THE EFFECT OF DIVERGENT ANGLE ON A CONVERGENT-DIVERGENT NOZZLE USING CFD

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Report

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DECLARATION

I declare that this project report entitled “The Effect of Divergent Angle on A Convergent-Divergent Nozzle Using CFD” is the result of my own work except as cited in the references

Signature : ……………………….

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Date : ……………………….

SUPERVISOR’S DECLARATION

I have checked this report and the report can now be submitted to JK-PSM to be delivered back to supervisor and to the second examiner.

Signature :…………………….

Name of Supervisor : Ir. Dr. Nazri Bin Md Daud

Date :…………………….

DEDICATION

This study report is passionately dedicated to my beloved parents, Norhayati Bt Mohammad and Badrul Hisham B Ibrahim who have been my source of inspiration who continuously provide their emotional, spiritual, financial, and moral support.

To my lecturers, mentors and friends in UTeM who have shared their piece of advice and knowledge to encourage me to finish this study report.

And last but not least, I dedicate this study report to the Almighty God, Allah swt. Thank you for providing a healthy state of mind and body, protection, and skills. Without the guidance of Allah swt who helped me throughout hard times I could have never achieved this success.

ABSTRACT

The work focuses on the numerical simulation on the fluid performance of converging diverging nozzles through nozzle dimension. In the present work, 3 models of convergent-divergent nozzles with divergent angle of 7º, 13º, and 19º are numerically investigated using a software Ansys Fluid Fluent. Computational work is carried out using a double precision method at the solution in Ansys, two-dimensional modelling, and implicit scheme of linear method. The nozzle has a throat diameter of 0.509 m, convergent length of 0.64 m, and a convergent angle of 21º. The inlet boundary conditions were specified as such the fluid used in this study s ideal gas, mass flow rate of fluid to be 826 kg/s, and atmospheric pressure of 101.325 kPa. The main objectives of this study is to design 3 models of convergent-divergent nozzle with different divergent angles, and to analyze and compare maximum Mach number, exit velocity, pressure drop, and thrust force for the 3 models of convergent-divergent nozzle. Numerical findings show that there are changes in Mach number, exit velocity, pressure drop, and thrust force in 7º, 13º, and 19º models. Model 1 with 7º divergent angle has a maximum Mach number of 2.231, exit velocity of 2287 m/s, pressure drop of 3479.9 kPa, and thrust force of 1889.062 kN. Model 2 with 13º divergent angle has a maximum Mach number of 2.328, exit velocity of 2376 m/s, pressure drop of 3568.6 kPa, and thrust force of 1962.576 kN. Model 3 with 19º divergent angle has a maximum Mach number of 2.376, exit velocity of 2396 m/s, pressure drop of 3590.9 kPa, and thrust force of 1979.096 kN Numerical results show that there is no choking flow that reduces the performance of fluid flow in the nozzles in terms of Mach number, velocity, pressure drop, and thrust force.

ACKNOWLDEGEMENTS

Firstly, I would like to say my biggest thank you and blessing to both my beloved mother and father for supporting me to finish this study report. Since day one they have been very helpful in providing a mental and financial support. I dedicate my success in this report to them specifically.

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LIST OF ABBREVIATIONS

CFD	Computational Fluid Dynamics
CD	Convergent-Divergent
2D	2 Dimensional
3D	3 Dimensional
NPR	Nozzle Pressure Ratio
NAR	Nozzle Area Ratio
SST	Shear Stress Transport
LES	Low Eddy Simulation
MOC	Method of Characteristics

LIST OF SYMBOLS

M = Mach Number

α^{o} = Divergent Angle

β^{o} = Convergent Angle

D_t = Throat Diameter

ε = Divergence Half Angle

C_f = Thrust Coefficient

C_d = Drag Coefficient

F = Thrust Force

$\dot{m}$ = Mass Flow Rate

V_e = Outlet velocity

P_e = Outlet Pressure

P_a = Atmospheric Pressure

V_a = Atmospheric Velocity

w = Thermodynamic work

v = kinetic viscosity

u = velocity profile

ρ = density of working fluid

R_A = Area Ratio

A_c = Cross-sectional Area of Nozzle exit Area

A_t = Throat Area

CHAPTER 1

INTRODUCTION

1.1 Background of Study

A nozzle is a venturi device intended to control the qualities and direction of a liquid, and when given some flow conditions and adequate pressure, it might bring about choked stream at its throat. The uses of nozzle are extremely wide and have numerous reasons, for example, to quicken stream for atomization of fluid stages, as a major aspect of airplanes to increment active kinetic energy and to thrust gas in rocket motors and many more.

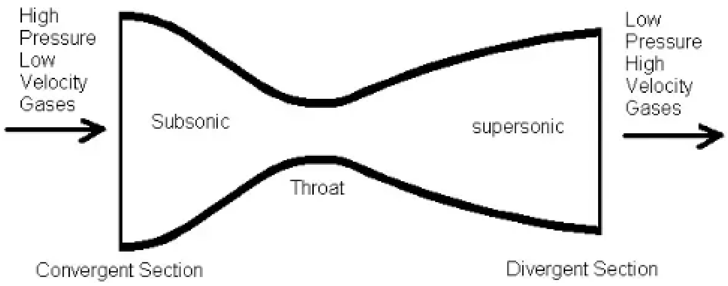


Figure 1. 1 parts of Convergent-Divergent Nozzle

Nozzles have three different sections, a converging section, throat, and a diverging section, as appeared in **Figure 1.1**. The point that has the smallest diameter across is known as the throat. The throat is normally stretched yet can likewise be a single point throat. The left section (upstream) of the throat is the converging section, and the right section (downstream) of the throat is the diverging section. The region of the converging section diminishes as the nozzle profile goes from funnel to the start of the throat. The territory of diverging section increments as the nozzle profile goes from the end of the throat to the funnel. The diameter of inlet and outlet of the throat ought to and must stay equivalent.

This report attempts to set up the methods of developing a convergent-divergent nozzle in assisting with boosting the performance of steam turbine and aircraft engines. The test is led at a similar Mach numbers, where the flow conditions are resolved. The fluid flow conduct through nozzles relies upon the sort of fluid flowing through the nozzle. The dimensionless Mach number, M, which is the proportion of fluid speed to speed of sound in the encompassing medium, can be determined to decide whether the flow is compressible ($M > 0.2$) or incompressible ($M < 0.2$). In this report, compressible flow is considered by utilizing air as working fluid. Flow velocity increments as fluid enters the nozzle, until the nozle throat is reached. At this point flow is subsonic (for example $M < 1$). Once fluid flows through the throat, given sufficient upstream pressure and flowrate conditions, the fluid velocity could get equivalent to the speed of sound, arriving at sonic conditions ($M = 1$). As fluid flows out of the throat, entering the separating area, the fluid velocity speeds up beyond the speed of sound arriving at supersonic flow ($M > 1$). This happens in light of the fact that when air is flowing through the diverging section of the nozzle, there is an expansion in kinetic energy to the detriment of an enthalpy drop because of gas expansion.

The course through a converging-diverging nozzle is one of the benchmark issues utilized for displaying the compressible flow through Computational Fluid Dynamics, CFD. Event of shock in the flow field shows one of the most noticeable impacts of compressibility over fluid flow. Accurate shock predication is a test to the CFD clique. So as to determine the high-pressure gradients, we have to utilize some extraordinary numerical plans alongside fine grid. Now and again, local grid adaption can be useful. The one-dimensional inviscid isentropic flow in a convergent-divergent nozzle is an old problem, which has diverse flow systems relying on the nozzle pressure ratio (NPR).The inviscid hypothesis predicts a basic shock structure comprising of an normal shock followed by a smooth recuperation to exit pressure in the divergent part of a chocked nozzle for the nozzle pressure ratios comparing to the over-extended flow systems. In any case, in practical, multi dimensionality and viscous impacts like wall boundary layer and flow separation definitely change the stream in a Convergent-Divergent nozzle. The over-extended flow system in Convergent-Divergent nozzle of various shapes and sizes has been a topic of various investigations due to their wide scope of applications. One of the recent investigations in an experimental investigation of flow in rectangular over extended supersonic nozzles investigating the intricacy of such flows. The prediction of such flows likewise presents incredible challenges to any CFD code.

1.2 Problem Statement

Prior to previous research and experiments, this report is conducted in the same manner but with slight differences. Based on the previous research, it can be concluded that the performance quality of convergent-divergent in mechanical machines is determined by several factors.

The first problem is the lack of research in the conical convergent-divergent makes it hard to validify and compare results from previous experiment or research that has the similar methods and design. However, the results that had been acquired were quite similar as they all focused on getting the same readings, which are the Mach number, outlet pressure, outlet velocity and coefficient drag.

Adding to the existence problem is the design of the convergent-divergent nozzle. Different geometry and design of the convergent-divergent nozzle will give different results in mass flowrate, pressure drop, maximum velocity and coefficient drag. In this report, the

3 designs are mainly conical convergent-divergent, and modified conical convergent-divergent nozzle. The 3 designs are analysed to determine which has the best performance quality suitable for high performance mechanical applications.

On a final note, an addition to the design of the convergent-divergent nozzle, the divergence angle is considered one of the factors in determining the performance quality. One of the main problems in a convergent-divergent nozzle is that the existence of a ‘chocking’ flow in the nozzle that narrow down the overall performance of the convergent-divergent nozzle.

1.3 Objectives

Objectives are included to give an idea of what the aim and purpose of writing this study report. The objectives of this study are:

1. To design 3 models of convergent-divergent nozzle with different in divergent angles.
2. To analyze and compare maximum Mach number, exit velocity, pressure drop and thrust force for the 3 models of convergent-divergent nozzle.

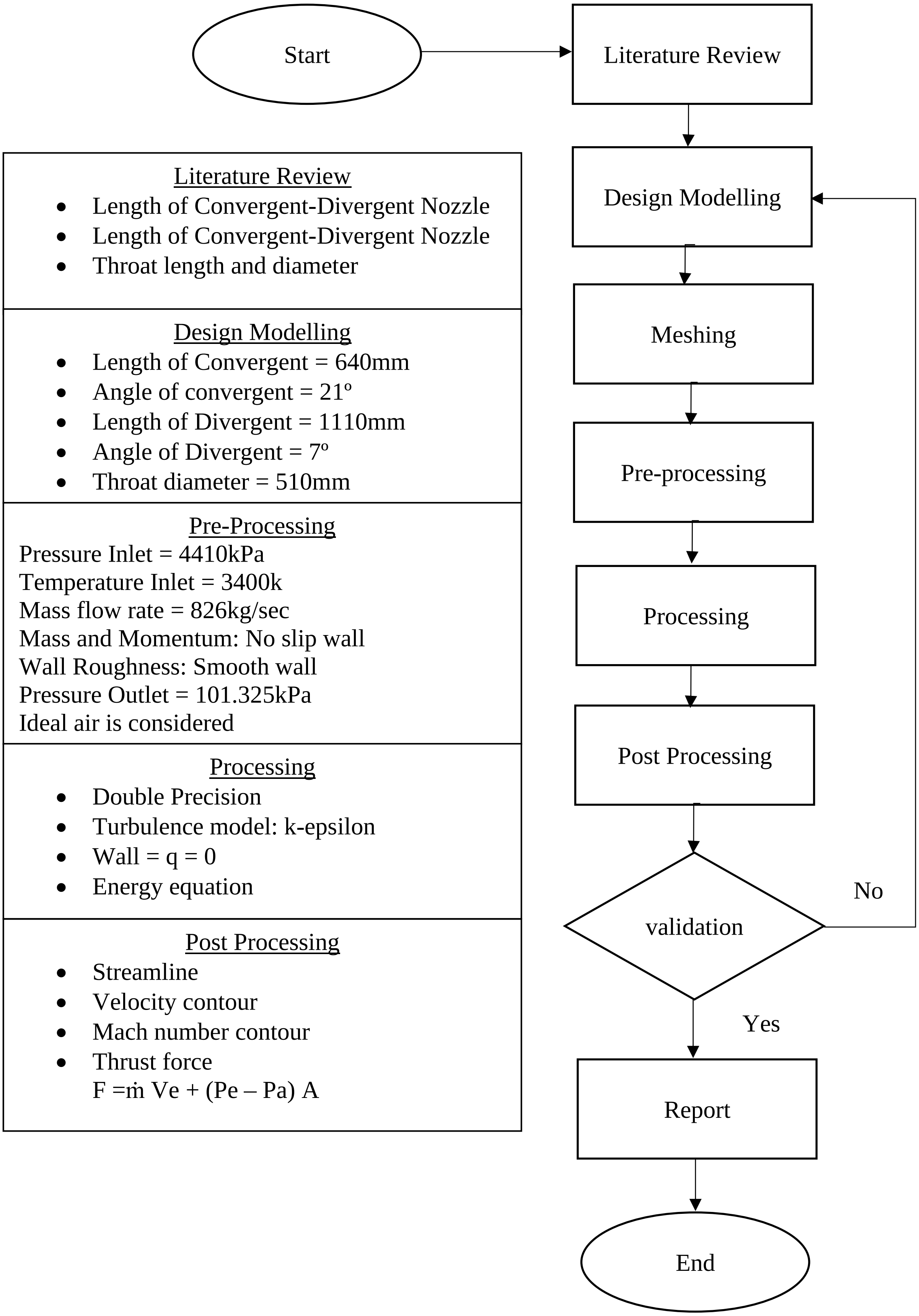
1.4 Scope of Project

To achieve the objectives of this report, the study has been done by using Ansys Fluid Flow (Fluent) software to analyse the fluid flow inside of the Convergent-Divergent nozzle. The total length of the Convergent-Divergent nozzle excluding the throat is 1750mm. The convergent angle, β is set to be 21º and the divergent angle, α is set to be 7º. Then, the divergence angle is changed to be 13º and 19º. Lastly, the Convergent-Divergent nozzle undergone analysis in Ansys Fluid Flow (Fluent) to determine the pressure drop, Mach number, velocity, and the then velocity is used to calculate the thrust force.

1.5 General Methodology

1. Literature Review
    - doing research on past experimentation and journal report.
2. Domain Modelling
    - model the design using the same design on past experiments and change some parts to see the effects on the flow
3. Meshing
    - set the appropriate meshing size to get more accurate data
4. Pre-Processing
    - Set the boundary conditions at the inlet, outlet, and wall of the convergent-divergent nozzle.
5. Processing
    - Let Ansys Fluent run the data to get the results after setting the boundary conditions.
6. Post Processing
    - Getting the contours and streamlines in the Convergent-Divergent nozzle.
7. Comparing Results with Past Simulation
    - Compare the results that we did to other past experiments' results to validate that our result is correct.

1.6 Flowchart



Literature Review
- Length of Convergent-Divergent Nozzle
- Length of Convergent-Divergent Nozzle
- Throat length and diameter

Design Modelling
- Length of Convergent = 640mm
- Angle of convergent = 21°
- Length of Divergent = 1110mm
- Angle of Divergent = 7°
- Throat diameter = 510mm

Pre-Processing

Pressure Inlet = 4410kPa
Temperature Inlet = 3400k
Mass flow rate = 826kg/sec
Mass and Momentum: No slip wall
Wall Roughness: Smooth wall
Pressure Outlet = 101.325kPa
Ideal air is considered

Processing
- Double Precision
- Turbulence model: k-epsilon
- Wall = q = 0
- Energy equation

Post Processing
- Streamline
- Velocity contour
- Mach number contour
- Thrust force
  $F = \dot{m} V_e + (P_e - P_a) A$

CHAPTER 2

LITERATURE REVIEW

2.1 Design of Convergent-Divergent Nozzle

In a rocket, a nozzle is mostly utilized to control mass flow rate, velocity appropriation and pressure of the fumes gas that rises out from the ignition chamber. The nozzle is utilized to change over the compound and thermal energy created in the ignition chamber into thrust. In the nozzle, the high pressure, high temperature, and low velocity gas will be changed in the ignition chamber into high velocity, low pressure, and temperature. The structure of nozzle is a significant part to accomplish the most extreme Mach number and least turbulent intensity. (Raghu Ande, 2018). The geometry of Convergent-Divergent nozzles influences the conditions at which basic subcritical flow transition happens. To make a network of different nozzle geometries and shapes, nozzles are executed in various applications, for example, aviation, farming, atomic and oil. In view of past research, nozzles can be classified into two significant structures which are cone conical and parabolic (Jagmit Singh, 2019). But in this report, only the conical nozzles were analysed.

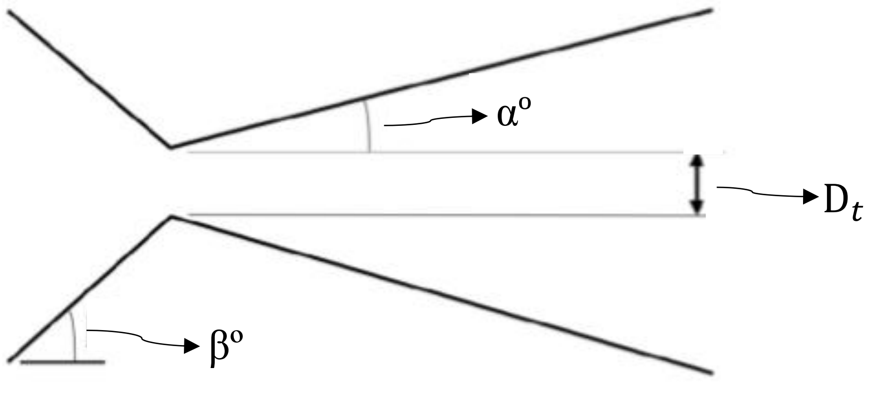


Figure 2. 1 Simple diagram of Convergent-Divergent Nozzle

Figure 2.1 shows the simple diagram of convergent-divergent nozzle. From figure above, it tends to be seen that a convergent-divergent nozzle has a descending tightening linear inlet area which decreases in cross-sectional area along the profile until the throat diameter across has been reached, and afterward has an upward tightening linear outlet area where the cross-sectional region increments along the profile. The point at which the channel tightens is called converging angle (β°). The edge at which the outlet tapers is known as the diverging angle (α°). The measurement of the smallest point in the nozzle is known as the throat diameter ($D_{t)}$.

Nozzles come in various shapes relying upon the application. The shape of the divergent section of a nozzle assumes a significant role in the development characteristics of the fluid. The convergent section is structured with a bigger volume to get the greatest mass flow into the nozzle. The flow then will be packed (total mass flow) at the throat and afterward will be extended to arrive at its optimal condition, through the divergent section of the nozzle. Most nozzles inside the aviation discipline have a convergence section to create pressure that is from profoundly warmed fumes gas accelerated from the burning. To accomplish the perfect execution, the state of the divergence section might be either shaped convergent or divergent relying upon the application. Some jet motors fuse a basic convergent type nozzle, which comprises of a convergent end downstream. At the point when the convergent type nozzle is chocked, a portion of the development happens downstream in the jet wake. A significant part of the gross thrust delivered from the stream energy with extra thrust from pressure will create an imbalance between the throat static pressure and atmospheric pressure. Jet motors consolidating a Convergent-Divergent spout will permit the vast majority of the development to happen within the nozzle to augment the thrust. (Ekanayake, 2013).

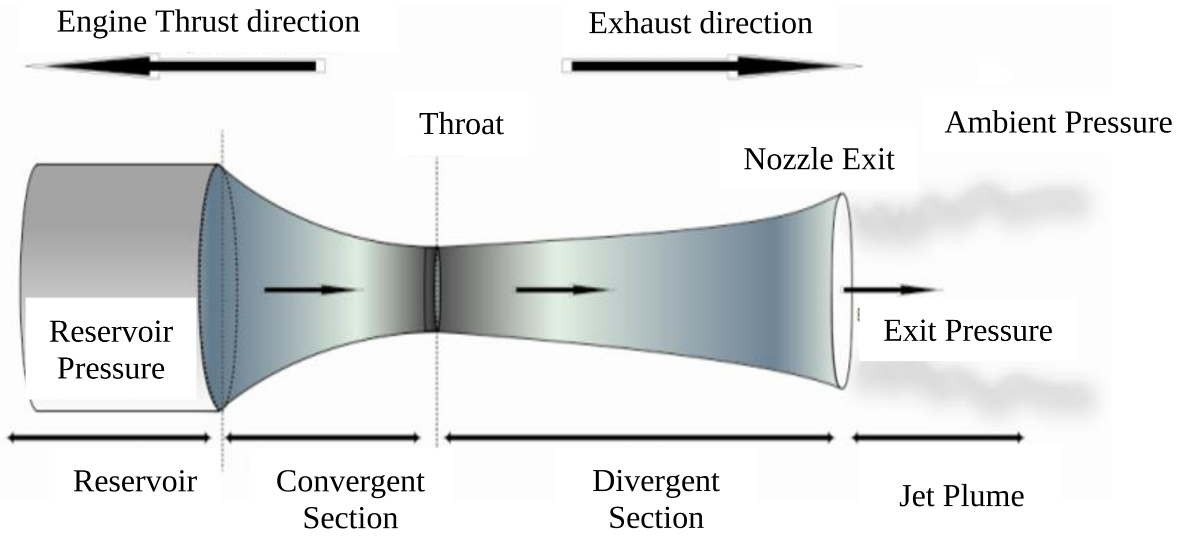


Figure 2. 2 Design of Convergent-Divergent Nozzle for Jet

Figure 2.2 shows the design of Convergent-Divergent nozzle application in a jet system. From the figure above, it can be seen that the direction of thrust is directly opposite to the exhaust direction. At the reservoir, the inlet of the nozzle is where the fluid begins to flow. it then goes through the convergent section to increase its velocity and convert the flow from subsonic to transonic in the throat section. After the velocity increases, it goes through the divergent section to increase its thrust force. At this phase, the flow becomes supersonic where the flow becomes turbulent which produces thrust. To produce enough thrust to move the jet, the exit pressure must be higher than the ambient pressure.

In nozzle terminology, the performance is determined on the phase that is implemented in the system. Some uses only one phase whereas there are others who implement two or more phases. Two phase flows in a nozzle will show altogether various practices contrasted with a single gas flow through a convergent–divergent nozzle. Two-phase flows are viewed as isentropic streams that isentropic relations can be utilized for homogeneous harmony model (Guang Zhang, 2017).

After doing some research, size of throat is crucial in determining the quality of air flow in a convergent-divergent nozzle. The sole reason for utilizing a throat in a nozzle is to quicken the flow to accomplish critical or sonic conditions. Henceforth, maintaining a strategic distance from a situation where choking occurs. When choking occurs, the general execution will be disturbed. At a specific pressure differential, the flow rate that goes through the nozzle for that particular throat size arrives at greatest flow rate and the Mach number becomes 1. Any further increment in pressure differential does not bring about an expansion in flow rate. (Jagmit Singh, 2019).

2.2 Flow Conditions in The Convergent-Divergent Nozzle

To fathom the numerical simulation of a nozzle, proper turbulent model is required. The last arrangement of the last step in Navier-Strokes equation is tied in with finding the flow velocity.

$$\frac{\partial u}{\partial t} + (u.\nabla) - v\nabla^2 u = -\nabla w + g. \tag{2.1}$$

$$\frac{\partial}{\partial t}(\rho u) + \nabla.(\rho u \Theta u + pI) = \nabla.\tau + \rho g \tag{2.2}$$

From **Equation 2.1**, it represents the Navier-Strokes equation where the term ‘*w*’ symbolizes the specific thermodynamic work, ‘*v*’ is the kinetic viscosity of the fluid in the nozzle, ‘*u*’ is the velocity profile of the fluid which is useful in many single phase fluid flows. When the flow velocity is distinguished, different estimations, for example, temperature or pressure can be found without any problem. The Cauchy momentum equation, which is **Equation 2.2** is gotten initially from Navier-Strokes momentum equation. **Equation 2.2** shows preservation form of Cauchy momentum equation, the left half of the