# ANALYSIS OF THE PERFORMANCE AND FLOW CHARACTERISTICS OF CONVERGENT DIVERGENT (C-D) NOZZLE

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***ABSTRACT***

*A nozzle is a device designed to control the direction or characteristics of a fluid flow (especially to increase velocity) as it exits (or enter) an enclosed chamber or pipe via orifice. A numerical study has been carried out to analyse the performance and flow characteristics of the convergent-divergent nozzle under various operating pressure ratio and with different nozzle profiles, also to determine the location and strength of the normal shock in the divergent portion of the nozzle .Various flow parameters across the normal shock had been obtained by using gas table.*

***KEYWORD:*** *Mach number, Sub-sonic, Super-sonic, Sonic, Compressible flow, Throat*

## I. INTRODUCTION

A de Laval nozzle (or convergent-divergent nozzle, CD nozzle or con-di nozzle) is a tube that is pinched in the middle, making an hourglass-shape. It is used as a means of accelerating the flow of a gas passing through it to a supersonic speed. It is widely used in some types of steam turbine and is an essential part of the modern rocket engine and supersonic jet engines. Similar flow properties have been applied to jet streams within astrophysics [1]. The nozzle was developed by Swedish inventor Gustaf de Laval in 1897 for use on an impulse steam turbine.[1] This principle was used in a rocket engine by Robert Goddard, and very nearly all modern rocket engines that employ hot gas combustion use de Laval nozzles.

## II. OPERATION

Its operation relies on the different properties of gases flowing at subsonic and supersonic speeds. The speed of a subsonic flow of gas will increase if the pipe carrying it narrows because the mass flow rate is constant. The gas flow through a de Laval nozzle is isentropic (gas entropy is nearly constant). At subsonic flow the gas is compressible; sound, a small pressure wave, will propagate through it. At the "throat", where the cross sectional area is a minimum, the gas velocity locally becomes sonic (Mach number = 1.0), a condition called choked flow. As the nozzle cross sectional area increases the gas begins to expand and the gas flow increases to supersonic velocities where a sound wave will not propagate backwards through the gas as viewed in the frame of reference of the nozzle (Mach number > 1.0).

### 2.1 Conditions for operation

A de Laval nozzle will only choke at the throat if the pressure and mass flow through the nozzle is sufficient to reach sonic speeds, otherwise no supersonic flow is achieved and it will act as a Venturi tube. In addition, the pressure of the gas at the exit of the expansion portion of the exhaust of a nozzle must not be too low. Because pressure cannot travel upstream through the supersonic flow, the exit pressure can be significantly below ambient pressure it exhausts into, but if it is too far below ambient, then the flow will cease to be supersonic, or the flow will separate within the expansion portion of the nozzle, forming an unstable jet that may 'flop' around within the nozzle, possibly damaging it. In practice ambient pressure must be no higher than roughly 2-3 times the pressure in the supersonic gas at the exit for supersonic flow to leave the nozzle.

### 2.2 Analysis of gas flow in de Laval nozzles

The analysis of gas flow through de Laval nozzles involves a number of concepts and assumptions:

1. For simplicity, the gas is assumed to be an ideal gas.
2. The gas flow is isentropic (i.e., at constant entropy). As a result the flow is reversible (frictionless and no dissipative losses), and adiabatic (i.e., there is no heat gained or lost).
3. The gas flow is constant (i.e., steady) during the period of the propellant burn.
4. The gas flow is along a straight line from gas inlet to exhaust gas exit (i.e., along the nozzle's axis of symmetry)
5. The gas flow behaviour is compressible since the flow is at very high velocities.

## III. METHODOLOGY

Let us consider a convergent divergent nozzle with inlet and outlet section specified in the diagram as 1 and 5 respectively. In the diagram shown below section 2 represent the throat i.e, the maximum mass flow rate, Section 3 and 4 represents the flow conditions before and after the shock respectively.

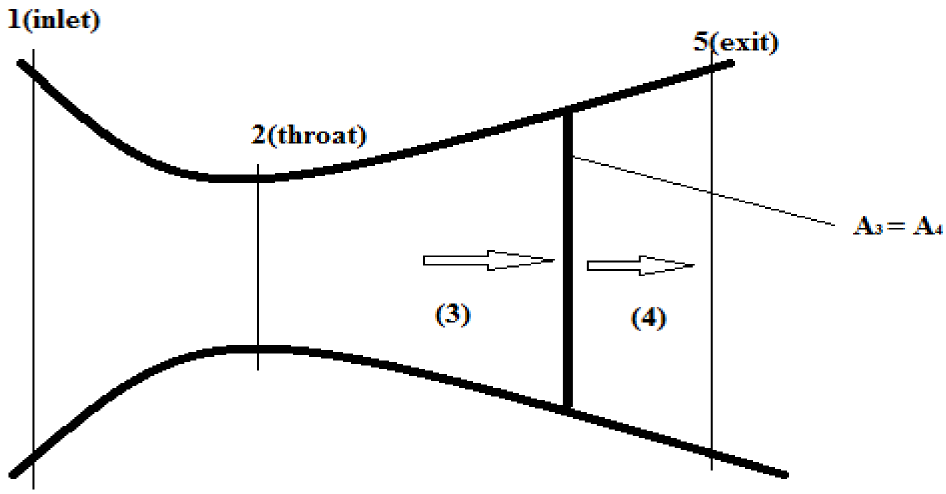


**Figure 1.1** C-D Nozzles

Let,

$A_e/A_t$ = Exit area/throat area = 2.494

Inlet condition $P_0$ = 100 Psi

**STEP I:**

For 1st Critical point, from isentropic flow table at $A_e/A_t = 2.494$

$M_3 = 0.24$

$P_3/p_{03} = 0.961$

Operating pressure ratio for 1st critical point is 0.961

**STEP II :**

For 3rd critical point, from isentropic flow table at $A_e/A_t = 2.494$

$M_3 = 2.44$

$P_3/p_{03} = 0.0643$

Operating pressure ratio for 3rd critical point is 0.0643

Now, As we know that normal shock takes place in divergent portion of the nozzle i.e. in supersonic flow .Therefore, for supersonic flow condition we have

$M_3 = 2.44$
$P_3/p_{03} = 0.0643$

**STEP III:**

Now from Normal Shock Table for $M_3 = 2.44$,
We have
$M_4 = 0.519$
$P_4/P_3 = 6.780$
And operating pressure ratio :$P_{receiver}/P_0 = P_4/P_{01} = P_4/P_3 \times P_3/P_{03} \times P_{03}/P_{01}$
$P_4/P_{01} = 6.780 \times 0.0643 \times 1$
$P_4/ p_{01} = 0.4359$
Thus for our Convergent Divergent Nozzle with $Ae/A_t = 2.494$, any operating pressure ratio between 0.961 and 0.4359 will cause a normal shock to be located somewhere in the divergent portion of the nozzle.

**STEP 4:**

Let us find the shock location and shock strength of a normal shock at operating pressure ratio
$P_{receiver}/P_0 = P_4/P_{01} = P_5/P_0 = 0.60 = P_e/P_{01}$
Note: we may assume that losses occur only across the shock and $M_2 = 1$
$A_5/A_2 \times P_5/P_{01}$ i.e. $A_e/A_t \times P_e/P_{01} = 2.494 \times 060$
$A_e/A_t \times P_e/P_{01} = 1.4964$
Now, we know that
$A \times P/ A^* \times P_{01} = f(\gamma, M)$
For $\gamma = 1.4$(air)
From isentropic flow table, corresponding to $A_e/A_t \times P_e/P_{01} = 1.4964$
$M_5 = 0.38$
To locate a shock seek a ratio
$P_{05}/P_{01} = P_{05}/P_5 \times P_5/P_{01}$
From isentropic flow table corresponding to $M_5 = 0.38$
$P_5/P_{05} = 0.905$
Therefore, $P_{05}/P_{01} = 1/0.905 \times 0.60$
$P_{05}/P_{01} = 0.6628$
As loss is assumed only across the shock, therefore
$P_{05} = P_{04}$ and $P_{01} = P_{03}$
Therefore $P_{04}/P_{03} = 0.6628$
Now from normal shock table corresponding to $P_{04}/P_{03} = 0.6628$
$M_3 = 2.12$
$P_4/P_3 = 5.077$
Now from isentropic flow table, we can find that at what area ratio, this Mach number will occurr.
Shock location $A_s/A_t = 1.869$
Shock strength $P4 - P_3/ P_3 = 4.077$
Therefore, from above methodology we can calculate various flow parameters across C-D Nozzle for different area ratios.

# IV. RESULTS AND DISCUSSION

**1. For area ratio $(A_e/A_t)$=1.53**

| | | $P_e/P_O$ | | | | | |
| --- | --- | --- | --- | --- | --- | --- | --- |
| | | .88 | .85 | .8 | .75 | .7 | .6 |
| across shock | $M_e$ | .422348 | .436733 | .462977 | .492512 | .525984 | .608290 |
| | $P_{02}/P_e$ | 1.130532 | 1.140004 | 1.158257 | 1.180346 | 1.207429 | 1.283866 |
| | $P_{02}/P_{01}$ | .994869 | .969003 | .926606 | .885259 | .845200 | .770320 |
| | $M_1$ | 1.177000 | 1.354000 | 1.510000 | 1.627000 | 1.726000 | 1.894000 |
| | $(P_y-P_x)/P_x$ | .449550 | .972202 | 1.493450 | 1.921650 | 2.308922 | 3.018442 |
| | $T_2/T_1$ | 1.113557 | 1.225164 | 1.326884 | 1.406696 | 1.477088 | 1.603245 |
| | $P_2/P_1$ | 1.449550 | 1.972202 | 2.493450 | 2.921650 | 3.308922 | 4.018442 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| properties | $\rho_2/\rho_1$ | 1.301730 | 1.60974 | 1.879177 | 2.076959 | 2.240166 | 2.506443 |
| | $A_s/A_t$ | 1.024046 | 1.090993 | 1.182991 | 1.272489 | 1.362584 | 1.547841 |

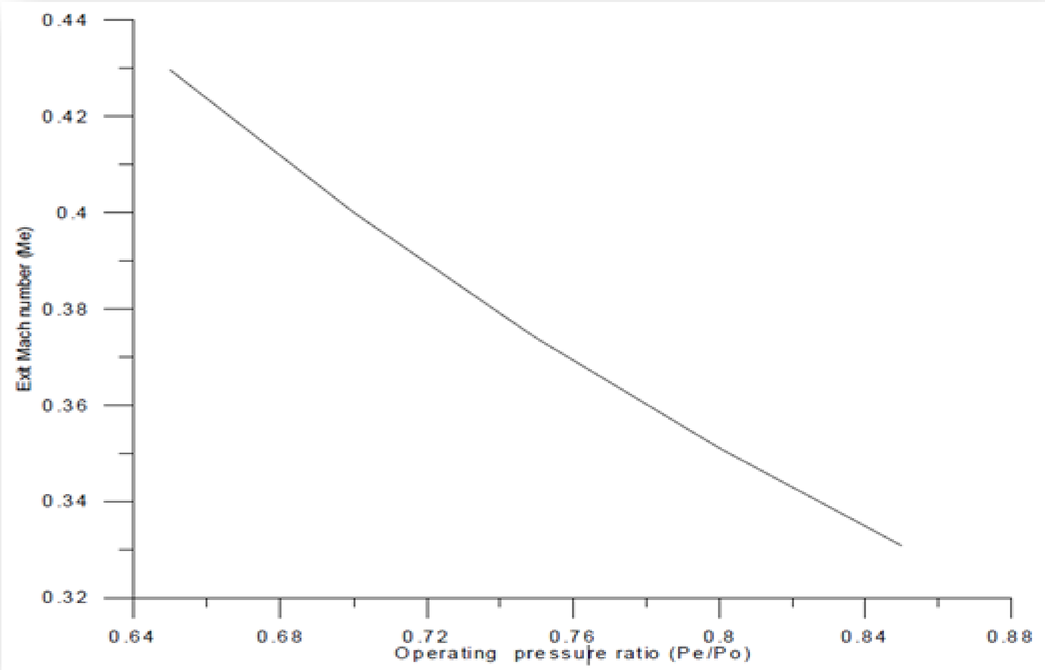


**Figure 4.1** Variation of exit mach no. with OPR =1.53

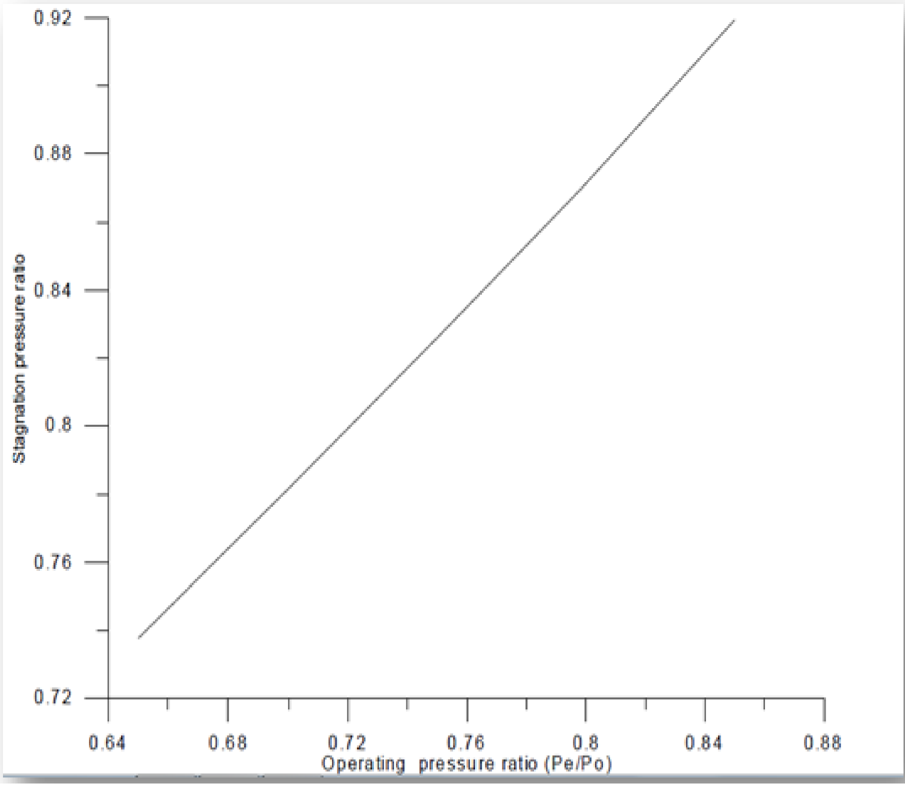


**Figure 4.2** Variation of stagnation pressure ratio with OPR =1.53

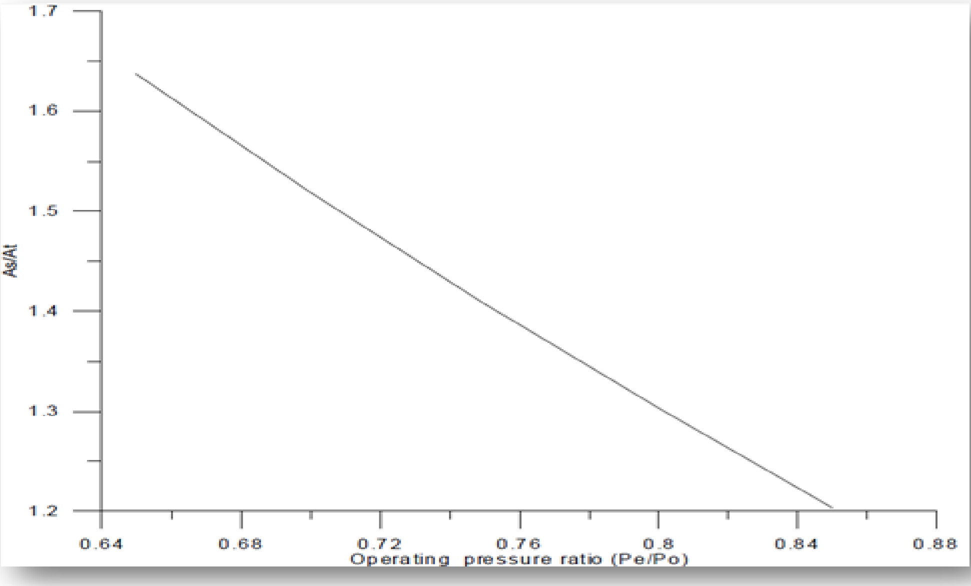


**Figure 4.3** shock location with OPR= 1.53

**1) Shock strength**

| $A_e/A_t$ | $p_e/p_o = .80$ | $p_e/p_o = .70$ | $p_e/p_o = .60$ | $p_e/p_o = .50$ |
|---|---|---|---|---|
| 1.53 | 1.4934 | 2.336 | 3.0184 | 3.6505 |
| 2.035 | 2.0598 | 2.9130 | 3.7601 | 4.6298 |
| 2.494 | 2.288 | 3.1745 | 4.096 | 5.0965 |
| 4 | 2.5631 | 3.5 | 4.526 | 5.699 |
| 7.8 | 2.689 | 3.655 | 4.7343 | 6.0030 |

**2) Shock location**

| $A_e/A_t$ | $p_e/p_o = .80$ | $p_e/p_o = .70$ | $p_e/p_o = .60$ | $p_e/p_o = .50$ |
|---|---|---|---|---|
| 1.53 | 1.1829 | 1.3625 | 1.5478 | 1.733 |
| 2.035 | 1.3036 | 1.5187 | 1.7674 | 2.0573 |
| 2.494 | 1.3577 | 1.5919 | 1.8755 | 2.2272 |
| 4 | 1.4260 | 1.687 | 2.021 | 2.4614 |
| 7.8 | 1.458 | 1.734 | 2.0945 | 2.5856 |

## V. CONCLUSION

1. As shown in above result we can conclude that the shock strength goes on increasing with Decreasing operating pressure ratio and also the shock location move towards exit.
2. Exit mach number ($M_e$) and mach number ahead of the shock ($M_1$) goes on increasing by decreasing the operating pressure ratio.

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