using Gambit and Fluent software. The boundary conditions applied were Pressure inlet, Pressure outlet, Wall and the Symmetry. Viscous model was defined as Spalart-Allmaras for the fluid flow, solver as Fluent 5/6 and mesh type as QUAD. Inlet pressure of 2 Bar (initially and varied later) and inlet temperature values of 300K were given as input. The iteration values were set was about 1000 initially and iterated until the solution converges. Then the results were plotted for pressure and velocity vector for analyzing shock waves and Mach discs. The CFD results were plotted for the CD nozzles and C nozzles for the different pressure ratios to obtain pressure plots and velocity vector plots as discussed below:

B. *CFD Plots for CD – Nozzle*

For the different combination of P0, Pa and Pe the results were obtained for CD nozzle (namely pressure plot and velocity vector plot). Figure 4 shows pressure plot for CD nozzle when P0/Pa is 7. (Note: P0 is the stagnation pressure and Pa is the ambient pressure and Pe is the exit pressure)

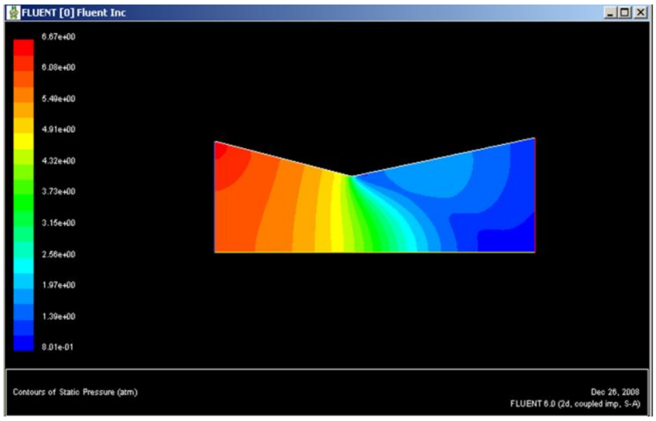
Fig. 4: Pressure plot (Po/Pa = 7) for CD nozzle

Figure 5 shows the velocity vector plot for CD nozzle when P0/Pa is 7. This plot can be used to determine the shock wave produced inside the nozzle.

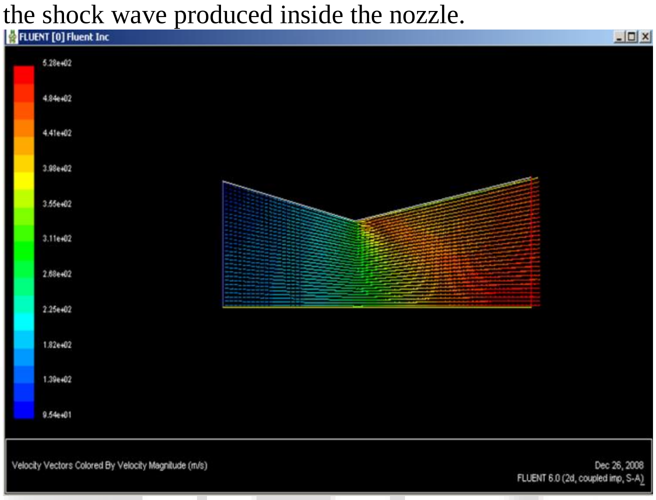
Fig. 5: Velocity vector plot when P0/Pa = 7 for CD nozzle

For the different combination of P0, Pa and Pe, following results were obtained for CD nozzle.

When "P0/Pa" is 2: "Pe/Pa" is 0.240.
When "P0/Pa" is 3: "Pe/Pa" is 0.341.
When "P0/Pa" is 4: "Pe/Pa" is 0.456.
When "P0/Pa" is 5: "Pe/Pa" is 0.576.
When "Po/Pa" is 6: "Pe/Pa" is 0.692.
When "P0/Pa" is 7: "Pe/Pa" is 0.801

C. *CFD Plots for C – Nozzle:*

For the different combination of P0, Pa and Pe the results were obtained for C nozzle (namely pressure plot and velocity vector plot). Figure 6 shows pressure plot for C nozzle when Po/Pa is 7

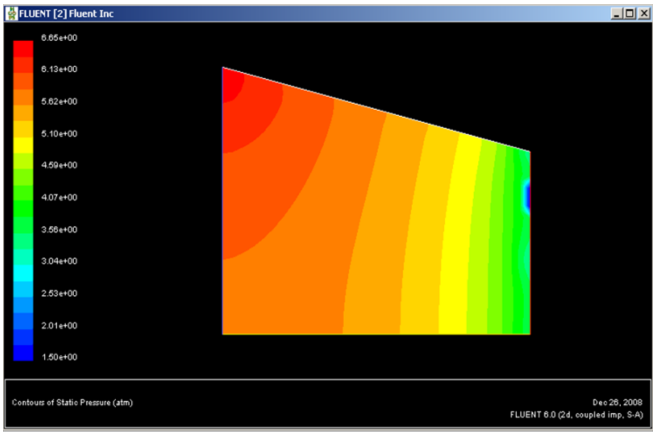
Fig. 6: Pressure plot when P0/Pa is 7 for C nozzle

Figure 7 shows velocity vector plot for C nozzle when P0/Pa is 7. This plot can be used to analyze the shock wave inside the C Nozzle.

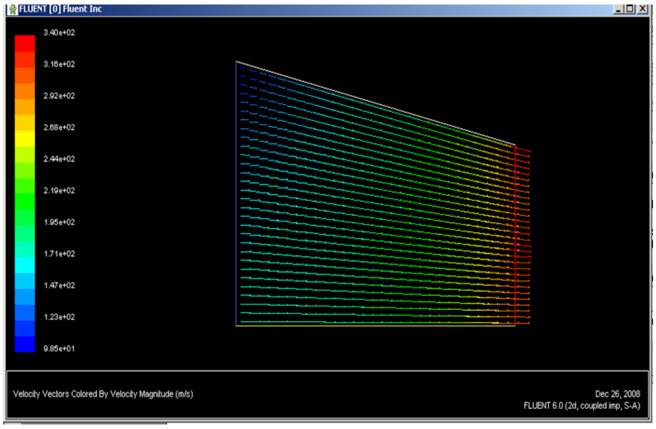

Fig. 7: Velocity vector plot when P0/Pa is 7 for C nozzle

For the different combination of P0, Pa and Pe, following results were obtained for C nozzles.

When “P0/Pa” is 2: “Pe/Pa” is 1.20
When “P0/Pa” is 3: “Pe/Pa” is 1.50
When “P0/Pa” is 4: “Pe/Pa” is 1.91
When “P0/Pa” is 5: “Pe/Pa” is 2.30
When “P0/Pa” is 6: “Pe/Pa” is 2.74
When “P0/Pa” is 7: “Pe/Pa” is 3.50

D. Comparison Table for C-Nozzle and CD Nozzle

Po/Pa	C nozzle (Pe/Pa)	CD nozzle (Pe/Pa)
2	1.20	0.240
3	1.50	0.341
4	1.91	0.456
5	2.30	0.576
6	2.74	0.692
7	3.50	0.801

Table 2: Comparison table for C-Nozzle and CD Nozzle

As per Udo Fitching [1], in the supersonic nozzle, gas is not fully expanded in the exit area and expands in front of the nozzle. The main parameters affecting this behavior are pressure ratio (Po/Pa) and the geometry of nozzle. Up to a pressure ratio of Po/Pa = 1.89, the pressure in a converging nozzle is lowered until ambient pressure is reached. If pressure ratio exceeds the critical pressure ratio, further expansion outside the nozzle occurs and gas pressure in the exit is above ambient. Remaining pressure potential in the gas is decomposed by expansion waves that start at edges of nozzle exit. Such expansion waves are reflected as compression waves and combine in front of nozzle to form oblique or straight shocks at higher pressure ratios. Such shock waves cases energy losses. At even higher pressure ratios, a Mach disc (straight shock in front of the center of the jet) with specifically high losses is formed. Such highly under expanded flows will form at the pressure ratio Po/Pa > 3.85. Behind the Mach disk, the flow velocity is subsonic. For moderately under expanded gas jets, at pressure ratio 1.89 < Po/Pa < 3.85, the compression waves from the jet boundary coalesce to form oblique shocks.

The C nozzle flow is highly under-expanded over the entire test range. Its near-region flow pattern is dominated by a strong internal shock wave. The CD nozzle, by contrast, because it operates with a near-unity exit pressure, does not produce a strong internal shock wave and suffers no wake-closure event.

IV. Conclusions

When P0/Pa is between 2 to 4 (1.89 < Po/Pa < 3.85), Pe/Pa for C nozzle is more than unity (above ambient pressure). But for CD nozzle, this is less than unity. In the case of C nozzle, it can be observed that there is an under expanded pressure and shock waves are formed (Fig – 5) and Mach discs are observed.

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