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Effect of Flow Compressibility in Convergent-Divergent Nozzle

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Abstract: Nozzles come in a range of shapes and sizes based on a purpose such as De Laval nozzle also known as the converging diverging nozzle. Convergent- divergent nozzle is commonly used in modern rocket engines that accelerates at high velocity till the supersonic region Ma>1. This paper aims to investigate numerically the effect of area ratio of the convergent divergent throat and the Mach number from the incompressible flow to compressible flow. The software that were used to simulate cases is ANSYS Computational Fluid Dynamics (CFD) code FLUENT. The area ratio throat (AR= 5mm, 6mm, 7mm, and 8mm) and Mach number (Ma = 0.2, 1.0 and 1.8) was varied to obtain more specific result. The result from this paper has shown that the most effective Mach number and area ratio are at the 0.2 Ma with the AR=5mm According to the findings of this research, the most effective Mach number and area ratio are at 0.2 Ma with AR=5mm. According to the calculations performed in this research, the percentage variation of velocity at 0.2Ma was larger than at 1.0 Ma and 1.8 Ma. This happen cause at the sonic and supersonic flow there is factor that disturb the flow such as the back pressure and normal shock

Keywords: converging–diverging nozzle, FLUENT, Mach number, back pressure, normal shock

1. Introduction

A nozzle is a relatively simple system that consists of a specially shaped tube that is used to regulate the trajectory or characteristics of a fluid flow as it exits or enters an enclosed chamber or pipe [1]. Nozzles come in a range of shapes and sizes based on a purpose. The mathematics that characterizes the nozzle's function, on the other hand, requires some consideration. A gas jets can be used such as in gas stoves, ovens, and grills. Before the invention of electric light, gas jets were a popular source among citizens. In wide rooms where air diffusion through ceiling diffusers is not feasible or practicable, jet nozzles are still used. Jet diffusers are air diffusers that use jet nozzles that are mounted on the sidewalls of buildings to disperse air [2,3]. De Laval nozzle or known as the converging-divergent (CD) nozzle is a relatively simple system. Subsonic fluids are accelerated by convergent nozzles [4-6]. The flow will achieve sonic velocity at the narrowest point if the nozzle pressure ratio is high enough. The nozzle is said to be choking in this case. Subsonic fluids are slowed by divergent nozzles, but sonic or supersonic fluids are accelerated.

1.1 Problem Statement

Flow in the converging-diverging nozzle is complex to be predicted due to its design that often leads to the misfit function of nozzle. For instance, spray nozzle is used specifically to increase the velocity and distribute the fluid evenly over an area [7,8]. The wrong choice nozzle may damage and burst the pipe. In addition, it is essential to identify the optimum temperature and material for the nozzle to withstand the corrosion. For the initial flow in the throat were subsonic, meaning the Mach number in the throat is equal to one [9]. Supersonic flow is defined as a flow with a Mach number greater than 1.0. The geometry diverges downstream of the throat, and the flow is entropically expanded to a supersonic. Mach number, which is determined by the area ratio of the exit to the throat. Because the static pressure and temperature of a supersonic flow diminish as it expands from the throat to the exit, the amount of expansion also controls the exit pressure and temperature. The exit temperature determines the sound velocity [10-12] which is determined by the exit temperature. The amount of thrust generated by the nozzle is determined by its exit velocity, pressure, and mass flow of the nozzle.

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In this study, the effect of flow compressibility on convergent-divergent nozzles performance will be numerically carried out. As a result, the context analysis must be improved, with a priority on the effect of flow compressibility on convergent-divergent nozzles. The main objectives of the study are to numerically investigate the effect of flow compressibility on convergent-divergent nozzle. Besides that, the optimum configuration of nozzle subjected to incompressibility and compressibility effect will be propose at the end of this research.

2. Methodology

ANSYS CFD code FLUENT was used to experiment the potential of dynamics of expansive flow in a CD nozzle. The investigation used a variety of variables, including pressure, temperature, velocity, and Mach number. Figure 1 illustrates the overall CFD workflow that involves pre-processing, processing and post-processing phases. A convergent-divergent nozzle shown in Figure 2 was considered to configure with AR of 5, 6, 7 and 8 mm. C–D nozzle's detailed aspects shown in Table 1.

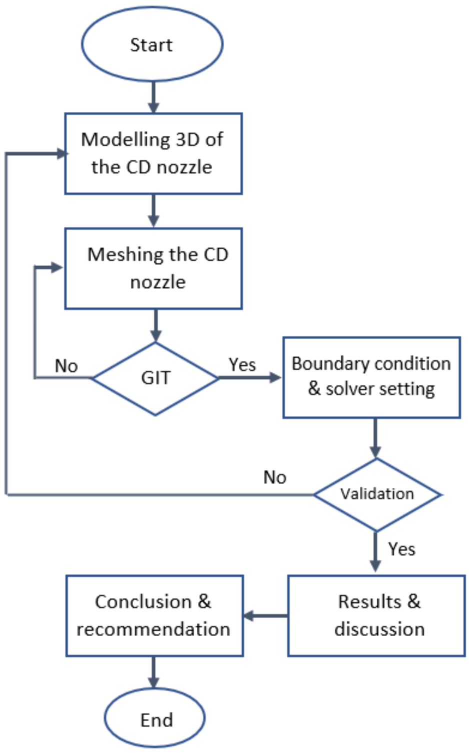

Fig. 1 – Methodology Flow Chart

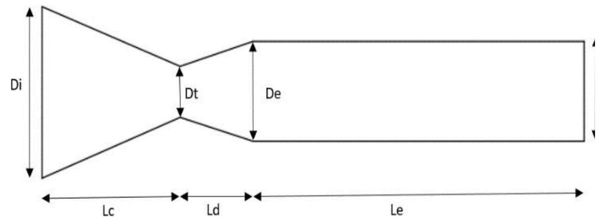

Fig. 2 – Nozzle with enlarged duct

Table 1 – The Boundary Condition

Parts	Dimension
Inlet width (Di)	25.9 mm
Throat diameter (Dt)	7.7 mm
Exit diameter (De)	10 mm
Extended diameter(D)	10 mm
Convergent length (Lc)	25 mm
Divergent length (Ld)	13.2 mm
Extended length (Le)	60 mm
Convergent angle (Ac)	20º
Divergent angle (Ad)	5º

2.1 Meshing

The surface body is divided into seven conspicuous faces when the model has been completed. To alter the mesh and add the proper boundary conditions, the faces are divided into many faces the number of divisions may be modified by adding edge scaling. There are a total of eight edges, with a total of 20 divisions. The wall is split into three edge sizes with a total of 40, 30, and 250 divisions, respectively. The grid independence test was carried out as shown in Figure 3, with Mesh 10 chosen to offer the least variation relative to the finest mesh while keeping CPU solving time to a minimum. At the end of the graph, the value of pressure starts to stable it is because the pressure not affected by the meshing.

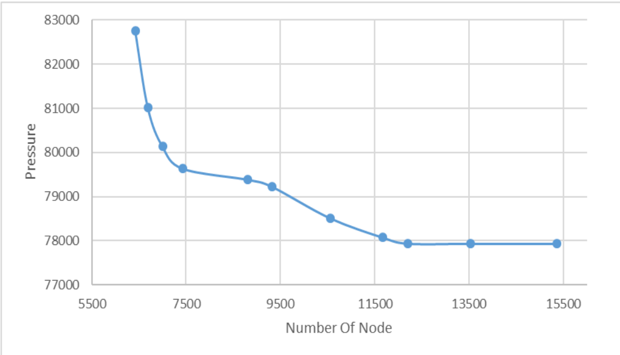

Fig. 3 – Chart Pressure Against the Number of Node

2.2 Solver and Boundary Condition Settings

Five different kinds of boundary operating conditions were enforced, as shown in Table 2. V_{in}, the inlet velocity, was changed between 69.57 and 626.17 m/s. The pressure at the outlet border was set to atmospheric pressure. The initialization mechanism for the solution was standard, and it was computed from the nozzle's intake. The semi-implicit SIMPLE technique was used to implement the pressure- linked equation. The SIMPLE method was developed to obtain the pressure equation from a combination of the continuity equation, the momentum equation and energy equation, as illustrated in Table 3. In Table 4, each area ratio was categorized into 3 Mach numbers, 0.2 for subsonic flow, 1.0 for sonic flow, and 1.8 for supersonic flow. The velocity value was calculated from the Mach number equation. The speed of sound that were used are 347.87 m/s.

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Table 2 – The Boundary Condition

Models	Energy: on Viscous: Standard *k-e* Near Wall Treatment: Enhanced wall treatment
Material	Density: Ideal gas Viscosity: Sutherland
Boundary Conditions	Velocity Inlet = 69.57 m/s = 357.87 m/s =626.17 m/s Inlet temperature = 300 K Outlet Pressure = 0 Pa Outlet temperature = 300 K
Solution initialization	Initialization Method: Standard Initialization Compute from: Inlet

Table 3 – Solver detail

Solver scheme	SIMPLE
Gradient	Green-Gauss Cell Based
Pressure	Second Order
Density	Second Order Upwind
Momentum	Second Order Upwind
Turbulent Kinetic Energy	Second Order Upwind

Table 4 – Results of velocity calculation

No	Mach number	Velocity
1	0.2	69.57
2	1.0	347.87
3	1.8	626.17

2.3 CFD validation

The numerical methodology, which resulted in acceptably proximal predictions, is used for future investigation of the situations considered in this work after validation of simulated findings with experimental results. For all scenarios, ANSYS FLUENT post processing features are utilized to create static pressure, total pressure, and velocity contours, as well as Mach number chart [7]. Parameters that are essential for detailed analysis of expansion like flow exit velocity, pressure at exit and position of occurrence of shocks are obtained from post processor generated contours and plots. Experiment data from was used for quantitative and qualitative validation of the current CFD works. It was used to validate the result of present work.

3. Results and Discussion

The prospective performance of a 2D Converging Diverging nozzle relative has been examined. The effect of geometrical and operating parameters on the performance of this nozzle were investigated systematically using the ANSYS R2 software.

3.1 Effect of area ratio and Mach number on pressure

Figure 4 shows that the differential pressure value depends on the set Mach number. The Mach number are 0.2,1.0 and 1.8 was considered in this work. From the figure, it shows that the chart pressure value increases proportional to the Mach number for all 4-area ratio. The pressure was reduced from the intake to the output based on this finding for the subsonic flow. This is shown by the convergent-divergent theory when the nozzle is not blocked, the flow through it is fully subsonic, lowering the pressure. The sonic and supersonic flow pressure progressively grew, but never exceeded the initial pressure. The velocity will rise as the pressure decreases. The flow travels faster and the flow rate increases with a subsonic flow because there is less backpressure. This differs from sonic and supersonic flow because the pressure rises and the velocity decreases.

Figure 5 Pressure contour (a) AR= 6mm, 0.2 Ma (b) AR= 5mm, 1.0 Ma and (c) AR=5mm, 1.8 Ma. Due to the pressure values legend was small, all the contours for pressure were represented by blue color. Although, the pressure color should be shown by red color at the convergent section based on the pressure at Mach number 0.2, since the pressure contour's range was too large, the red color switches to blue at the convergent-divergent nozzle. This is applied to all pressures at a certain area ratio.

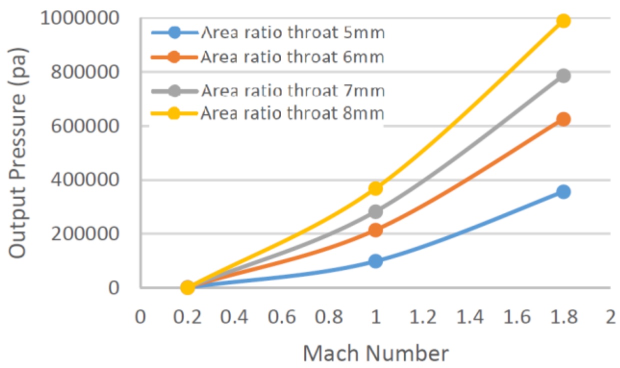
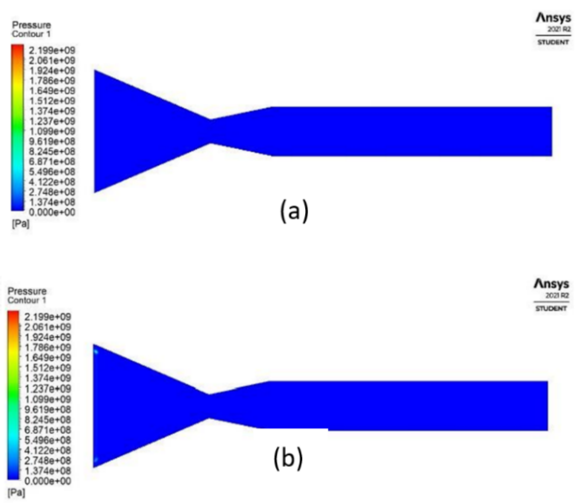


Fig. 4 – Output Pressure Against the Mach Number



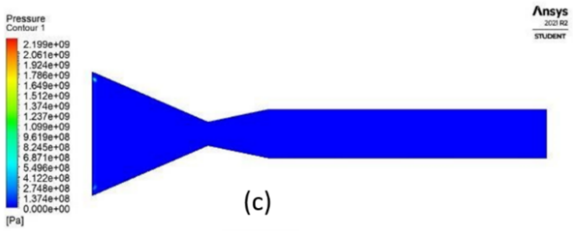


Fig. 5 – Pressure contour (a) AR=6mm, 0.2Ma (b) AR=5mm, 1.0Ma (c) AR=5mm, 1.8Ma

3.2 Effect of area ratio and Mach number on velocity

Figure 6 depicts how the velocity value graph varies with the Mach number. The relationship between the Mach number and velocity is straightforward. As shown in Figure 4, the pressure at area ratio 5mm was at the bottom of the graph compared to other area ratios. In Figure 6, the velocity at area ratio 5mm is the greatest compared to other area ratios. Pressure and velocity are proportional in an indirect way. Another factor that contributes to velocity validation is variations in flow cross sectional area on subsonic flow, which states that the velocity and cross section of a subsonic flow is in opposite directions. In other words, with subsonic flow in a diverging duct, the increase in area is followed by a decrease in velocity. The velocity of subsonic flow via a converging duct increase. However, compressible flow differs from subsonic flow in that when the flow reaches sonic or supersonic, the cross-sectional area and velocity point in the same direction. A diverging duct will increase supersonic flow. A converging duct will slow down a supersonic flow.

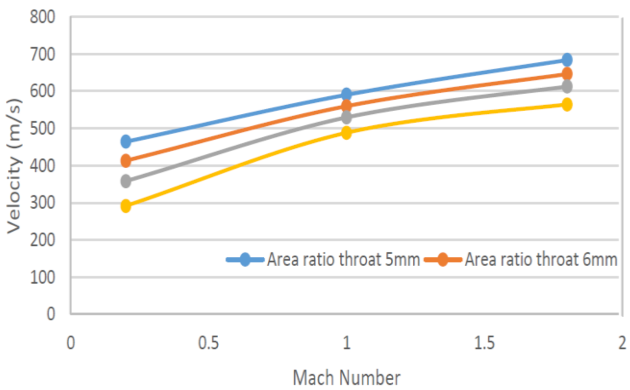


Fig. 6 – The velocity graph against the Mach number

At the sonic and supersonic levels, there are additional factors that influence velocity, resulting in changes in velocity and other parameters. Back pressure, for example, has an influence on the flow of velocity. Back pressure is a force that opposes the intended flow of fluid through the nozzle, resulting in friction loss and velocity decrease. Next is the normal shock that the shock wave flow mechanism is very irreversible and cannot be approximated as isentropic. If the flow is turned significantly in front of a supersonic flow, a normal shock occurs, and the shock cannot stay attached to the body, causing the velocity to decline and the nozzle to fail to attain its maximal capacity.

Figure 7 shows the velocity vector (a) AR= 6mm, 0.2Ma, (b) AR= 5mm, 1.0Ma (c) AR=5mm, 1.8Ma. In the area ratio of 5mm and Mach number of 0.2, the colors appeared blue at the convergent region because the velocity at the section was low. Because the velocity increases, the color changes at the throat. There was also a shocked fanno flow at the neck, but it was not as noticeable since the velocity was not as great when compared to another velocity at a different area ratio. At Mach number 1.8, the contrast of shocked fanno flow was visible, which might explain the difference in velocity values. Finally, at the area ratio of 6mm, there is the standard shock at the neck. Because the flow over the shock is adiabatic and irreversible, the entropy increases.

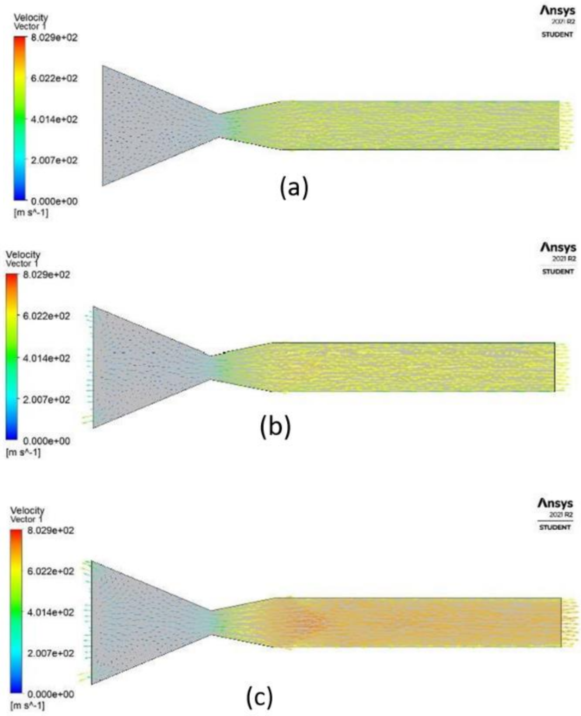


Fig. 7 – Velocity vector (a) AR=6mm, 0.2Ma (b) AR=5mm, 1.0Ma (c) AR=5mm, 1.8Ma

3.3 Effect of area ratio and Mach number on temperature

Output temperature against Mach number is illustrated in Figure 8. The graph demonstrated that the link between Mach number and temperature was precisely proportional. Thus, the area ratio throat 8mm has the maximum temperature value when compared to other area ratios such as 7mm, 6mm, and 5mm. The temperature contour is shown in Figure 9 (a) AR= 6mm, 0.2Ma (b) AR= 5mm, 1.0Ma (c) AR=5mm, 1.8Ma. There were many colors that represented the temperature value. The light blue colors indicate that the output temperature value was decreased during the convergent phase. The darkblue color contour shows the temperature drops at the diverging portion. The results demonstrate thatas the area ratio of the neck grows, the value of the output temperature likewise increases, as shown in Figure 9.

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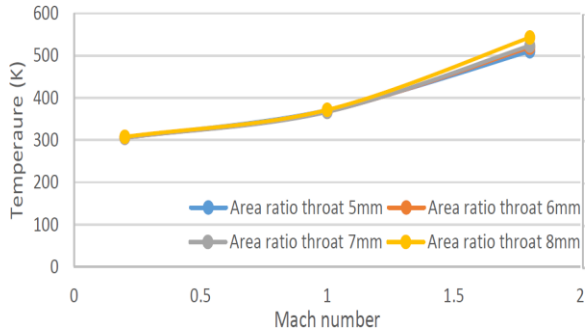

Fig. 8 – Temperature against the Mach number

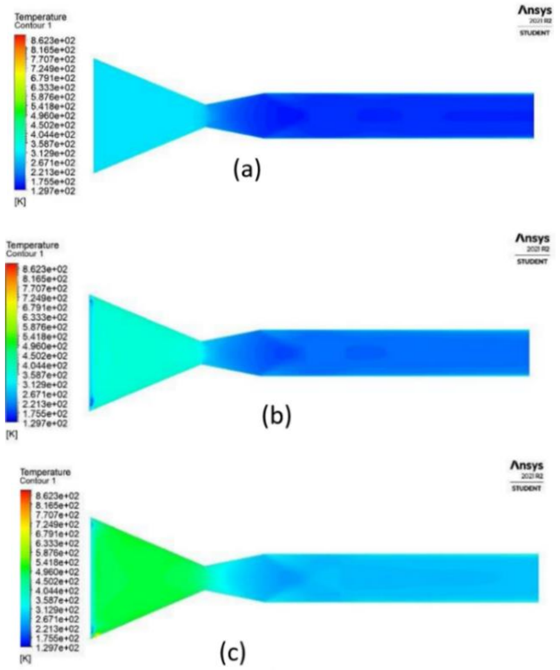

Fig. 9 – Temperature contour (a) AR=6mm, 0.2Ma (b) AR=5mm, 1.0Ma (c) AR=5mm, 1.8Ma

4. Conclusion & Recommendation

In conclusion, the numerical effect of the area ratio and the Mach number to the flow in the convergent-divergent nozzle was investigated successfully. The intensive simulation was successfully validated using the CFD method. A standard *k*- *ε* (ske) turbulence model with enhanced wall treatment was used in a detailed simulation. A few parameters were considered, such as the area ratio and Mach number applied in this intensive simulation.

The simulation result shows that the most effective Mach number to use is in the incompressible that is Ma < 1 compared with the compressible flow Ma > 1This is because several factors will impact the velocity result when the flow is supersonic. Back pressure, normal shock, and shocked fanno flow are some of the factors. This kind of factor has been identified as the source of the velocity decelerating and the nozzle's inability to raise the velocity at the divergent part's departure properly. As a result, the connection between Mach number and velocity is inversely proportional. Furthermore, another relationship was revealed as a result of the results. The pressure will decrease as the velocity increases to a certain point. After that, there's the temperature-velocity connection. If the velocity increases, the temperature rises in a direct proportionate manner. In addition, the area ratio might be causing the velocity to slow down. This shows that the velocity value at AR=5mm was higher than the value at AR=8mm. As a result, the ratio of the throat and the velocity have an indirect proportional connection. To summarize, the most efficient technique to archive the convergent divergent nozzle's maximum potential is for the Mach number to be below 1ma and the area ratio to be compatible with the flow to avoid the flow from choking.

For recommendation, there are many possible future works that can be continued from present work. first, Used improved computer specification. This higher processing demand can reduce simulation time and meet the computational need of meshing at a much finer scale. Second, Consider the variation of Mach number. This is to get the more specific result that can identify the theatrical with the numerical method. Lastly, Apply the CFD method that is more compatible with the nozzle. This can make the result smooth and easy to validate.

Acknowledgement

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