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CFD Analysis of De Laval Nozzle Geometry & Effect of Gas Pressure Variation at the Entrance

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***Abstract:** De Laval nozzle is a converging-diverging nozzle which has the ability to convert the chemical energy with high pressure into kinetic energy with high velocity and low pressure. The scheme of change of speed and pressure within the nozzle depends on the change of the cross-section area of the nozzle. The nozzle is used in jet engines. This study is concerned with the study of the performance of the work of de Laval nozzle, two models were designed; the first model: when the total pressure (gauge) of air at the entrance is equal to 9 bar and the second model: at the total pressure (gauge) of the entrance is equal to 11 bar. The total pressure in the two models was decreased, and the change in the Mach number was observed at the outlet of the De Laval nozzle. The models were designed and analyzed in the ANSYS Fluent program. The total air pressure changes at the nozzle entrance and their effect on changing the Mach number at the exit were studied. The results obtained from the ANSYS Fluent program were compared with the theories of gas dynamics.*
***Keywords:** Mach number, Convergent-Divergent Nozzle, Pressure variations, Contours.*

Nomenclature

A^*	Throat cross section area, m^2	T	Static temperature, K
A	cross section area, m^2	T_t	Total temperature, K
a	Sound speed at outlet, m/s	V	Velocity at outlet, m/s
V1	The diameter at inlet(ANSYS Fluent program), mm	V	Sensor output voltage
V_2	The diameter at throat(ANSYS Fluent program), mm	ρ_t	Density of stagnation, kg/m^3
V_3	The diameter at outlet(ANSYS Fluent program), mm	ρ	Density, kg/m^3
M	Mach number at outlet	γ	Ratio of specific heat capacities
P	Absolute static pressure, bar	θ_{in}	Half angle of the converging nozzle, deg.
P_t	Absolute total pressure, bar	θ_{out}	Half angle of the diverging nozzle, deg.

I. INTRODUTION

Flow of gases through a converging-diverging nozzle is one of the benchmark problems used for modeling compressible flow using computational fluid dynamics algorithms. In a converging nozzle, the highest speed that a fluid can be accelerated to is sonic speed, which occurs at the exit. The converging-diverging nozzle is used to accelerate the fluid to supersonic speeds depending on the average exit pressure to the total stagnation pressure. There is a possibility of creating shock waves in the flow-field. The flow out from a converging-diverging nozzle often has strong gradients of pressure, temperature, density, and speed in radial and axial direction. Ratios of pressure, density and temperature can be related to the stagnation temperature, pressure and density at a given Mach number as seen in equations 1 – 3. and ratio across section area to cross section area at throat a given Mach number as seen in equation 4, and relation between the speed of the sound and the temperature as seen in equation 5, and the relation between gas velocity and sound speed as seen in equation 6.

$$\frac{T}{T_t} = \frac{1}{1 + \frac{\gamma - 1}{2} M^2} \quad (1)$$

$$\frac{P}{P_t} = \left[\frac{1}{1 + \frac{\gamma - 1}{2} M^2}\right]^{\frac{\gamma}{\gamma - 1}} \quad (2)$$

$$\frac{\rho}{\rho_t} = \left[\frac{1}{1 + \frac{\gamma - 1}{2} M^2}\right]^{\frac{1}{\gamma - 1}} \quad (3)$$

$$\frac{A}{A^*} = \frac{1}{M}\left[\frac{1 + \frac{\gamma - 1}{2}}{1 + \frac{\gamma - 1}{2} M^2}\right]^{\frac{-(\gamma+1)}{2(\gamma - 1)}} \quad (4)$$

$$a = \sqrt{\gamma R T} \quad (5)$$

$$V = M\,a \quad (6)$$

A number of studies presented experimental have been carried out with the goal of improving the propelling nozzle system, such as T. Stoltenhoff, H. Kreye, and H.J. Richter 2001 [1] they studied An Analysis of the Cold Spray Process and Its Coatings, and Tien-Chien Jen, Longjian Li, Wenzhi Cui, Qinghua ChenXinming Zhang 2005 [2] they studied numerical investigations on cold gas dynamic spray Process with nano- and microsize particles, and Manolo Pires 2008 [3] studied turbulence modeling s and applications to

aerospike plug nozzle, and T. Gawehn A. Gülhan N. S. Al-Hasan G. H. Schnerr 2009 [4] they studied Experimental and numerical analysis of the structure of pseudo-shock systems in laval nozzles with parallel side walls, and k.m. pandey, a.p. singh 2010 [5] they studied cfd analysis of conical nozzle for Mach 3 at various angles of divergence with fluent software.

II. COMPUTER SIMULATION OF NOZZLE

Steps execution Simulations

A. (The first case @ 9 bar)

1) Modeling

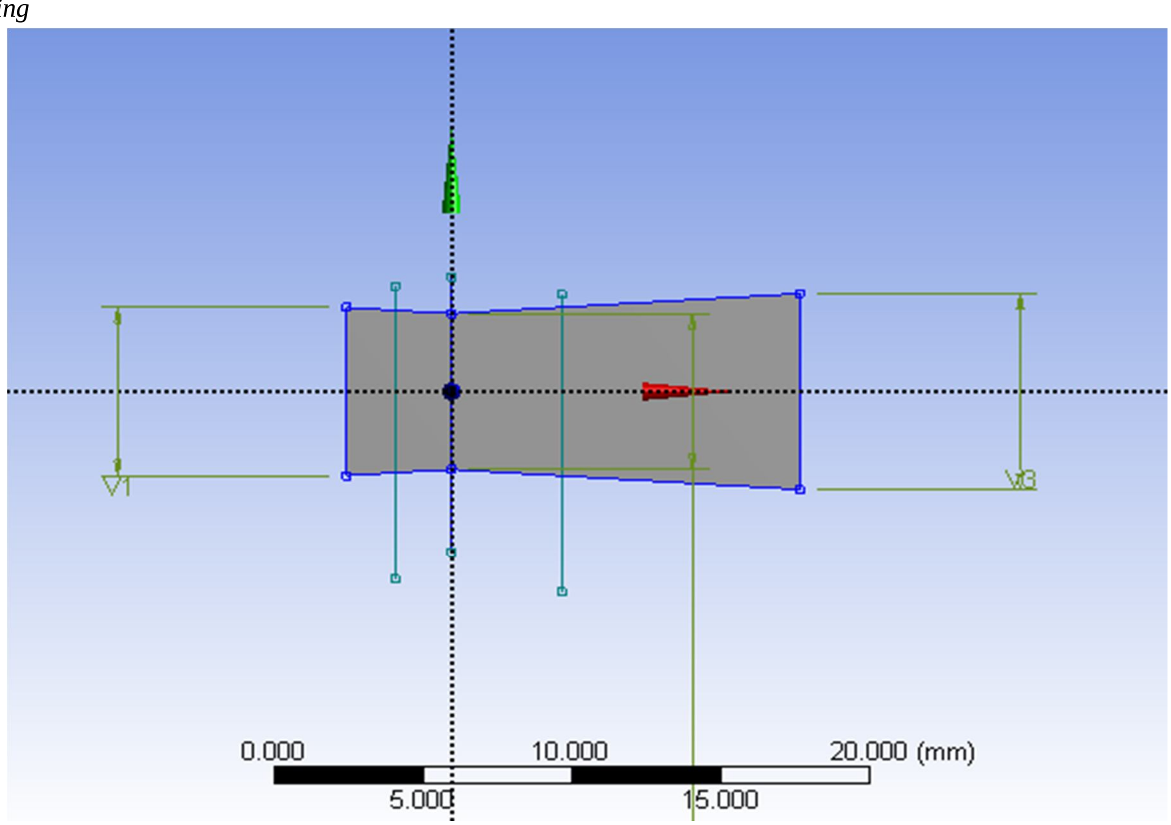

Figure 1Modelling

Table 1Dimensions & angles

V_1	V_2	V_3	Θ_{in}	Θ_{out}
6 mm	5.57 mm	7 mm	3.5 deg.	3.5 deg.

2) Mesh size

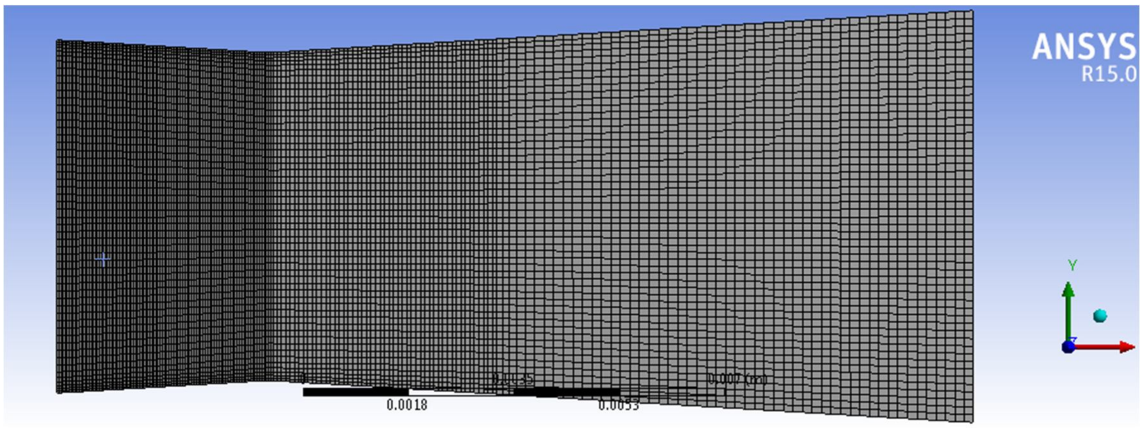

Figure 2 Mesh size

Details of "Edge Sizing" - Sizing	
Scope	
Scoping Method	Geometry Selection
Geometry	5 Edges
Definition	
Suppressed	No
Type	Number of Divisions
Number of Divisions	50
Behavior	Soft
Curvature Normal Angle	Default
Growth Rate	Default
Bias Type	No Bias
Local Min Size	Default (0. m)

Sizing	
Use Advanced Size Fun...	On: Curvature
Relevance Center	Coarse
Initial Size Seed	Active Assembly
Smoothing	Medium
Span Angle Center	Fine
Curvature Normal A...	Default (18.0 °)
Min Size	Default (8.3435e-006 m)
Max Face Size	Default (8.3435e-004 m)
Max Size	Default (1.6687e-003 m)
Growth Rate	Default (1.20)
Minimum Edge Length	1.6423e-003 m

Figure 3 Meshing attributes of the nozzle

3) Solution Setup

a) General

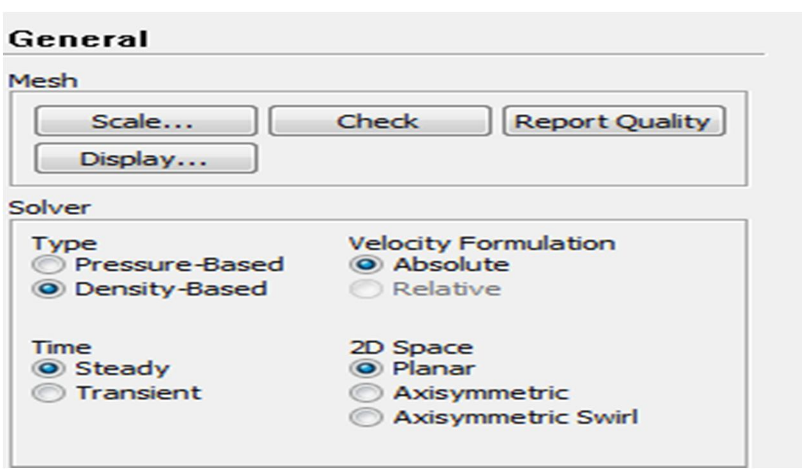

Figure 4 Solution Setup – general

b) Mateial type

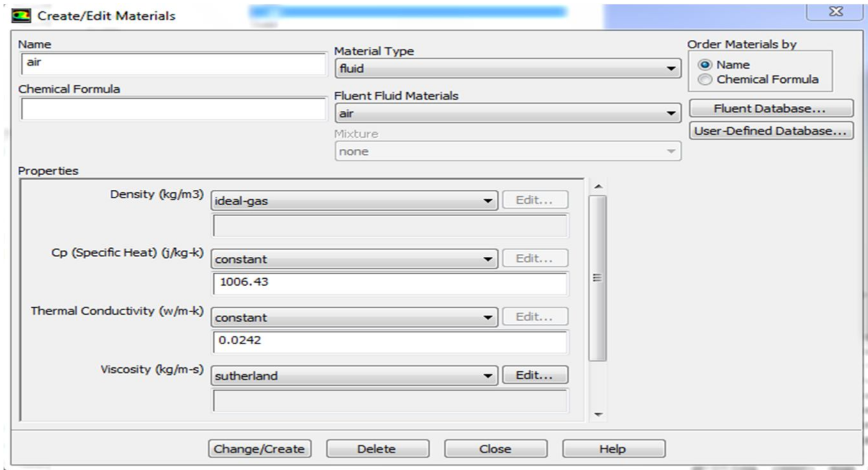

Figure 5 Material type

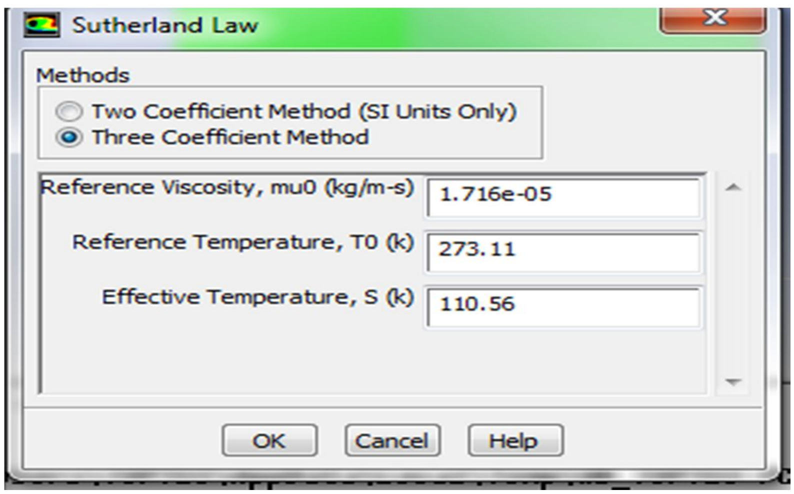

Figure 6 Sutherland reference

c) Viscous Model

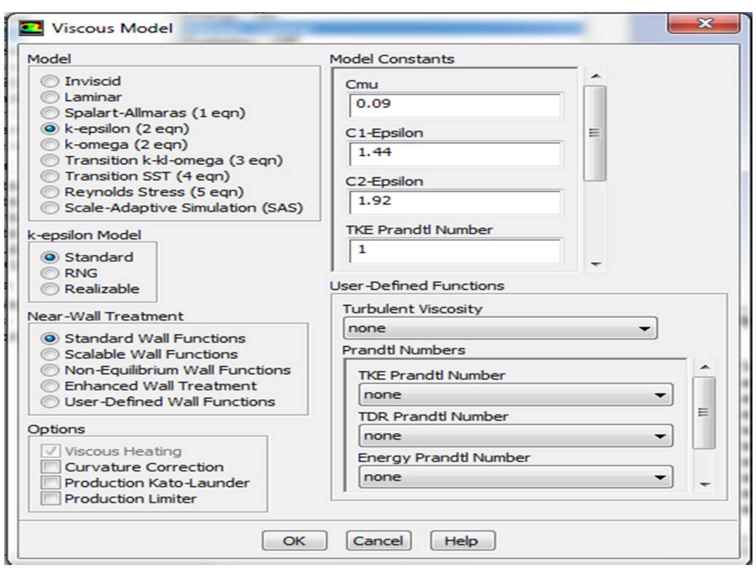

Figure 7 Viscous Model K- epsilon

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d) Boundary condition

Total pressure at inlet (gauge) = 9 bar

Total Temperature at inlet = 320 K

e) Reference values

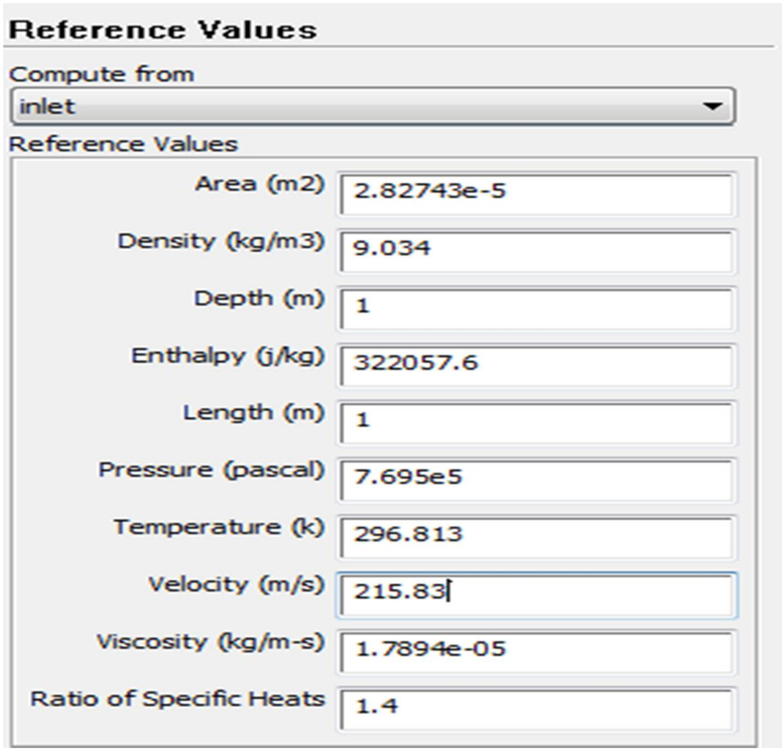

Figure 8 Reference values for first model

4) Solution

a) Solution Methods

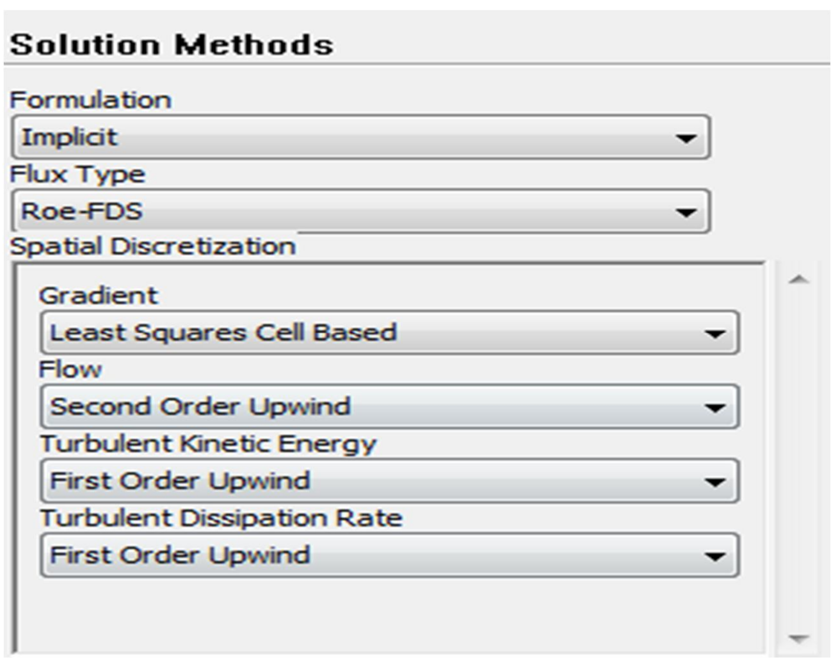

Figure 9 Solution methods

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b) Convergence

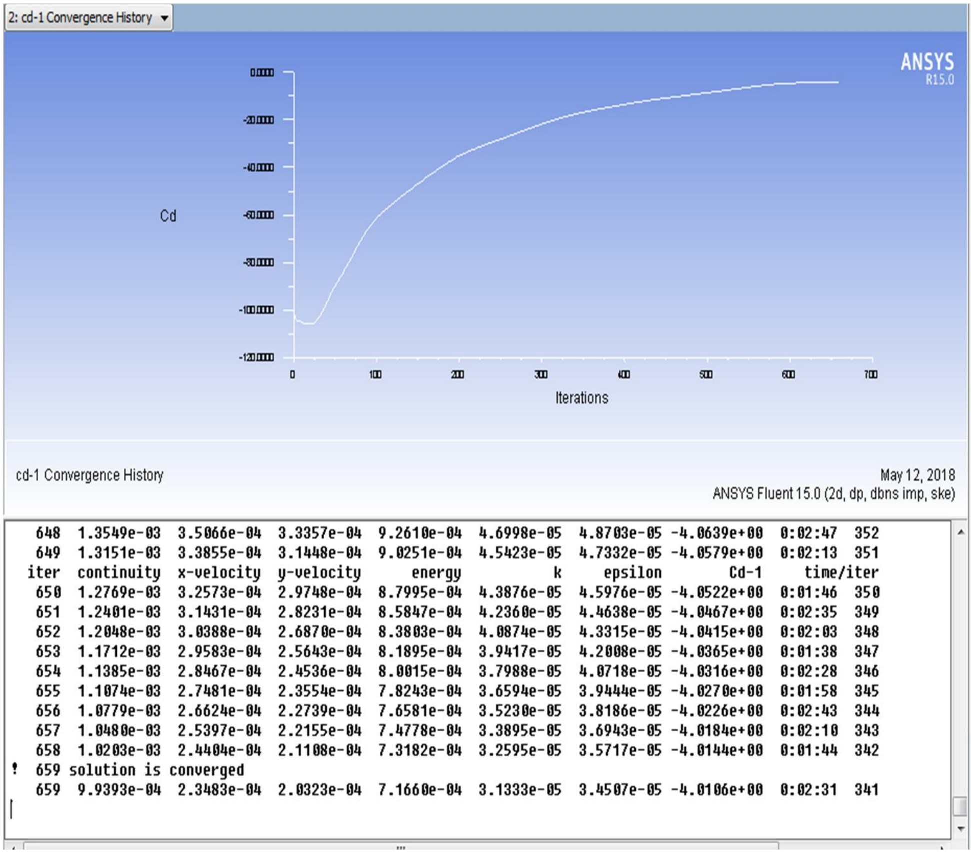

Figure 10 Convergence for first model

5) Results

a) Static pressure contour

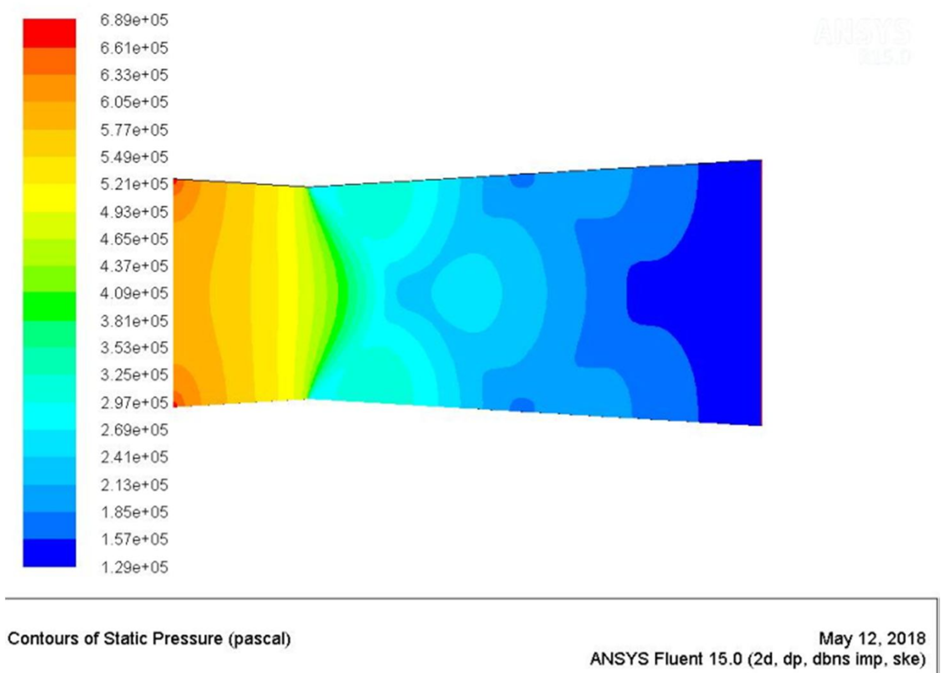

Figure 11 Static pressure contour

In Figure (11) the static pressure gradually decreases in the direction of the outlet due to the gradual increase in Mach number in the direction of the outlet.

Velocity distribution

b) Contours of Velocity Magnitude

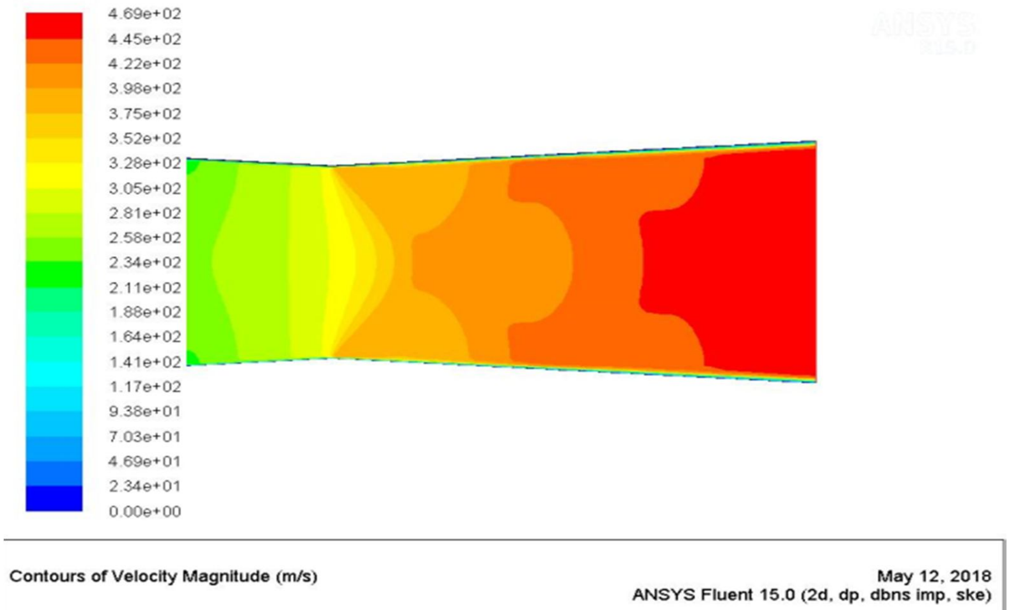

Figure 12 Contours of Velocity Magnitud

In Figure (12) velocity gradually increases in the direction of the outlet due to the gradual increase in Mach number in the direction of the outlet V = M a

c) Contours of Mach number

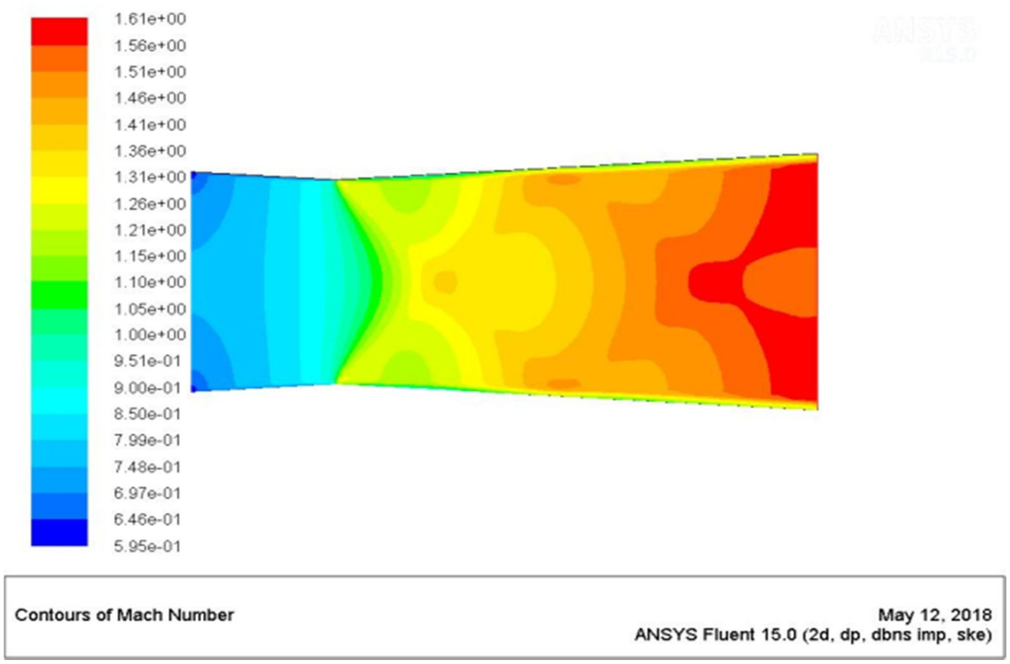

Figure 13 Contours of Mach Number

In Figure (13) Mach number gradually increases in the direction of the outlet.

d) Static Temperature Contours

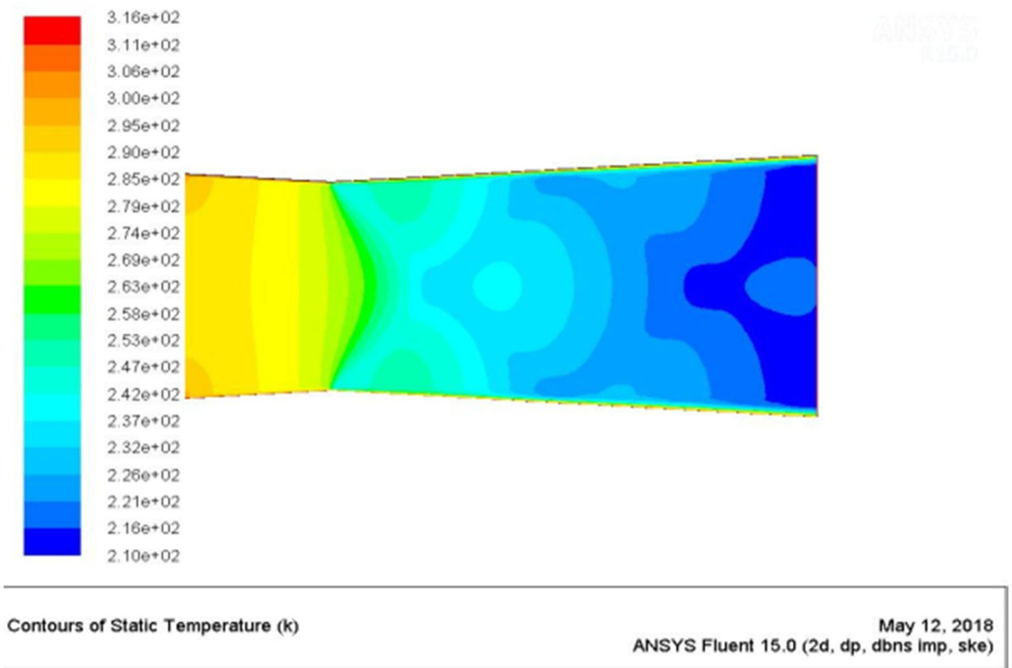

Figure 14 Static Temperature Contours

In Figure (14) the static temperature gradually decreases in the direction of the outlet due to the gradual increase in Mach number in the direction of the outlet.

e) Density contours

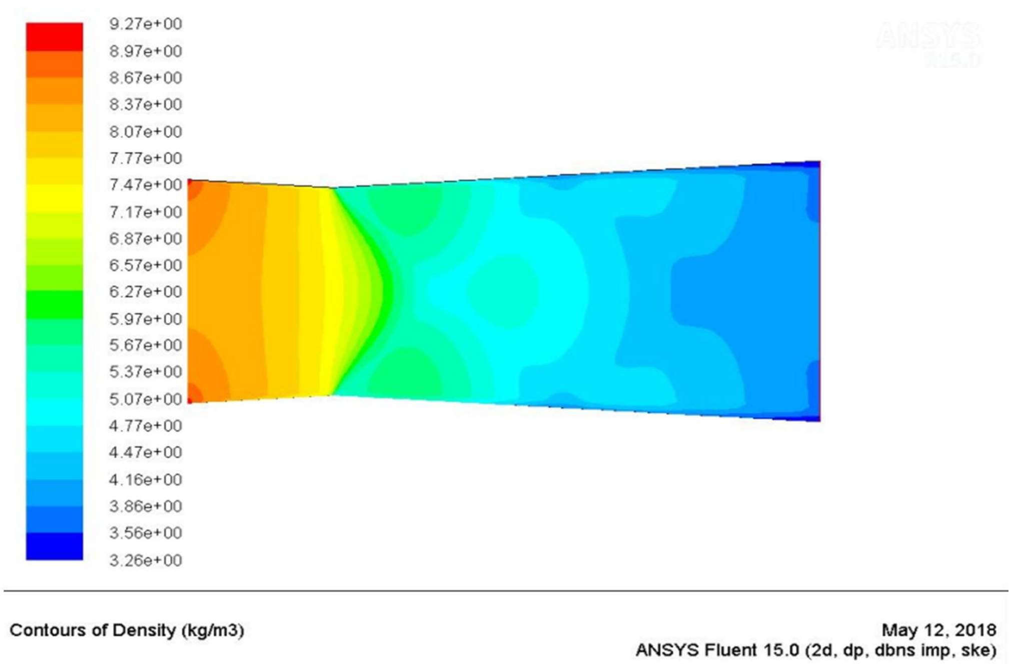

Figure 15 Density contours

In Figure (15) the density gradually decreases in the direction of the outlet due to the gradual increase in Mach number in the direction of the outlet.

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f) Change in Total Pressure At Inlet

Effect of changing total pressure value at the entrance on the value of the static pressure and Mach number at the exit

Table 2 Results of pressure change

P_t Total pressure (gauge) (bar)	P_s Static pressure (gauge) at outlet (bar)	M Mach number at outlet	V Velocity at outlet (m/s)	a sound speed at outlet (m/s)
20	3.79	1.62	471	290.13
15	2.65	1.62	470	290.13
9	1.29	1.61	469	291.3
8	1.06	1.61	469	291.3
7	0.83	1.61	468	290.68
6	0.602	1.61	467	290.062
5	0.373	1.61	466	289.441
4	0.143	1.61	466	289.441
3	-0.0875	1.61	466	289.441
0.90454	0.0673	1.07	350	327.1

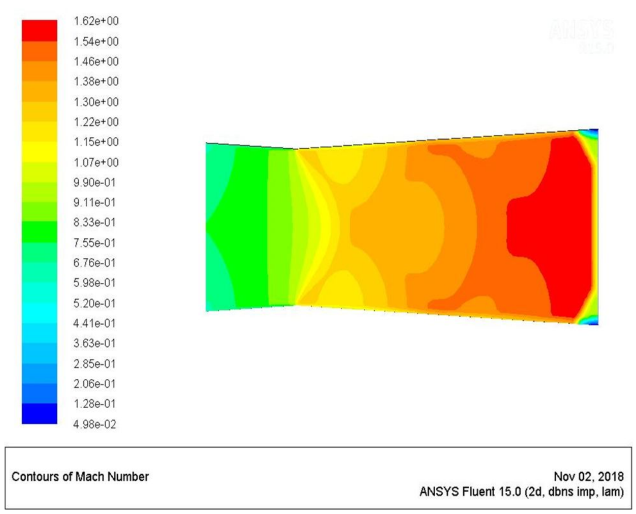

Figure 16 Contours of Mach Number (gauge total pressure 0.90454 bar at inlet)

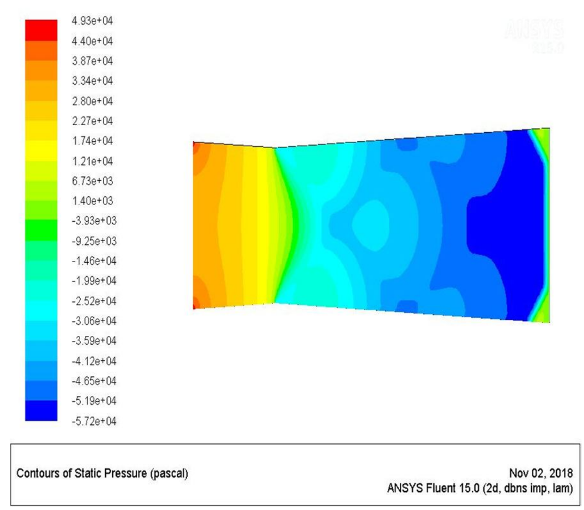

Figure 17 contour of gauge Static pressure (gauge total pressure 0.90454 bar at inlet)

When the total pressure of the nozzle entrance tends to increase, it works to increase the static pressure and the velocity of gas pressure at the outlet, thus increasing the Thrust force of the nozzle. When the total pressure at the entrance of the nozzle is lower than the total pressure on which the nozzle is designed, the static pressure at the outlet is reduced. When the static pressures at the outlet of the nozzle reach a value lower than the atmospheric pressure, a normal shock wave occurs, thereof reducing the Mach number. When the absolute total pressure of the entrance is small so that it is less than 1.91754 bar. The Flow turns from supersonic flow to the subsonic flow, the static pressure increases at the outlet and the speed of the fluid decreases in figure (16) and (17), thus the work of the nozzle de Laval breaks down.

The second case @ 11 Bar

B. Modeling

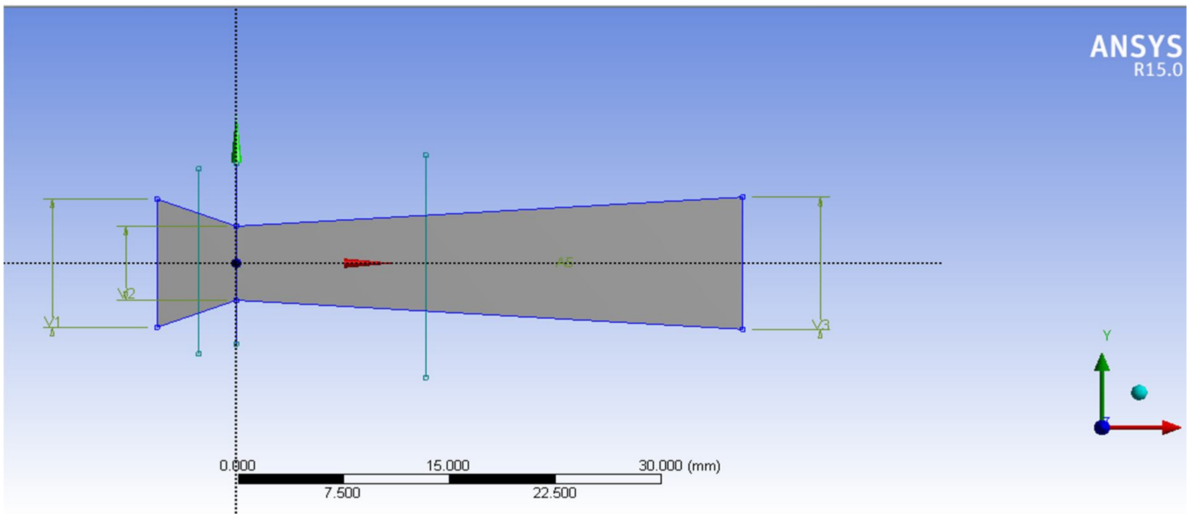

Figure 18 modelling

Table 3 Dimensions & angles

V_1	V_2	V_3	θ_{in}	θ_{out}
9.7 mm	5.61 mm	10 mm	20 deg.	3.5 deg.

1) Meshing

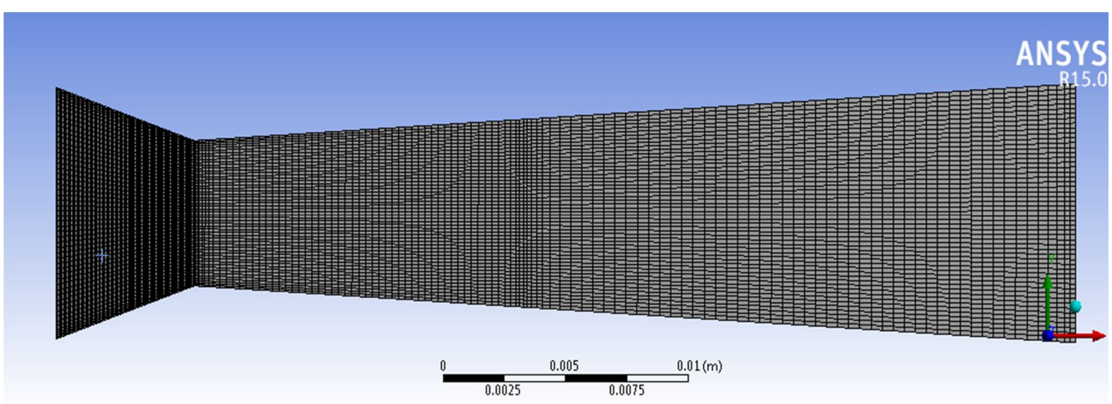

Figure 19 Mesh size

2) Boundary Condition

Total pressure at inlet (gauge) =11bar

Total Temperature at inlet = 320 K

3) *Change In Total Pressure At Inlet:* The effect of changing the total pressure value at the entrance on the value of the static pressure and Mach number at the exit:

Table 4 Results of pressure change

P_t Total pressure (gauge) (bar)	P_s Static pressure (gauge) at outlet (bar)	M Mach number at outlet	V Velocity at outlet (m/s)	a sound speed at outlet (m/s)
20	1.26	2.1	550	261.905
15	0.722	2.1	549	261.429
11	0.287	2.1	548	260.952
10	0.178	2.1	548	260.952
9	0.0699	2.1	548	260.952
8	- 0.0385	2.1	548	260.952
0.90454	0.193	1.02	270	264.1

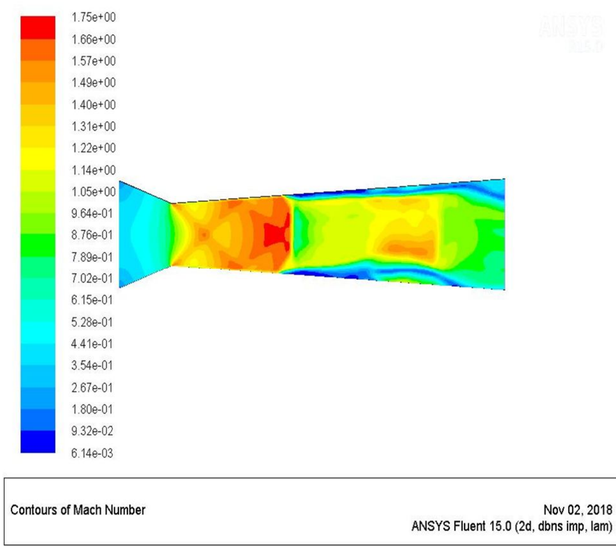

Figure 20 Contours of Mach Number (gauge total pressure 0.90454 bar at inlet)

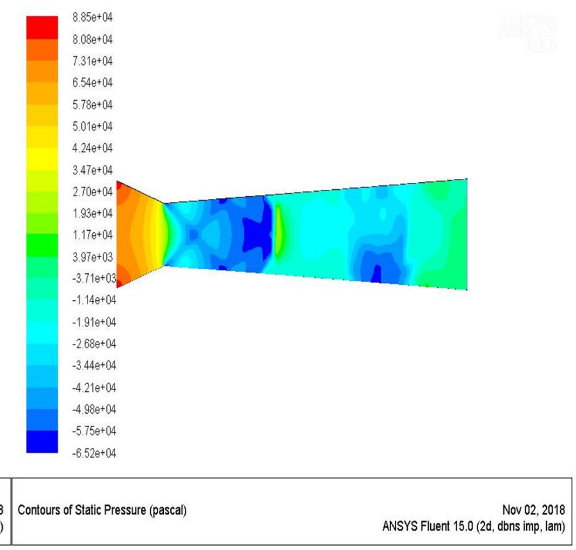

Figure 21 contour of gauge Static pressure (gauge total pressure 0.90454 bar at inlet)

In this case a normal shock wave occurs within the nozzle after the throat. The gauge static pressure is increasing from -0.0625 bar after the throat before normal shock wave to 0.193 bar at the outlet in figure (20). The Mach number is decreased from 1.75 after the throat before normal shock wave to 1.02 at the outlet in figure (21). Flow is turning from supersonic flow to sonic flow, a gradual decrease in the Mach number occurs but remains in the supersonic stage. With a gradual decrease in absolute total pressure at inlet to less than 15.962 % of Pt 12.013 bar, Mach number is decreasing to the subsonic stage.

III. CONCLUSION

To obtain a Mach number equal to one in the throat area, the total absolute pressure should be equal to 1.91537 bar when the output pressure is equal to the atmospheric pressure according to the equation 7.

$$\frac{P}{P_t} = [\frac{2}{\gamma + 1}]^{\frac{\gamma}{\gamma - 1}} \quad (7)$$

A. *First Model*

1) *Theoretically:* This model is theoretically designed to work at absolute total pressure 10.013 bar at inlet. Absolute pressure at outlet 1.45 bar and Mach number M=1.92 at outlet.
2) *ANSYS Fluent program:* When the value of the total pressure of the input decreases, there is a decrease in output pressure while maintaining the value of Mach number 1.61, but when the absolute total pressure of the entrance decreases to the 1.91754 bar, it forms a normal shock wave which occurs within the nozzle after the throat thus the gauge static pressure is increased from -0.0572 bar after the throat before the normal shock wave to 0.0673 bar at the outlet. The Mach number is decreased from 1.62 after the throat before the normal shock wave to 1.07 at the outlet. When flow turns from supersonic to sonic, the velocity is decreased from 467 m/s to 350 m/s. With a gradual decrease in the absolute total pressure at the inlet to less than 19.15 % of P_t 10.013 bar (1.9175 bar), Mach number is decreased to the subsonic stage.

B. *Second Model*

1) *Theoretically:* This model is theoretically designed to work at absolute total pressure 12.013 bar at the inlet, absolute static pressure 0.52 bar at the outlet and Mach number M=2.7 at outlet.
2) *ANSYS Fluent program:* When the value of the total pressure of the input decreases, there is a decrease in the output pressure while maintaining the value of Mach number 2.1. But when the absolute total pressure of the entrance decreases to the 1.91754 bar, it forms a normal shock wave that occurs within the nozzle after the throat. The gauge static pressure is increased from -0.0625 bar after the throat before a normal shock wave to 0.193 bar at the outlet. The Mach number is decreased from 1.75 after the throat before the normal shock wave to 1.02 at the outlet. When flow turns from supersonic to sonic, the velocity decreases from 491 m/s to 270 m/s, and a gradual decrease in the Mach number occurs but remains in the supersonic stage with a gradual decrease in the absolute total pressure at the inlet to less than 15.962 % of P_t 12.013 bar, Mach number is decreased to the subsonic stage.

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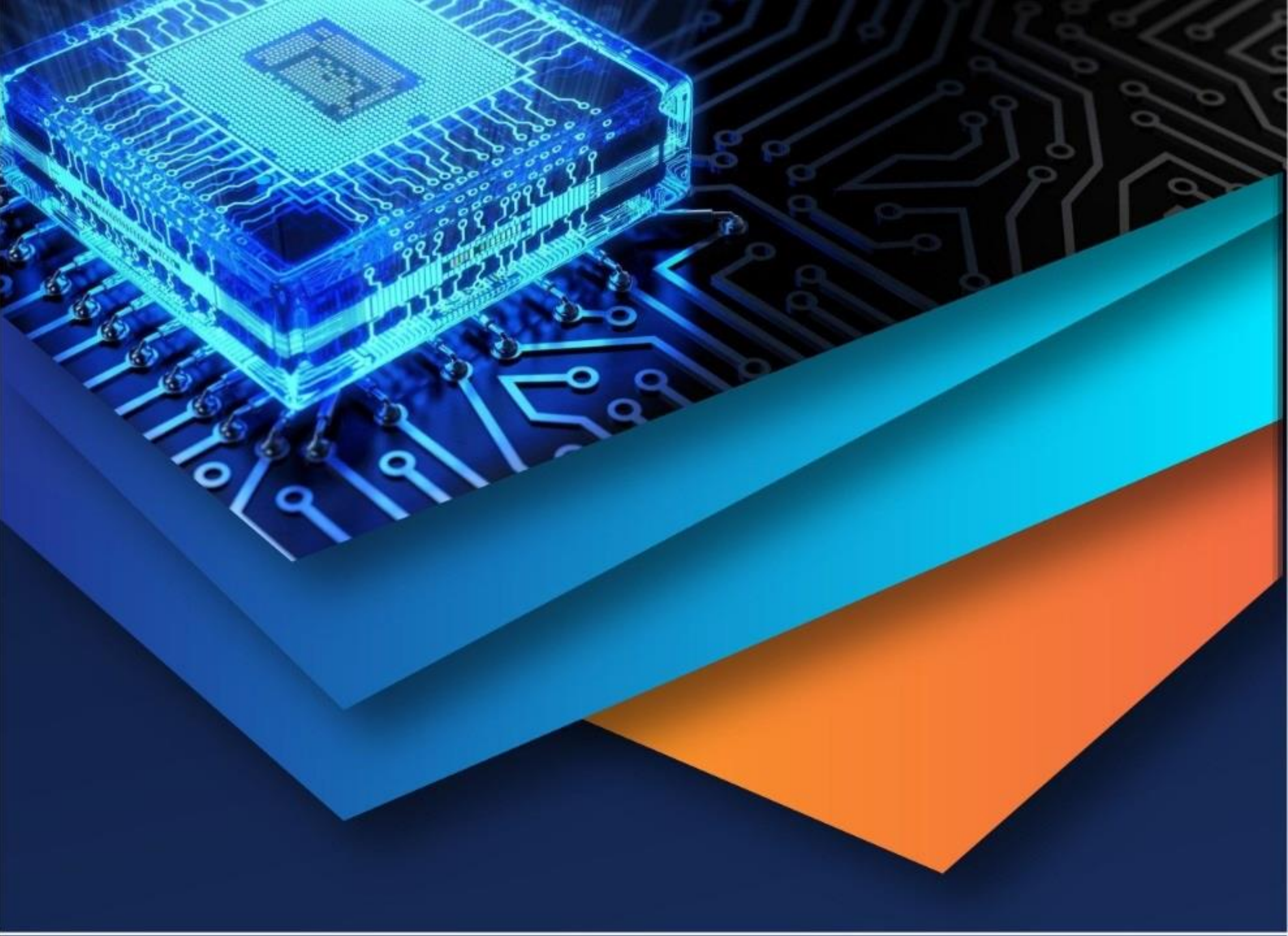

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