Ejector for Vacuum Distillation Ejector System

A Final Year Project Report

Presented to

SCHOOL OF MECHANICAL & MANUFACTURING ENGINEERING

Department of Mechanical Engineering

NUST

ISLAMABAD, PAKISTAN

In Partial Fulfillment

of the Requirements for the Degree of

Bachelors of Mechanical Engineering

by

Muhammad Daniyal Khalid

Bilal Ahmed Khan

Aqib Mehmood

Mirza Muhammad Ibraheem

May, 2019

EXAMINATION COMMITTEE

We hereby recommend that the final year project report prepared under our supervision by:

Bilal Ahmed Khan	00000125122.
Muhammad Daniyal Khalid	00000132694.
Mirza Muhammad Ibraheem	00000120945.
Aqib Mehmood	00000123914

Titled: “Ejector for Vacuum Distillation Ejector System” be accepted in partial fulfillment of the requirements for the award of Bachelor of Mechanical Engineering degree with grade ___

Supervisor: Dr Emad-ud-din, HoD, Mechanical Affiliation	Dated:
Committee Member: Sir Abdul Naeem Khan, Assistant Professor Affiliation	Dated:

(Head of Department) (Date)

COUNTERSIGNED

Dated: ________________

(Dean / Principal)

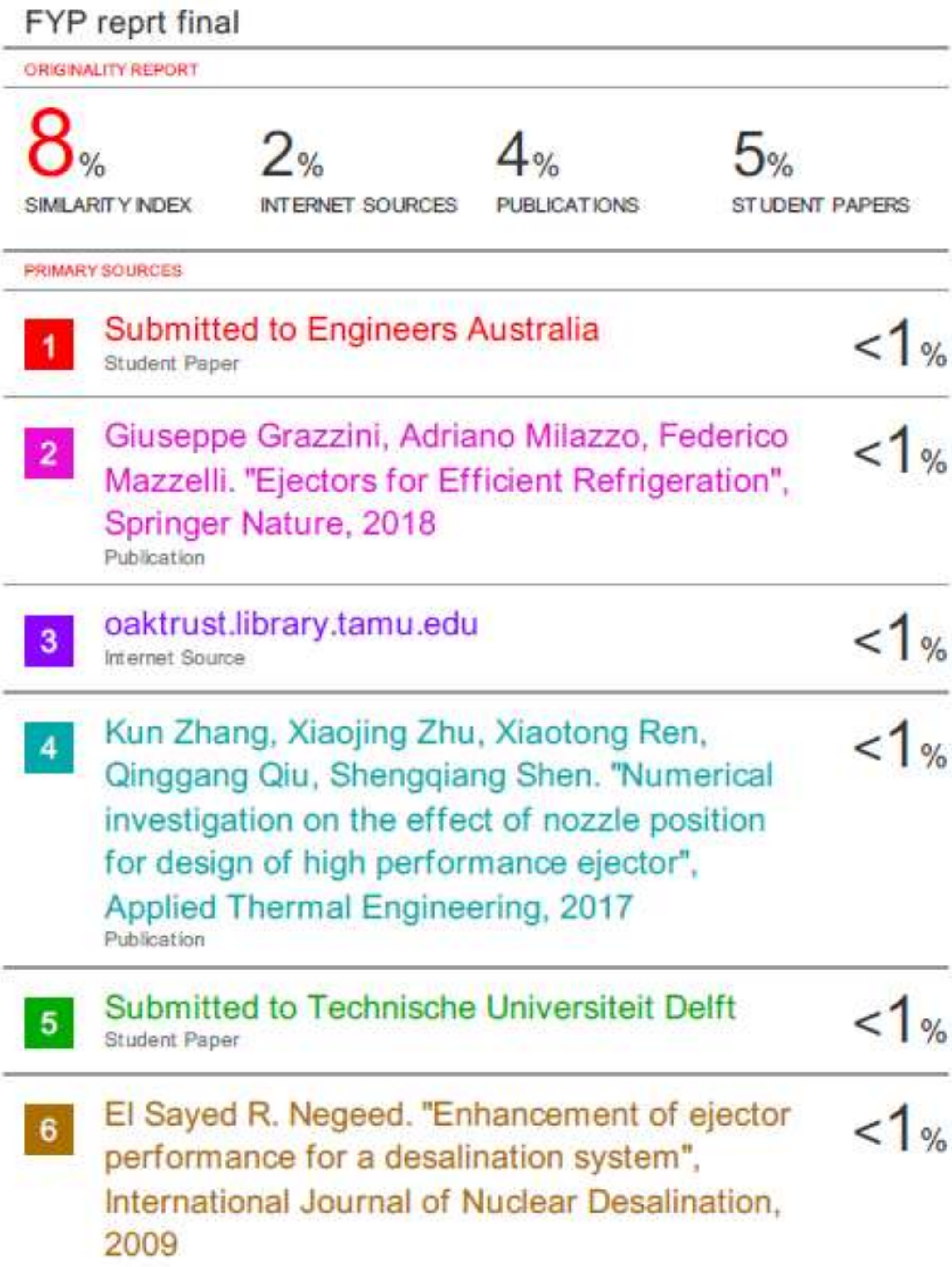
Abstract:

The following report deals with the designing and analysis of steam/gas ejector. Inlet pressure, mass flow rate and temperature of both primary fluid and secondary fluid, back pressure of diffuser, temperature of mixed fluid at diffuser end and entrainment ratio were initial parameters used to design the ejector. Isentropic relations were used for designing the primary nozzle which were obtained from various sources. Deciding factor in its designing was the back pressure which was linked with nozzle position. Designing of secondary nozzle was done partially by ESDU approach and partially with isentropic relations of shockwave. First Shut off condition was also calculated for different nozzle positons. Results obtained analytical were corroborated by CFD analysis of both primary and secondary nozzle. Angles of convergence and divergence of both primary and secondary nozzle and length of mixing chamber were selected after thorough CFD analysis. The prototype was manufactured after detail review of the prototyping methods i.e. casting, machining. Experiments were performed on the prototype while testing it in real time after connecting it to an outlet of a boiler. The results were then compared and conclusions were drawn.

Acknowledgements

We as a team would like to acknowledge Dr Emad-ud-din for his support and guidance which ensured our continuous progress. Furthermore, we would like to express our gratitude towards Dr Ali Zaidi for bearing with our numerous visits to his office and our long list of questions. In the end we would like to acknowledge MS students of SMME for their advice with regard to the Computational Fluid Dynamic Analysis portion of our project.

Originality Report:



FYP reprt final

ORIGINALITY REPORT

8%	2%	4%	5%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	Submitted to Engineers Australia Student Paper	<1%
2	Giuseppe Grazzini, Adriano Milazzo, Federico Mazzelli. "Ejectors for Efficient Refrigeration", Springer Nature, 2018 Publication	<1%
3	oaktrust.library.tamu.edu Internet Source	<1%
4	Kun Zhang, Xiaojing Zhu, Xiaotong Ren, Qinggang Qiu, Shengqiang Shen. "Numerical investigation on the effect of nozzle position for design of high performance ejector", Applied Thermal Engineering, 2017 Publication	<1%
5	Submitted to Technische Universiteit Delft Student Paper	<1%
6	El Sayed R. Negeed. "Enhancement of ejector performance for a desalination system", International Journal of Nuclear Desalination, 2009	<1%

Table of Contents

List of Tables

List of Figures

Abbreviations:

Ldiv	Length of Divergent portion
Lconst	Length of Constant area
Lconv	Length of Convergent portion
MolarmassS	Molar mass of secondary fluid
MolarmassP	Molar mass of primary fluid
MoleP	Moles of primary fluid
MoleS	Moles of secondary fluid

Nomenclature

β	Angle of Convergence
α	Angle of Divergence
k	Specific Heat Ratio
$\dot{m}_p$	Mass Flow rate of primary fluid
P_{o1}	Primary nozzle pressure
T_{o1}	Primary nozzle temperature
P_{1e}	Back Pr. of Primary Nozzle
$\dot{m}_p$	Mass Flow rate of primary fluid
R	Gas Constant
Pth	Throat Pressure:
Tth	Throat Temperature:
Dth	Diameter Of Throat:
Te	Temperature. at Exit
Ma	Mach
De	Diameter of Exit
mtotal	total mass flow rate
Po2	Condenser Pressure:
To2	Condenser Temperature
P2e	Diffuser exit pressure.
D2i	Dia of Inlet
Np	Molar Fraction of Primary fluid
Ns	Molar Fraction of Secondary fluid
P2total	Total Pressure at throat
T2total	Total Temperature at throat
Matotal	Mach at mixing
P2U	Static pressure at upstream of shockwave
T2U	Static temperature at upstream of shock
Ma2D	Mach at downstream of shock

INTRODUCTION

Ejector is a device that uses a high pressure motive fluid to compress a low pressure entrained fluid. The device creates a low pressure region in which the entrained fluid enters, mixes with the motive fluid in the mixing chamber, and then gets discharged at a desired intermediate pressure. It is an environment friendly device which is used for recovering energy in many fields like petroleum, refrigeration, paper industry and nuclear plant. The terms "ejector" and "jet pump" are alternative names for the same device and the term "injector" is also used. Although common usage, it is not strictly correct to assume that the terms "ejector" and "injector" are used when the working fluids are gases and the term "jet pump" when they are liquids. Due to their simplicity and high reliability, they are widely used in chemical industrial processes; however, ejectors have a low efficiency because many factors affect steam jet ejector performance, including the feed temperature, mixing tube length, fluid molecular weight, nozzle position, throat dimension, motive velocity, Reynolds number, pressure ratio, and specific heat ratio.

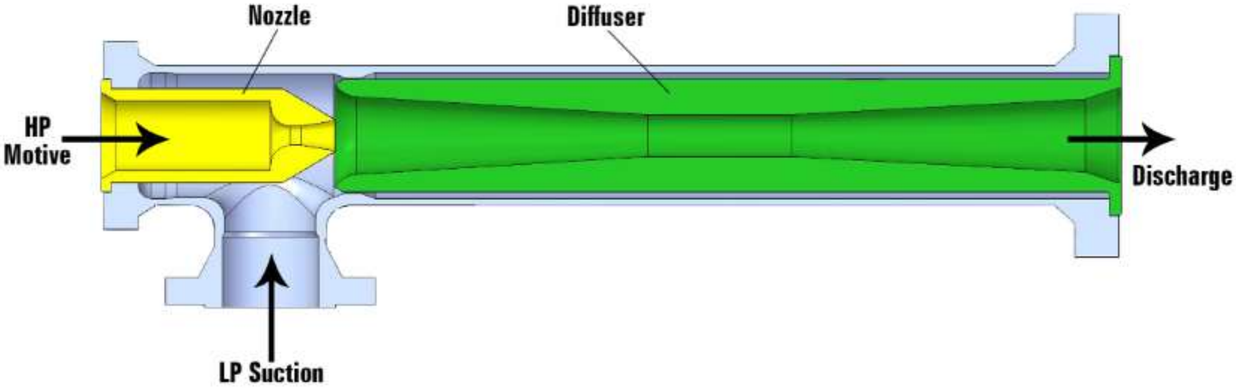


Figure a: schematic of an ejector

Types of Ejectors:

Following are the types of ejectors:

1. Gas/Gas Ejectors
2. Steam/Gas Ejectors
3. Steam/Liquid Ejectors
4. Liquid/Liquid Ejectors

The above mentioned types are explained below:

Steam/Gas Ejectors and Steam/Liquid Ejectors:

Ejectors that use steam as the primary fluid (motive) can be used for both gaseous and liquid secondary fluids (entrained). In a steam/gas ejector the gas is induced into motion by the turbulent mixing and entrainment at the edges of the steam jet. In a steam/liquid ejector, the steam jet and liquid move initially as an annular flow in the mixing chamber. Mixing may take place gradually, as the steam condenses, but usually occurs suddenly at a condensation shock. In both types of steam driven ejector, mixing may occur violently following a compression shock in the steam flow.

Gas/Gas Ejectors and Liquid/liquid ejectors:

Gas ejectors use high-pressure (HP) gas to safely and economically compress flare, vent, and surplus or low-pressure (LP) gas. A high pressure gas well can be used to enhance both the production and the total recovery from a depleted well using a multiphase ejector. In liquid/liquid ejectors a liquid motive medium is used to suck off another liquid and to convey it to a higher pressure. High turbulence achieves a homogeneous intermixture of both flows. It has various applications in ship building, water treatment, synthetic fertilizer plants etc.

Motivation:

Ejector is an environment friendly device which is used for recovering energy in many fields like petroleum, refrigeration, paper industry and nuclear plant. It has a huge demand in petroleum industry particularly because it has no moving parts and hence requires less maintenance. As a whole, the concepts learnt in the whole degree of mechanical engineering will be used such as mechanics of materials, engineering materials etc. but the main focus during the project will be on the concepts of thermodynamics, fluid mechanics and CFD as the project is based on fluid flow through nozzles.

The compressible relations were obtained from the book “Introduction to Compressible Fluid Flow, Second Edition “by Carscallen, William E._ Oosthuizen, Patrick H. The CFD analysis was carried out for the geometry and boundary conditions that were obtained through analytical analysis.

Ejector	**Compressor**
No moving g parts , no lubrication, no vibration	Has moving parts, requires lubrication, has vibrations
Low cost and easy to operate	Relatively expensive
Maintenance free equipment	High maintenance cost
Ejectors can be operated with many different motive fluids: steam, air, organic vapor and other liquids	Compressors can be used for gases only.
Can be installed at any orientation. Hence space requirement will be very low.	Specific space has to be reserved for a compressor.

Table 1: Comparison Between Ejectors and Compressors

Problem Statement:

Following is the problem statement of our final year project:

"Design and analysis of prototype Steam/Gas ejector using isentropic relations which works on the principle of pressure drop created by use of a nozzle to entrap the entrained fluid with motive fluid, similar to a pump or a compressor except has no moving parts."

To further explain the problem statement, the design analysis covers the design of the ejector using a CAD software. The CAD modelling was done after obtaining certain parameters from the analytical isentropic relations for nozzle designing like the length of mixing chamber, constant area chamber, converging and diverging portion, angles and areas of the converging and diverging portions etc. Furthermore, the analytical results obtained will also be checked and validated using a simulation software for CFD, preferably ANSYS.

Objectives/Deliverables:

The objectives of the project are as stated below:

- Literature review
- Analytical Analysis
- CAD Model
- Parametric Study
- CFD Analysis
- Metallurgy
- Manufacturing of the prototype
- Testing and Analysis of Prototype

Tasks	September	October	November	December	January	February	March	April	May
Literature Review	🟩	🟩							
Analytical Analysis			🟩	🟩					
CFD Analysis				🟩	🟩				
Manufacturing of prototype				🟩	🟩	🟩	🟩		
Testing of prototype							🟩	🟩	
Validation of prototype								🟩	🟩

Table 2: Project Plan Gant Chart

Literature Review

For the purposes of manufacturing the prototype of the ejector, a lot of work had to be done. The group had to start from scratch and build from there. So each member of the group was involved in the literature review of basically what an ejector is and what is it used for. During the literature review, the group went through several research papers available online, several websites that provide information and schematics regarding the device. After understanding the basics of the ejector and its types, the group focused on what were the deliverables and molded the route accordingly. More focus was put on the type of ejector that was to be manufactured that is the steam/gas ejector. The ejector was to be manufactured in collaboration with the Attock Oil Refinery. The parameters that are required for the starting of the design analysis were obtained by the literature provided by the refinery situated in Rawalpindi.

Once the initial parameters were obtained, work was started on the analytical analysis and CAD modelling of the device which will be further explained in the report. Focusing on the literature review in this section, the various principles learnt, types explored, workings and components of the device will be discussed. The steam/gas ejector will be discussed in great detail. Its working components, and parts will be discussed.

Ejectors and their working:

Principle:

"Ejectors are characterized by the use of the kinetic energy of one fluid stream (the primary, motive or driving flow) to drive a second fluid stream (the secondary, induced or driven flow) by direct mixing. The design parameters, requirements and methods vary considerably depending on whether the working fluids are gases, liquids, vapors or mixtures of these components."

Ejectors using steam as the primary fluid can be used to pump both gaseous and liquid secondary fluids. In a steam/gas ejector the gas is induced into motion by the turbulent mixing and entrainment at the edges of the steam jet.

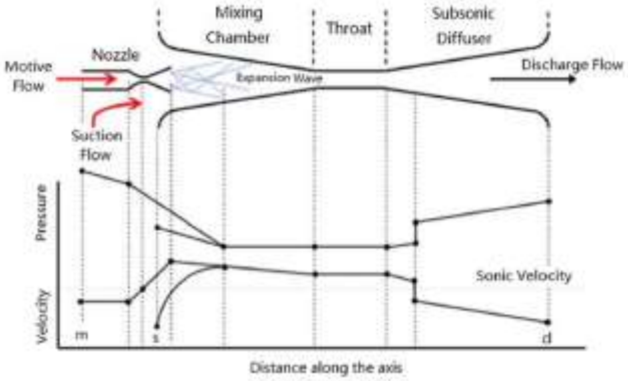


Figure b:Components and working principle[1]

Components of steam/gas ejector and necessary guidelines:

The ejector consists of four main components: the primary nozzle, the mixing chamber, the diffuser and the secondary inlet. It should be kept in mind that the names of the components mentioned above are not unique and the different names are also common. The mixing chamber and the secondary nozzle together form a unit called the diffuser. Usually, understandably the main aim of the design is to figure out the optimum geometric parameters to reach the stated performance. The following schematic shows the components and their locations in the ejector.

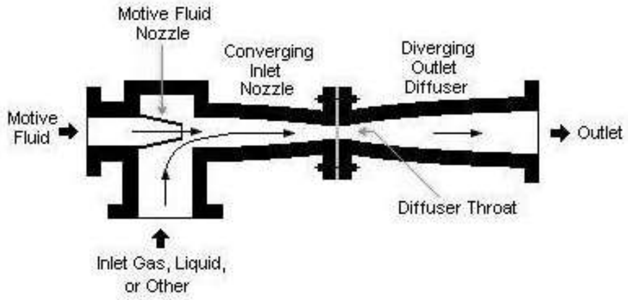


Figure c: components of an ejector

Primary Nozzle:

A primary nozzle is a converging or a converging diverging nozzle handling the motive stream and its basic function is to increase the steam velocity as expense of pressure drop converting subsonic flow to supersonic to maintain a suction pressure for secondary fluid to get entrained. For non-critical operation ($P_1/P_e \leq 1.84$) a simple convergent nozzle is optimum. However, most ejector nozzles are operated under critical conditions and highest efficiency is achieved if a convergent-divergent nozzle is used instead of a convergent nozzle. The steam accelerates in the convergent section and reaches Mach number of 1.0 just downstream of the throat of the nozzle. The steam expands and accelerates in the divergent section and exits the nozzle as supersonic. If the divergent portion of the nozzle is not present, this expansion still occurs but it is accompanied by compression shocks that induce shocks and reduce the efficiency of the ejector.

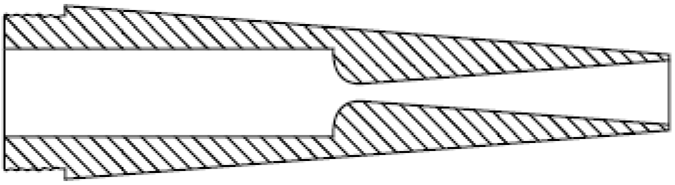


Figure d: design of convergent-divergent primary nozzle for a steam ejector

For both convergent and convergent-divergent nozzles, it is good practice that the nozzle's convergent portion has a circular or elliptical profile with a radius or minor axis of at least $0.3d_{th}$. If a simpler converging cone section is used, the included angle of the cone should be about 24°. The drawback of using a cone is that it is less efficient. A long convergent section causes increased friction losses, and hence lowers C_D, without improving the smoothness of the flow at the throat.

The divergent portion of the nozzle is mostly conical and an included angle of about 10º is good practice. For an area ratio, A_e/A_{th}, smaller angles cause a longer divergent section which causes higher friction losses, in comparison, larger angles lead to a concern of flow separation at low pressure ratios. The throat joining of the nozzle should be as short as possible, and should be able to deliver a smooth transition, with no discontinuities. For both convergent and convergent-divergent nozzles, the nozzle exit has a sharp lip, like a feather edge. The outer surface of the nozzle should be smooth and converging. These two factors together cause a narrow wake from the nozzle lip which causes increased mixing between the primary and secondary streams. For reduced friction all the internal surfaces of the nozzles should be of high quality.

Secondary inlet and mixing chamber entry:

In nozzle designing, the secondary flow is entering the mixing chamber from the gap between the primary nozzle and the ejector body. This passage of flow should be smooth and should not have any constrictions or expansions that are sudden. For steam/liquid ejectors, a bell mouth inlet of the flow passage is a good practice, while the outer surface of the primary nozzle is shaped to provide a converging inlet channel. Although a conical inlet’s machining is simpler but the drawback is that the entry losses are higher. An angle in between 20º and 40º is good practice for conical inlets. To minimize the risk of friction losses and cavitation, any joints that are present inside the secondary inlet need to be smoothed and also the entrance should be as short as it can be. It should be properly checked that the speed of the secondary stream is within the set limits in the whole inlet channel. To minimize the wear and friction losses, the maximum velocities that are between 10 and 20 m/s are good practice for steam/liquid ejectors. For steam/gas ejectors, the value should be less than 100 m/s as to achieve similar results as compared with the steam/liquid ejector and also avoid losses associated with compression shocks as well. It is god practice to maintain minimum clearance of 1mm to 2mm between the primary nozzle and the body of the ejector.

Mixing Chamber:

Mixing chambers are widely available in designs: first is a circular cylinder whose sides are parallel and is attached with a converging section with a short parallel section. During the theoretical analyses, it is assumed that the flow mixing in the mixing chamber occurs under the condition of constant area or it occurs under the condition of constant pressure. While in development phase, there is no reason to believe that one design is more superior to the counterpart. In general practice, steam/gas ejectors are made with constant pressure mixing chambers and steam/liquid ejectors are made with constant area chambers.[2] Obviously, as the name indicates, the main purpose of the mixing chamber is to mix the steam and the secondary flow whatever it may be. Ejectors with an efficient design, the transfer of momentum and energy transfer occurring between the steam and secondary flow is completed before the flow which is now combined enters the diffuser. If the length of the mixing chamber is not optimum rather is too short, the exchange in energy as well as momentum will enter into the diffuser, which will cause higher losses due to friction and an increased risk of flow separation. Considering the opposite scenario, if the length of the mixing chamber is too much, the friction losses will increase and will offset any performance gains that were obtained from the improved mixing between primary and secondary streams.

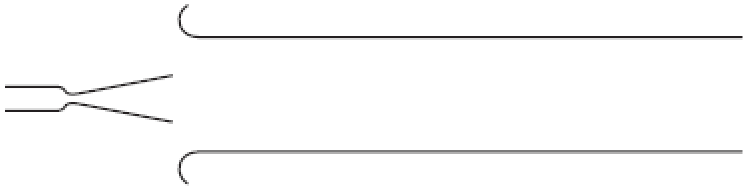


Figure e: constant area design of mixing chamber[3]

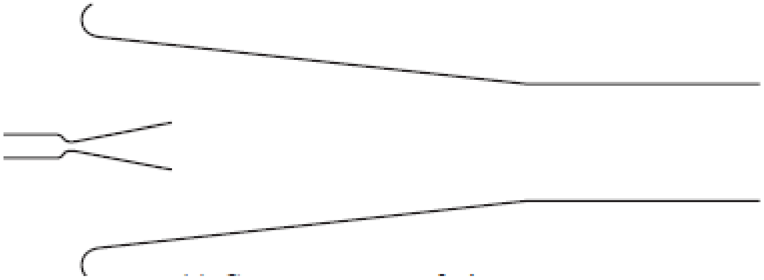


Figure f: Constant pressure design of mixing chamber[3]

5 to 10D (D being diameter of the constant area mixing chamber) is considered to be the optimum length of the constant area mixing chamber. This is true for designs that have operate on a constant area design. On the other hand, we have more difficulty in providing precise and accurate readings for ejectors that operate using a constant pressure design of mixing chamber because the length that is being utilized for the mixing is dependent on the primary nozzle's axial location inside the mixing chamber. A generic guideline states that the mixing chamber's size should be according to the fact that the distance of 5 to 10D is present between the nozzle exit to the start of the diffuser.

The half angle of the section that is conical of the "constant pressure" mixing chamber, Φ_1 should be in the range of 2° to 10°[4]. Using a double tapered cone is more advantageous as it gives a smoother transition to the flow as it is entering the parallel section of the mixing chamber. The length of the parallel section should be made so that the total length for mixing is in the range mentioned above. Typically, this section has a length of 2 to 4D. This is valid for all designs.[5]

Diffuser:

Diffusers are used to produce a required exit pressure or velocity, or they can also be used to connect an ejector to a downstream duct of different diameter. If the internal wall is smooth and the angle of contraction is not very extreme, the efficiency of the diffuser is usually high. Designing and manufacturing of a diffuser must be done very carefully as flow separation and losses may occur if the diffuser's divergence angle is large or even if the velocity profile at the exit of the mixing chamber comes out to be non-uniform. Optimum length mixing chamber diffuser's half angle (Φ_2) range is around 3 to 4° and should not exceed 7° in any scenario. Small included angles are used for short mixing chambers that are used to create highly non-uniform flows. The usual recommendation regarding the area ratio of the diffuser, A_5/A_4, is that it should rather not exceed value of 5. Sometimes due to space limitations, a properly designed diffuser might not be used. So in the above mentioned circumstance, in a steam/gas ejector, boundary layer suction devices are used to permit reductions in diffuser length.

Primary nozzle position:

Usually the geometry of the mixing chamber and the application for what the ejector is being used determine the desired or optimum position of the primary nozzle inside the mixing chamber. Movable nozzles were often used in earlier designs of ejectors. This motion of the nozzle helped in achieving the optimum performance under various different conditions for example during startup and normal routine functionality, the positioning was changed as to obtain the desired output. However, that kills the purpose of an ejector which is to design a machine with no movable parts and hence requires minimum maintenance. Also, there is also the fact that it becomes quite a stressful job to devise a mechanism that can hold a movable nozzle rigidly in place, and also incorporates in the system, a possibility of fatigue failure. That is why the modern steam ejectors are made using fixed primary nozzles after determining the optimum position. Movements even as small as 1mm can be large enough to be responsible for noticeable changes in the performance of a large ejector. In case of a single primary nozzle, as in our project's case, the recommended practice is that the nozzle should be placed centrally on the axis of the

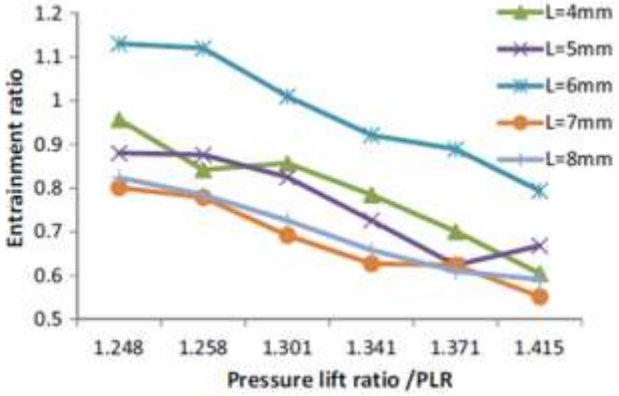


Figure g: Graph between pressure lift ratio and entrainment ratio and effect of nozzle positioning mixing chamber. Ejectors that operate using a constant area design, the recommended nozzle position is that the nozzle exit should be placed 0.5 to 1.0D upstream of the mixing chamber.[6] Again, it becomes quite difficult to provide the precise and accurate guidelines for nozzle positioning for the ejectors using constant pressure mixing chamber. If the nozzle is retracted, the area that is available for the secondary flow for entering the chamber increases, that means that the mass flow rate of the secondary flow increases. But this is at an expense of the decrease of the discharge pressure P_5. In some cases, the secondary flow may get separated from the inside walls, which results in very high losses and instability of the operation of the ejector. While, on the other hand, moving the nozzle into the mixing chamber reduces the mass flow rate of the secondary flow and increases the discharge pressure at the exit P_5. This is due to the fact that the area available for the secondary flow is reduced and the flow stops. Also, it should be kept in mind that the optimum position of the nozzle depends on the composition of the steam/gas ejectors.

There are two most important parameters used to describe the performance of an ejector are:

$$Entrainment\ Ratio\ (ER) = \frac{Mass\ of\ Suction\ flow\ rates}{Mass\ of\ motive\ flow\ rates}$$

$$Pressure\ Lift\ Ratio\ (PLR) = \frac{Static\ pressure\ at\ diffuser\ exit}{static\ pressure\ in\ suction\ flow}$$

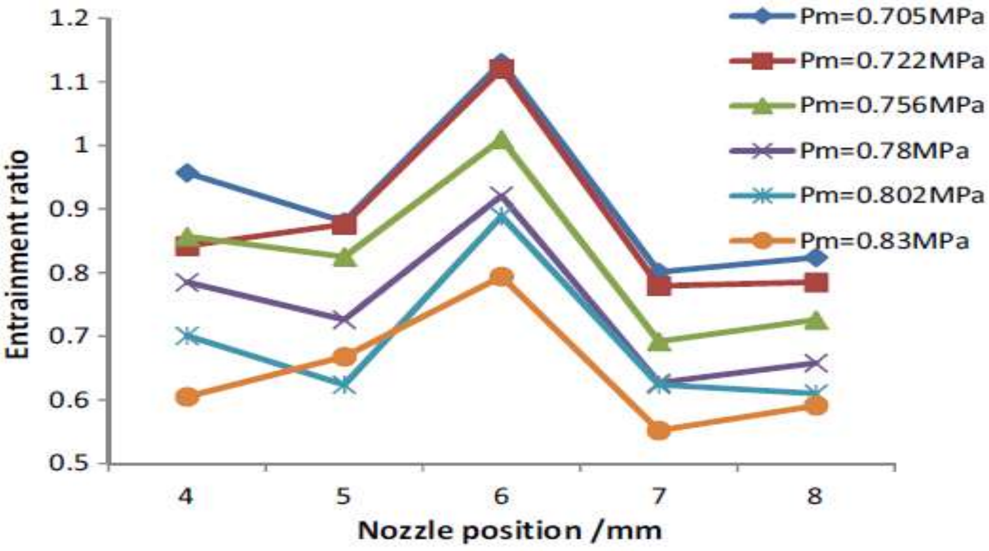


Figure h: Effect on entrainment ratio due to change in nozzle position

The above mentioned parameters are used to describe the performance of the ejector and are affected by the movement of the nozzle inside the chamber. The graph attached below shows the change in entrainment ratio as we change the nozzle position at a fixed motive pressure.

Group's Approach:

The above mentioned part of the literature review covers the components and their generic guidelines that should be kept in mind while designing the ejector. Here the approach that the group followed will be discussed while the depth and in detail discussions about methodology of our approach will be discussed later on in the methodology section of the report.

Isentropic Relations Used for Designing of Primary Nozzle:

As the name indicates, for the analytical designing of the primary nozzle of the ejector, isentropic relations were used. The convergent diverging primary nozzle parameters were obtained from the Attock Oil Refinery. The inlet pressure of the primary motive fluid was known and the composition of the entrained fluid was also known that is the entrained fluid was fumes of diesel. So after all this information being obtained, the group started the designing of primary nozzle with the inlet stagnation pressure, stagnation temperature, mass flow rate of steam and the inlet diameter of the pipe. The flow at throat was choked which means that the Mach number was 1. Value of Specific heat ratio was obtained at three stages. First at inlet, second at throat and third at the exit of CD nozzle. Various isentropic relations that are discussed in detail in methodology were used for calculations of area and Mach number at throat, exit etc. steam tables were also used along with data from the ESDU approach guidelines was utilized in order to obtain a satisfactory analytical design of the primary nozzle which then could be modelled using a computer aided design software (CAD). As the back pressure of the primary nozzle was determined by nozzle positioning of the primary nozzle, it remained constant as the project incorporates the usage of the **constant pressure** mixing chamber.

Isentropic Relations Used for Designing of Secondary Nozzle:

Secondary nozzle designing was different as compared to the designing of the primary nozzle as now we to incorporate the mixing of two fluids rather than one. The secondary fluid pressure at the inlet of the constant pressure mixing chamber was equal to the back pressure of primary nozzle which was calculated via nozzle positioning. Also, the mixing chamber was constant pressure mixing chamber so the pressure was equal to the back pressure from the start of the mixing chamber to the point where shockwave was generated. The pressure varied after the generation of the shockwave as the shockwave causes a rapid change in static pressure. The next crucial step of the design was to find the total temperature and total Mach number in secondary nozzle. Also the fluid that is now a mixture of the motive and entrained fluid gets choked at the start of constant area section of mixing chamber. So in order to find the above mentioned parameters, the moles of primary fluid (Steam) and secondary fluid (High Speed Diesel) were calculated. Shockwave was necessary to occur within the constant area section. According to ASME rules if the constant area length is from 1 to 6d then shockwave will be produced in it. Parameters calculated for secondary nozzle earlier were considered as the upstream parameters of the shockwave and using isentropic relations of shockwave the downstream parameters were calculated. These values were then utilized in designing the diffuser end of the secondary nozzle. Outlet conditions of the diffuser end were already given in Attock Oil Refinery's data sheet while inlet parameters were the equal to the downstream parameter of shockwave.

Metallurgy:

In this study we will describe the steps that we have taken to narrow down the materials for the design of the ejector for vacuum distillation ejector systems. Selecting the appropriate material for a specific application is very important as it needs to be perfect for that specific application. This step also minimizes the overall cost that will be spent on this material as it is the optimal solution to the problem.[7]

The qualities of a material that we take into account are:

1. **Mechanical properties**
    - a. **Strength** We will study this property below.
    - b. **Stiffness:** It is the ability to resist deformation. It is measured by the modulus of elasticity. It should be high enough to not cause any deformation.
    - c. **Elasticity:** It is the ability to get back to original shape after being deformed. It should be very high because we don’t want any deformations.
    - d. **Plasticity**: It is the ability to retain the new shape after stress is applied. We do not want this quality in the ejector.
    - e. **Ductility:** It is the ability to be molded into wires. It is the relative measure of process ability. We certainly want a material that is easily processed because it will be cheaper.
    - f. **Brittleness:** It is the ability to break by applying even the little amount of shear stress. We do not prefer this quality in our ejector. But cast iron is a brittle material and also a very good candidate for this application.
    - g. **Malleability:** It is the ability to be molded into sheets. It is also a relative measure of process ability. We certainly want this quality in our final material as it will reduce the processing cost.
    - h. **Toughness:** It is the ability to absorb high impact blows and not be much affected. This quality is certainly desired in the final material.
    - i. **Resilience:** It is the ability to resist shocks and not be much effected by them. This quality is necessary in the spring materials.
    - j. **Creep:** It is the measurement of the effectiveness of a constant amount of load for a long period of time. This can cause permanent deformation. This quality is measured when making engines, turbines etc.
    - **k.** **Fatigue:** It is the ability to fracture a material by applying cycles of loads which are below the yield stress. This quality is not desired in this particular application**.**
    - l. **Hardness:** It is the ability of resistance to wear, friction, machinability. We want to material to be soft enough to be machined but not too soft to cause permanent deformations during operation.

2. **Physical properties**
    a. **Density:** A lighter material will be preferred as it will be easy to manage and install.
    b. **Thermal conductivity:** We want as little thermal conductivity as possible as it results in loss of energy and also heats the material very much.
    c. **Thermal expansion:** We do not want this quality in ejectors as it can should be able to operate at a range of 450K without any deformation.
    d. **Electrical conductivity:** This property is neutral as this application does not involve any electric fields.
    e. **Magnetic properties:** This property is also neutral as it does not involve any magnetic fields.
3. **Cost**
   Cost is a very important factor and it should be as less as possible while serving the desired operation.
4. **Process ability**
   The material should be process able as it directly is related to cost of the entire project.
5. **Availability**
   The material for this application should be available to manufacture in Pakistan as we do not have the resources to import it.

Failure Criteria:

Generally, the failure of a material is determined under failure theories proposed by different scientists.[8] Of those theories we will study three theories on which we will base our results. The theories are.

1. Tresca failure criteria
2. Von Mises failure criteria
3. Maximum normal stress theory

These theories determine whether a certain material will fail under certain conditions or not.

Tresca Failure Criteria:

It says that a ductile material will fail if its shear stress is equal or more than the shear stress that the material undergoes when it fails under a simple tension test. i.e.

Maximum shear = Maximum Tension/ 2

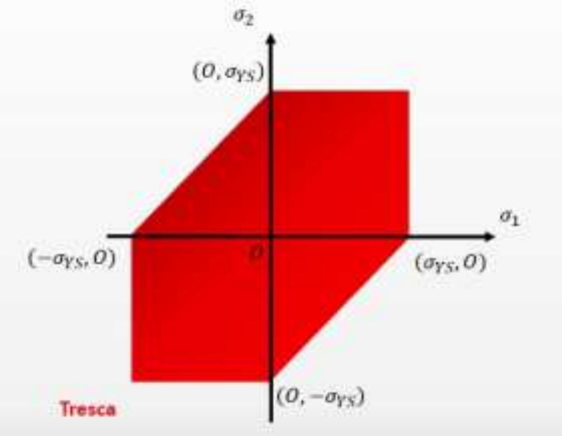


Figure i: Tresca failure criteria

If a stresses lie within the colored region than the material is said to be safe.

Von Misses Failure Criteria:

This theory states that a material will fail if its strain energy density is equal or more than the strain energy density of a material when it fails under a simple tension test.

The material will fail if the stresses lie outside the colored region.

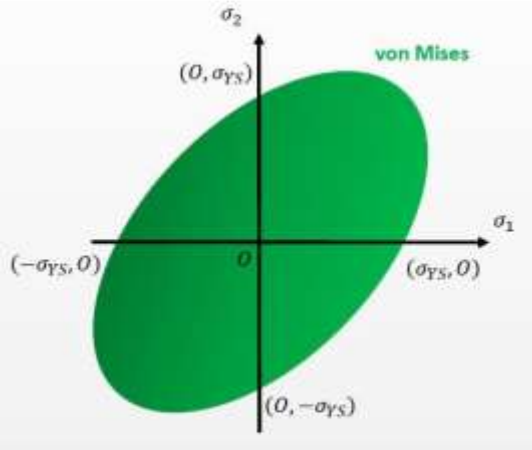


Figure j: Von Mises failure criteria

Maximum Normal Stress Theory:

This theory states that a brittle material will fail if its tension is equal to the ultimate tension when it fails under a simple tension test.

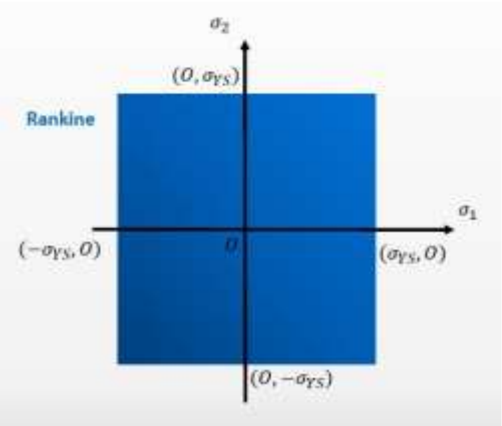


Figure k: Maximum Normal Stress criteria

The material will fail if it lies outside the colored region.

Now we can compare these theories to see which one will be suitable to use for this application.

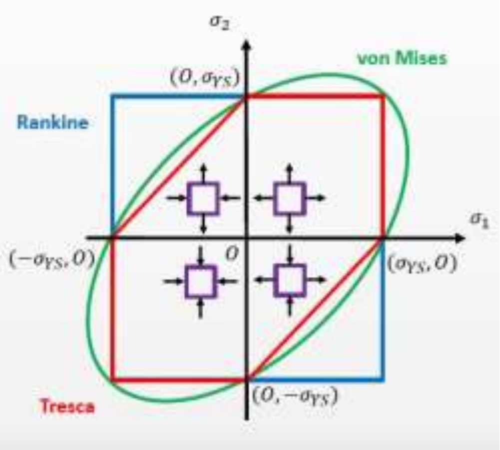
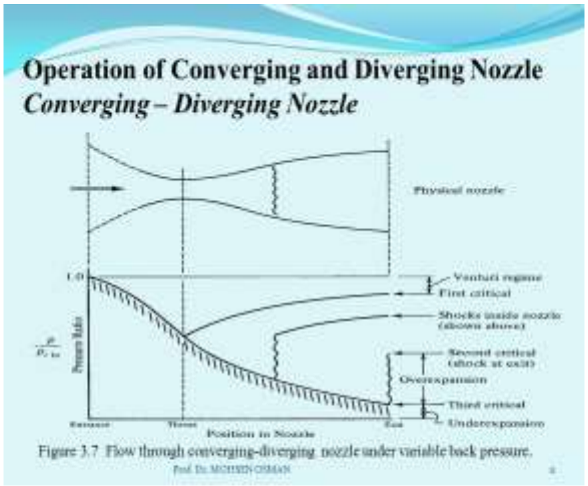


Figure l: 3 criteria combined

Methodology:

As discussed above in primary nozzle fluid enters at high pressure and exits at low pressure with the massive increase in velocity. This is because flow gets converted into supersonic and as the velocity increases pressure decreases. So a low pressure zone is created at the exit of primary nozzle which sucks the secondary fluid into the mixing chamber. The shape of primary nozzle is converging-diverging and the flow is choked at the throat. This is because in the start flow is subsonic and it enters the converging portion of nozzle. As its subsonic converging portion of nozzle will act as nozzle which means its pressure will decrease in converging portion and velocity will increase. At the throat the flow gets converted into sonic and it gets choked at throat which means its Mach number will be equal to 1. Now as the flow moves further in nozzle i.e. the diverging portion of nozzle its velocity increases further and flow gets converted into supersonic. Here when the flow is supersonic the diverging portion will act as a nozzle.[9] That's how we get a high velocity and low pressure fluid at the exit. Back pressure at the exit of primary nozzle is crucial in designing of the nozzle. Because if the back pressure of nozzle is higher than exit pressure, a shockwave will be generated which means that supersonic flow will be converted into subsonic and a rapid increase in pressure along with decrease in velocity will be observed. If this will happen it will cause less or no suction of secondary fluid.

In the graph if we set the back pressure equal to the exit pressure of nozzle than no shockwave will be generated and we want the same when designing the primary nozzle. In this graph the value of back pressure in this case is mentioned by Third critical. Under expansion and overexpansion are further details of shockwave that will be discussed with the CFD analysis of the design.


Operation of Converging and Diverging Nozzle

Converging – Diverging Nozzle

Figure 3.7 Flow through converging-diverging nozzle under variable back pressure.

Prof. Dr. MOHSIN OSMAN

Figure m: operation of converging and diverging nozzle

Isentropic relations were used to obtain the geometry. Initial pressure, temperature and velocity were the starting points. Back pressure were connected with the position of nozzle which will be discussed in parametric analysis. Designing was done by putting the back pressure equal to exit pressure in all scenarios. Below is the table of the input parameters that were given for the designing. Most of them were provided by the Attock oil refinery

Input Parameters for Primary Nozzle

Primary nozzle pressure	P_{o1}	245160	Pa
Primary nozzle temperature	T_{o1}	416	K
Mass Flow rate of primary fluid	$\dot{m}_p$	0.03861	m^3/s
Molecular Mass of primary fluid	Molar mass(P)	0.018	Kg/mol
Gas Constant	R	461.5	J kg^{-1} K^{-1}
Sp. Heat Ratio of steam	k(gamma)	1.33	-
Angle of Convergent Portion	β_1	30	Degree
Diameter of Inlet pipe	D_{1i}	0.0381	m
Back Pr. of Primary Nozzle	P_{1e}	5199.6	Pa
Angle of Divergent Portion	α_1	9.25	Degree

Table 3: input parameters of primary nozzle

Isentropic Relations Used for Designing of Primary Nozzle

We started the designing of primary nozzle with the inlet stagnation pressure, stagnation temperature, mass flow rate of steam and the inlet diameter of the pipe. This data was enough to find the throat Area, throat pressure, throat temperature, exit pressure, exit temperature and exit Mach number. The flow at throat was choked which means that the Mach number was 1. Value of Specific heat ratio was obtained at three stages. First at inlet, second at throat and third at the exit of CD nozzle.

Formulas used to calculate parameters at nozzle throat

$$\frac{P^*}{P_1} = [\frac{2}{\gamma+1}]^{\frac{\gamma}{\gamma-1}} \qquad \frac{T^*}{T_1} = [\frac{2}{\gamma+1}] \qquad A_t = \frac{m^{\cdot}}{P^*}\sqrt{\frac{RT^*}{\gamma}}$$

In these relations we only required stagnation pressure, temperature and specific heat ratio of the steam.

Following isentropic relations are used to calculate parameters like area and mach number at nozzle exit

$$A_e = \frac{\frac{2}{\gamma+1}^{\frac{\gamma+1}{2(\gamma-1)}} \sqrt{(\frac{\gamma-1}{2})}}{\sqrt{(\frac{P_e}{P_1})^{\frac{2}{\gamma}} - (\frac{P_e}{P_1})^{\frac{\gamma+1}{\gamma}}}} \qquad M = \sqrt{\left[\frac{2}{\gamma-1}\right]\{\frac{P_0}{P}\}^{\frac{\gamma-1}{\gamma}} - 1\}}$$

In these relations we again needed specific heat ratio but at the exit conditions of nozzle. So property table of steam was used to find the new value. But both fluids contributes in calculating exit parameters. In the above mentioned formulas primary fluid values that contibute in finding the exit parameters were calculated. In other words pressure and velocity generated at the exit of primary nozzle only by primary fluid were calculated here. When secondary fluid mixes with primary fluid at nozzle exit these values changes. The latter part will be discussed in secondary fluid designing.

Here for finding the exit area of primary nozzle we need specific heat ratio at that point and inlet and exit pressure of primary nozzle. As discussed in litrature the exit pressure of primary and secondary fluid is same so it will not be effected by mixing of the two fluids.

For finding the Mach number of steam at exit we only needed throat parameters and mass flow rate of primary fluid.

Length of convergent and divergent portion of nozzle were calculated using the following formulas

$$L_c = \frac{R_T\left(\sqrt{\varepsilon - 1}\right) + R_{DS}(\sec(\beta) - 1)}{Tan(\beta)}$$

$$R_{DS} = (1.5)R_T$$

$$L_D = \frac{R_T\left(\sqrt{\varepsilon - 1}\right) + R_{DS}(\sec(\alpha) - 1)}{Tan(\alpha)}$$

In above mentioned formulas we needed angle of convergence and angle of divergence. ESDU tells us that maximum angle of divergence should be 30 degrees while maximum angle of convergence for primary nozzle should be 15 degrees. Using these limits, we assumed a value and designed the nozzle accordingly after that we checked the design in CFD Fluent. So angles at which we obtained the best results less fluid separation and contours that were smooth and pleasant to eyes were selected. Further we need the area ratios for both divergence and convergence. We already calculated them above.

Results of Primary Nozzle

Below are the tables obtained from programmed excel sheet made for designing of primary nozzle

Convergent Section			
Throat Pressure:	P1th	132910.8413	Pa
Throat Temperature:	T1th	358.6206897	K
Diameter Of Throat:	D1th	0.011444141	M
Length of Convergent:	Lconv1	0.025384491	M
Divergent Section			
Diameter of Exit	D1e	0.02906554	m
Length of Divergent:	Ldiv1	0.054794079	m
Mach at Exit	Ma1e	3.025671432	-
Temp. at Exit	T1e	196.2802687	K

Table 4: Results of primary nozzle

Input Parameters for Secondary Nozzle

Condenser Pressure:	Po2	8666	Pa
Condenser Temp	To2	308	K
Angle of Convergence	β2	**8**	Degree
Angle of Divergence	α2	2.5	Degree
total mass flow rate	Mtotal	0.052999	kg/s
Diffuser exit pressure.	P2e	33850	Pa
Dia of Inlet	D2i	0.0762	m
Secondary fluid gamma	gamma4	1.05	-
Secondary Mass Flow	Ms	0.01438	Kg/s
Molar mass of secondary fluid	MolarmassS	0.0125	Kg/mol

Moles of secondary fluid	MoleS	1.1504	-
Molar Fraction of Sec. fluid	Ns	0.34909267	-
Molar mass of primary fluid	MolarmassP	0.018	Kg/mol
Moles of primary fluid	MoleP	2.145	-
Molar Fraction of Primary fluid	Np	0.65090732	-

Table 5: input parameters of secondary nozzle

The limits of angles of convergence and divergence in primary and secondary fluids are different. In primary nozzle the maximum convergence angle was 15 C but here it is 10 C while maximum divergence angle is 7 C which was 30 C in primary nozzle. This information was again gathered from research papers mentioned below and ESDU 86030.[3]

Relations Used for Designing of Secondary Nozzle

Secondary nozzle designing was a bit different from the primary nozzle because we have the mixing of two fluids in it. Secondary fluid pressure at the inlet of mixing chamber was equal to the back pressure of primary nozzle which we calculated through nozzle position. And as the mixing chamber was constant pressure mixing chamber so the pressure in mixing chamber was equal to the back pressure from the start to the point where shockwave was generated because shockwave causes a rapid change in static pressure. The next important step of the design was to find the total temperature and total Mach number in secondary fluid. Also Secondary fluid gets choked at the start of constant area section of mixing chamber. So in order to find them moles of primary fluid (Steam) and secondary fluid (High Speed Diesel) were calculated. Shockwave was necessary to occur within the constant area section. According to ASME rules if the constant area length is from 1s to 6d then shock will be produced in it. Parameters calculated for secondary nozzle earlier were consider as the upstream parameters of the shockwave and using isentropic relations of shockwave the downstream parameters were calculated. These values were then utilized in designing the diffuser end of the secondary nozzle. Outlet conditions of the diffuser end were already given in Attock Oil Refinery's data sheet while inlet parameters were the equal to the downstream parameter of shockwave.

Formulas used to calculate parameters at nozzle throat:

$$\frac{T^*}{T_1} = [\frac{2}{\gamma + 1}]$$

ESDU graph used to fined throught area, lenth of convergent and divergent portion

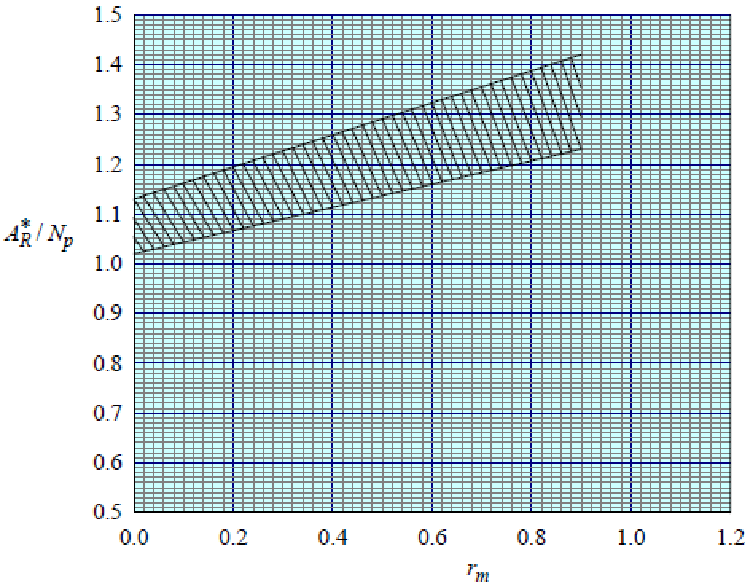


Figure n: ESDU diagram

In order to get the diameter of constant area portion of mixing chamber we need to parameters at the given entrainment ratio. In our case the entrainment ratio was constant i.e. 0.37 so we found two parameters from above mentioned graphs 1.16 and 1.25. By taking the average of these two parameters ratio of constant Ar* and pressure lift ratio was calculated. Actually inorder to find the the constant area of the mixing chamber we need Ar*. Also we have the pressure lift ratio so that how we caculated the diameter of constant area porton of mixing chamber

According to results mentioned in ESDU the length of constant portion of mixing chamber can be from 2D TO 4D where D is the diameter of constant area portion omixing chamber that we calculated in the above mentioned point. Similarly the length of whole mixing chamber can be from 5D to 10D. In our case we first assumed values in these ranges and checked the geometry on CFD Fluent the length at which we obtained best results were selected.

Formulas used for upstream parameters of shockwave

$T_2total = (np * Te_1) + (ns * T_2ths)$

Matotal = (n_1 * Me_1) + (n_2 * Mth_2)

These formulas were used to find the total temperature and total mach number of secondary nozzle while total pressure was the same as the exit pressure of primary nozzle. Mach of secondary fluid which was mentioned as Mth2 in above formula will be equal to 1 because it was choked in secondary nozzle and that's how we complete the required process of double choking. Temperature and Mach of primary fluid were equal to exit temperature and exit Mach of primary fluid that we calculated during designing of primary nozzle. By total we mean parameters of mixed fluid. These values are actually the upstream parameters of shockwave and will be changed within the constant area portion of the mixing chamber

Formulas used for downstream parameters of shockwave:

$$M_2 = \sqrt{\frac{(\gamma-1)M_1^2+2}{2\gamma M_1^2-(\gamma-1)}} \qquad \frac{P_2}{P_1} = \frac{2\gamma M_1^2-(\gamma-1)}{\gamma+1}$$

$$\frac{T_2}{T_1} = \frac{\frac{\gamma+1}{\gamma-1}+\frac{P_2}{P_1}}{\frac{\gamma+1}{\gamma-1}+\frac{P_1}{P_2}}$$

After the shockwave static pressure and temperature increases while Mach decreases The supersonic flow gets converted into subsonic flow. And a jump is observed on the pressure graph. Above mentioned formulas were used to calculate the changed values and only upstream parameters and specific heat ration of the mixed fluid was required.

Formulas for finding the stagnation values from downstream static values

$$\frac{T_0}{T} = [1+\frac{\gamma-1}{2}M^2] \qquad \frac{P_0}{P} = [1+\frac{\gamma-1}{2}M^2]^{\frac{\gamma}{\gamma-1}}$$

So in order to design the diffuser end of the secondary nozzle we need parameters in stagnation form just like we used stagnation conditions to design primary nozzle. So we need static parameter along with Mach and specific heat ration of the fluid to convert static value into stagnation.

Formulas for find the exit parameters of diffuser end:

$$\frac{A_2}{A_1} = \left(\frac{P_1}{P_2}\right)^{\frac{1}{\gamma}}\left[\frac{1-\left(\frac{P_1}{P_0}\right)^{\frac{\gamma-1}{\gamma}}}{1-\left(\frac{P_2}{P_0}\right)^{\frac{\gamma-1}{\gamma}}}\right]^{\frac{1}{2}} \qquad M = \sqrt{\left[\frac{2}{\gamma-1}\right]\left\{\left(\frac{P_0}{P}\right)^{\frac{\gamma-1}{\gamma}} - 1\right\}}$$

The last thing was to complete the geometry of diffuser end. So above mentioned formula was used in which constant area of the mixing chamber, stagnation pressure downstream of the shockwave and back pressure at the exit of diffuser was required

Results Of Secondary Nozzle

Intermediate Data			
P Secondary throat	P2ths	5199.6	Pa
T secondary throat	T2ths	300.4878049	K
Total Pr. at throat	P2total	5199.6	Pa
Total Temp. at throat	T2total	232.6583562	K
Mach at mixing	Matotal	2.318524374	-
Gamma for mixed fluid	Gamma	1.2257	-
Constant Section			
Dia Of Throat	D2th	0.033808213	m
Length of Constant area	Lconst2	0.101424638	m
Convergent Section			
Length of Convergent:	Lconv2	0.236657489	m
Divergent Section			
Dia of Exit of Divergence	D2e	0.091776223	m
Length of Divergent:	Ldiv2	0.367228551	m
Pressure. at Exit	P2e	33850	Pa
Temp. at Exit	T2e	374.8541236	Pa

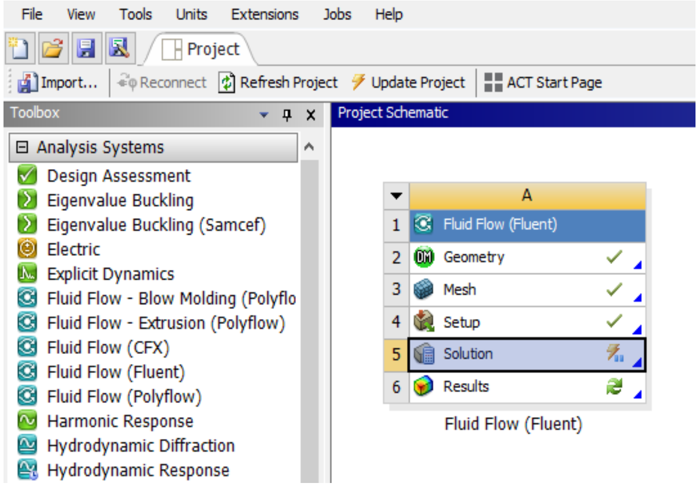
Mach at Exit	Ma2e	0.188186186	-
Shockwave			
Mach at upstream of shock wave	Ma2U=Matotal	**2.318524374**	**-**
St pressure at upstream of shockwave	P2U=P2total	**5199.6**	Pa
St temperature at upstream of shock	T2U=T2total	**232.6583562**	K
Mach at downstream of shock	Ma2D	**0.498097959**	-
St pressure at downstream of shock	P2D	30785.52413	Pa

Figure o: Results of Secondary nozzle

ANSYS Simulation:

To simulate the flow of required fluid and observe the possible pressure, velocity, temperature and Mach number change in an ejector ANSYS fluent was used.

Software interface is as follow.



Defining Geometry:

Geometry consisted of two parts primary nozzle and secondary nozzle. While setting up geometry in fluent, a 2-D sketch was made and we generate surface from sketch.[1] We also divide our surface into multiple region using projection tool. Inlet and outlet named selections were made, to mark the entry and exit point of fluid into the ejector.

Mesh Generation:

Mesh generation is the process of dividing a physical body into discrete regions (cells), so that solution can be performed on these regions. A good mesh not only gives a good reliable solution but it also lowers the requirement of computational power. There are different types of mesh like structured unstructured, different shapes of regions like hexagon pentagon etc. All of these have their own merits and demerits. To generate the mesh of ejector, face mapping and edge sizing with number of divisions were used.

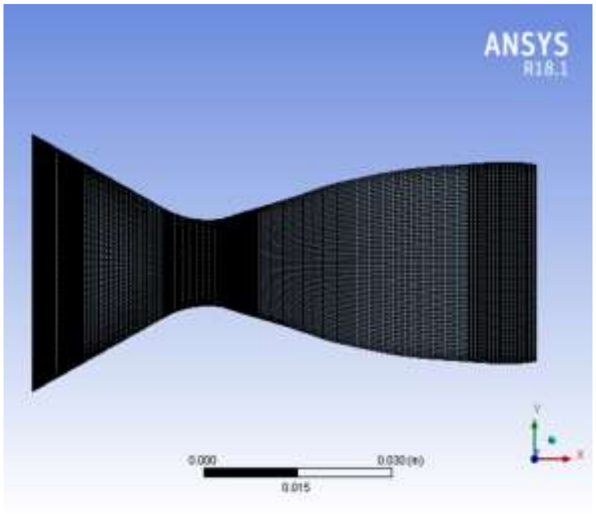


Figure p: meshing of primary nozzle

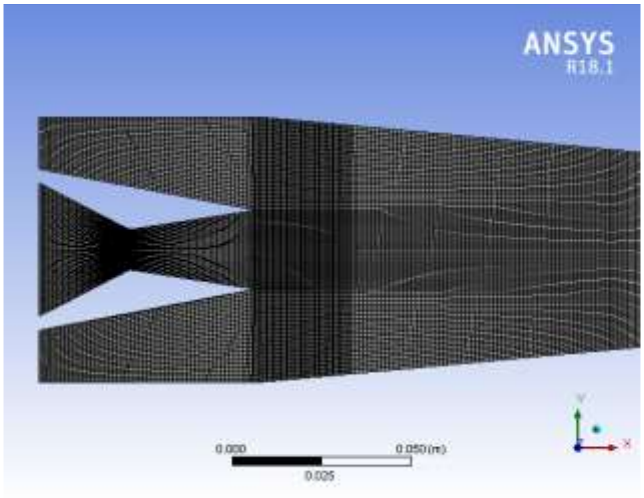
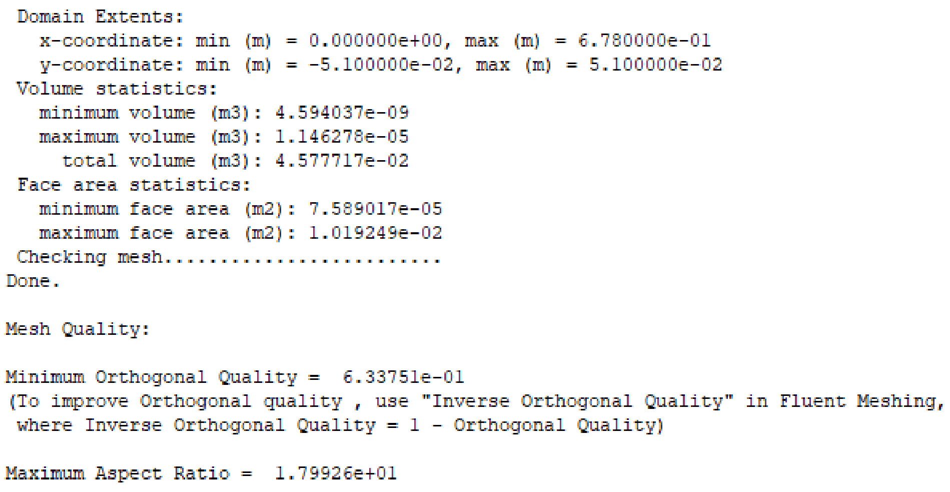


Figure q: meshing of primary plus & secondary nozzle

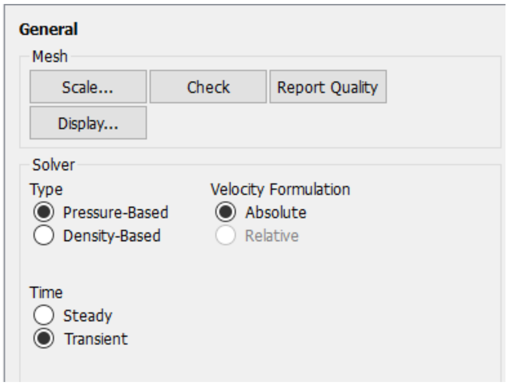


```
 Domain Extents:
   x-coordinate: min (m) = 0.000000e+00, max (m) = 6.780000e-01
   y-coordinate: min (m) = -5.100000e-02, max (m) = 5.100000e-02
 Volume statistics:
   minimum volume (m3): 4.594037e-09
   maximum volume (m3): 1.146278e-05
     total volume (m3): 4.577717e-02
 Face area statistics:
   minimum face area (m2): 7.589017e-05
   maximum face area (m2): 1.019249e-02
 Checking mesh.........................
Done.

Mesh Quality:

Minimum Orthogonal Quality =  6.33751e-01
(To improve Orthogonal quality , use "Inverse Orthogonal Quality" in Fluent Meshing,
 where Inverse Orthogonal Quality = 1 - Orthogonal Quality)

Maximum Aspect Ratio =  1.79926e+01
```

Figure r: meshing details.

Fluent Setup:

As flow of fluid (steam + diesel air) through ejector is subsonic and supersonic in different regions and it changes with time for initial period, when flow characteristics are changing with time. So Pressure based transient modal was selected. As the flow through an ejector is mainly turbulent so from model section of fluent setup, k epsilon turbulent model was selected.



Solver

Type
● Pressure-Based
○ Density-Based

Velocity Formulation
● Absolute
○ Relative

Time
○ Steady
● Transient

Figure s: fluent setup

Next step was the specification of materials, as we were modelling ejector and it deals with two phase fluid and their interaction. For this purpose, we used a multiphase model with primary phase as air and secondary phases as steam and diesel air.

Specification of the boundary conditions is the step on which whole solution is based. Intelligently specified boundary conditions not only makes the solution much more accurate but also reduce the requirement of computational power, much like a well-constructed mesh

Primary nozzle inlet is water vapors and secondary nozzle inlet is diesel air. Then we entered the required boundary conditions like inlet primary nozzle pressure to 245160 Pascal, secondary inlet pressure to 8660 Pascal. For outlet boundary conditions we didn't knew the specific details beforehand so a general pressure outlet boundary was selected and static/gage pressure at outlet was specified.

Solution:

The selection of solution scheme (method) also affects the result. Upwind schemes use the upstream value of a property (like turbulence kinetic energy, momentum etc.) to calculate its value at boundary of cell and then at cell center. The difference between second order and first order upwind scheme is that first order scheme uses one upstream point while second order scheme uses two upstream point per calculation. The upwind method introduces diffusion in the solution to some extent but it can be reduced by using fine mesh and 2nd order upwind scheme. So we used second order scheme for momentum, turbulence kinetic energy etc. And least square was used for gradient calculations.

Residual monitors are the convergence criteria of the solution for each equation it is solving. A lower convergence criterion is better for the solution quality while it increases the convergence time proportionally. We selected the convergence criteria of 0.0001 for continuity, velocity, epsilon etc.

Solution initialization is the process of providing the system an initial "guess" value to start the solution with. Standard initialization is good for laminar flow regime and hybrid initialization is best for turbulent regime. Hybrid initialization calculates the best value to start to start the solution with, in ten iterations. As flow regime was turbulent in our case so hybrid initialization was selected.

Approach for Finalizing Material:

We can see that the Tresca criteria is the most conservative approach of all the three theories. That is why we will go with the Tresca criteria.[10]

Our peak operating condition are 10 bar or 1 MPa at max and the fluids we are using are steam and diesel at a peak temperature of 430K.

The materials we will study are

Name	Tensile Strength MPa	Yield Strength MPa	Fatigue Strength MPa
Ferrite Ductile Iron A536	450	345	290
Grey Cast Iron A48	207	-	138
White cast iron	450	-	150
Malleable iron A47	358	180	100
Ductile iron A339	930	750	300
Stainless Steel SS430	530	360	237
Stainless steel SS304	240	230	235
SUSF316 Austenitic	480	170	256
ASTM 409 Ferritic	380	170	150

ASTM 420 Martensitic	655	345	220

Table 6: properties of different under consideration materials:

As we can see that our application can be done by either one of the above mentioned materials as it is comparatively working at a much lower pressure than the yield strength of the above mentioned materials.

The above also shows that our entire list is also safe when it comes to fatigue cyclic loading as none of them are failing at out required application.

Next the most important factor that we have is the compatibility of the substances with the materials at the above mentioned temperature.

Name	**Corrosion resistant**
Ferrite Ductile Iron A536	Low
Grey Cast Iron A48	Low
White cast iron	Low
Malleable iron A47	Good
Ductile iron A339	Good
Stainless Steel SS430	Good in mild environment
Stainless steel SS304	Very Good
SUSF316 Austenitic	Very good including in chlorine environment
ASTM 409 Ferritic	Very Good
ASTM 420 Martensitic	Very Good

Table 7: corrosion properties of under consideration materials

This results narrows down our list for a bit so that we now can focus on the materials which have good corrosion resistance. More precisely we see that stainless steels offers good corrosion resistance so we will now focus our study to stainless steels. Grade 316 and 304 have the same composition of all the other elements of stainless steel. The only difference between them is the addition of molybdenum in 316 which is not present in 304. 316 add the corrosion resistivity in the chloride environments and is more suitable to use in the chloride atmosphere rather than 304 which is a relatively cheaper option.

Next we need to focus on erosion resistance properties of each of the above mentioned elements to see how long will each material last as this is an important factor when deciding for the material of the ejector. Erosion is the property of slowly removal of material from the surface which results is less material day by day.

Name	Erosion Resistant
Stainless Steel SS430	Moderate
Stainless steel SS304	20% faster than ss316
SUSF316 Austenitic	Great
ASTM 409 Ferritic	Moderate
ASTM 420 Martensitic	Low as used mostly for hardness

Table 8: Erosion properties of under consideration materials

Next we will focus our attention to the thermal conductivity of the narrowed down stainless steel category. Keep in mind that thermal conductivity needs to be as less as possible to hold the isentropic relations that we base our calculations on. Also less thermal conductivity means that the ejector will get heated up under constant operation. Next we will list down the thermal conductivities of the stainless steel category and arrive at the results.

Name	Thermal Conductivity W/m.K
Stainless Steel SS430	23
Stainless steel SS304	14
SUSF316 Austenitic	16.2
ASTM 409 Ferritic	24
ASTM 420 Martensitic	23

Table 9: Thermal properties of under consideration materials

Above we can see that the thermal conductivities deviation is not that much between the different stainless steel. This means that we can choose anyone of the above for fabrication and the final decision will be made by the vendor. However, we will still prefer to go with the choice with the less conductivity like SS304 which is the best option of the above. But when we compare the overall properties the better option is SS316 because of its corrosive resistance in industrial environments and erosion resistant properties.

Next we will study creep properties of the above short listed materials. Creep is the deformation that occurs when subjected to loads below yields for long periods of time. We do not want this property or we want this creep limit to be as high as possible because in that way creep will be less.

Name	Creep rate 1% in 10000h
Stainless Steel SS430	50
Stainless steel SS304	120
SUSF316 Austenitic	160
ASTM 409 Ferritic	50 at 600^{o} C
ASTM 420 Martensitic	63

Table 10: creep properties of under consideration materials

This table shows that SS304 and SS316 are the best candidates for creep resistance. So our overall conclusion is that the best material for making an ejector is SS316 which is also the second most common stainless steel used in the world.

Manufacturing of prototype:

After the analytical analysis and the simulations were performed, it was time to manufacture our prototype and test the results, compare them with the results obtained by the analytical analysis. For this purpose, the group had two options, either to machine the entire prototype on a flatbed lathe machine, or either to prepare the larger nozzle by casting the metal in a mold. Eventually it was decided that machining the entire project would be more feasible and a better finish would also be attained. The entire project was machined which entailed the machining of the primary nozzle, the secondary nozzle, and the mixing chamber as well. The material used to manufacture the device was mild steel. The two nozzles were designed to be press fit inside the chamber and then welded in position form outside. Following are the photographs of individual components of the device taken before the welding process.

Figure t: flange for nozzle

Figure u: mixing chamber

Figure v: Primary nozzle

Figure w: press fit part

for secondary nozzle

Figure x: press fit part for primary nozzle

Figure y: internally tapered secondary nozzle

Following is the figure of the device after welding and painting of the device.

Figure z: ejector after being welded and painted

While testing the device, minor machining was done from time to time when minor defects were noticed. For example, the secondary nozzle was machined twice after originally manufacturing so that it was able to be press fit inside the press fit component present in between the mixing chamber and the secondary nozzle. The device was then tested in college of EME located in Rawalpindi.

Bill of materials

Material		
Particulars	Rate (Rs)	Amount (Rs)
Mixing chamber(39.9kg)	138/ kg	5506
Secondary Nozzle (68.4kg)	138/ kg	9439
Primary nozzle (3kg)	115/kg	345
2 Flanges (30.4kg)	155/kg	4712
Part 1 (6.3kg)	155/kg	976
Part 2 (6.3kg)	155/kg	977
Inward carriage of material	-	800

Table 11: Bill of materials for Material

Machining	
Particulars	Amount (Rs)
Mixing Chamber	3000
Mixing Chamber Welding	800
Secondary Nozzle	9000
Primary Nozzle	500
2 Flanges	2500
Part 1	1000
Part 2	1000

Table 12: Bill of materials for machining

Table 11 and table 12 depict the cost that was borne by the group in the purchase of material as well as the manufacturing of the device. An additional gasket was also purchased made of asbestos to stop the leakage, furthermore some links were designed to connect the device to the output of the steam boiler.

Figure aa: Device during testing

Results and Discussions:

After the fluent setup final step was drawing the contours of pressure, velocity and temperature contours along with vectors to help better visualize the flow of fluid inside an ejector.

- Pressure contour

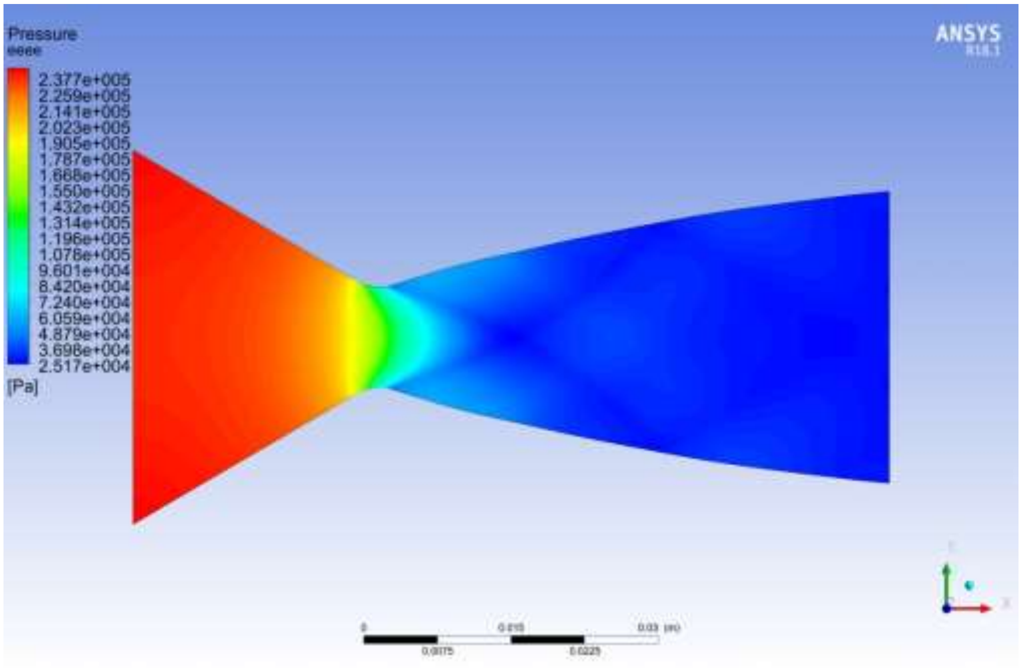


Figure bb: pressure of contour

- Velocity contour

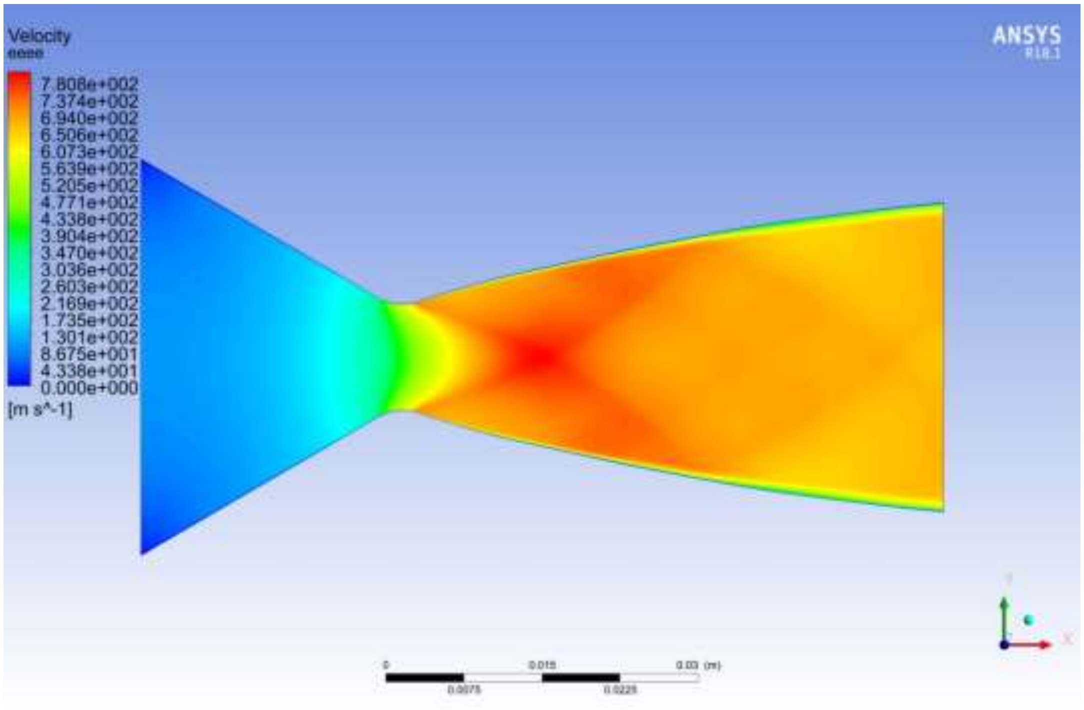


Figure cc: Velocity Contour

- Temperature Contour

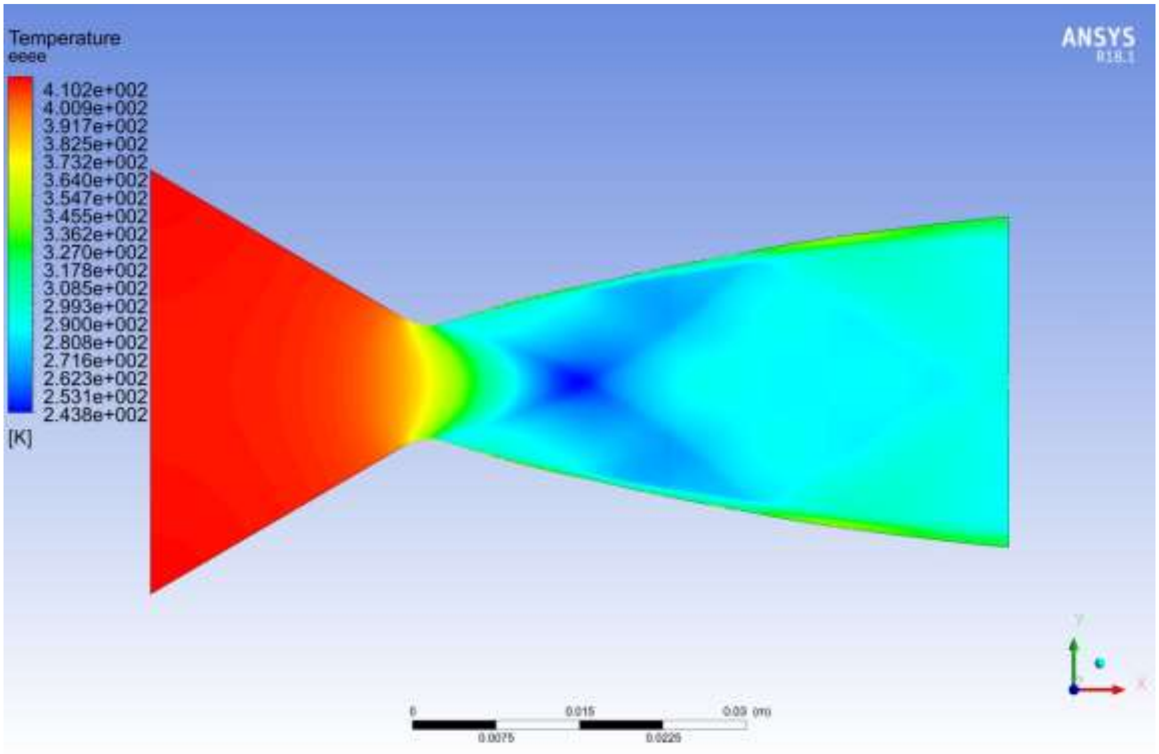


Figure dd: temperature contour

Primary and Secondary nozzle combined

- Pressure inlet of primary nozzle with steam and secondary inlet with diesel air mixture

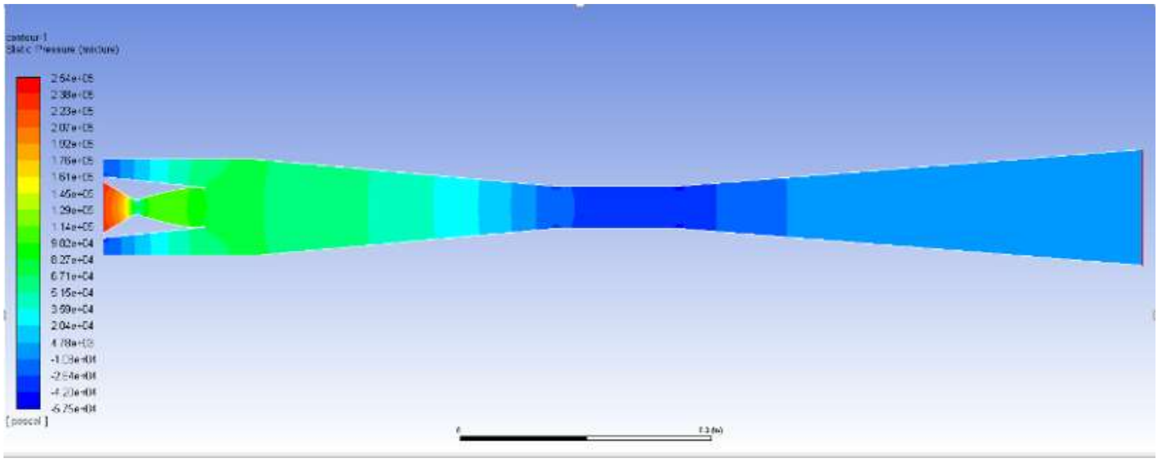


Figure ee: pressure inlet of primary nozzle and secondary inlet

- Velocity Contour

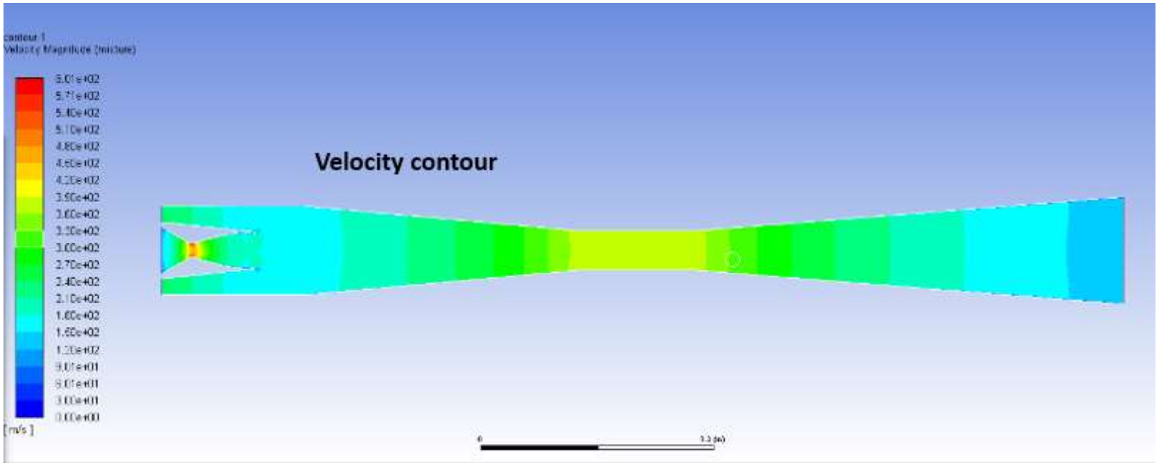


Figure ff: Contour of velocity of primary and secondary nozzle

Analytical results Analysis:

As mentioned in the literature review section of the report in figure b, the diagram shows the increase and decrease of the velocity and pressure of the fluid as goes it through different locations of the ejector. The pressure decreases as the fluid passed through the primary nozzle, creating a low pressure region which sucks the entrained fluid into the ejector and a mixture is formed. The mixed fluid then passes through the secondary nozzle as a supersonic fluid, which in turns tend to increase the pressure and hence creates a shockwave. The shockwave creates an increase in pressure and a sudden decrease in velocity. Thus the device is capable of providing the desired pressure at the outlet.

During the analytical analysis done by the group, similar results were obtained in forms of graphs that are displayed below.

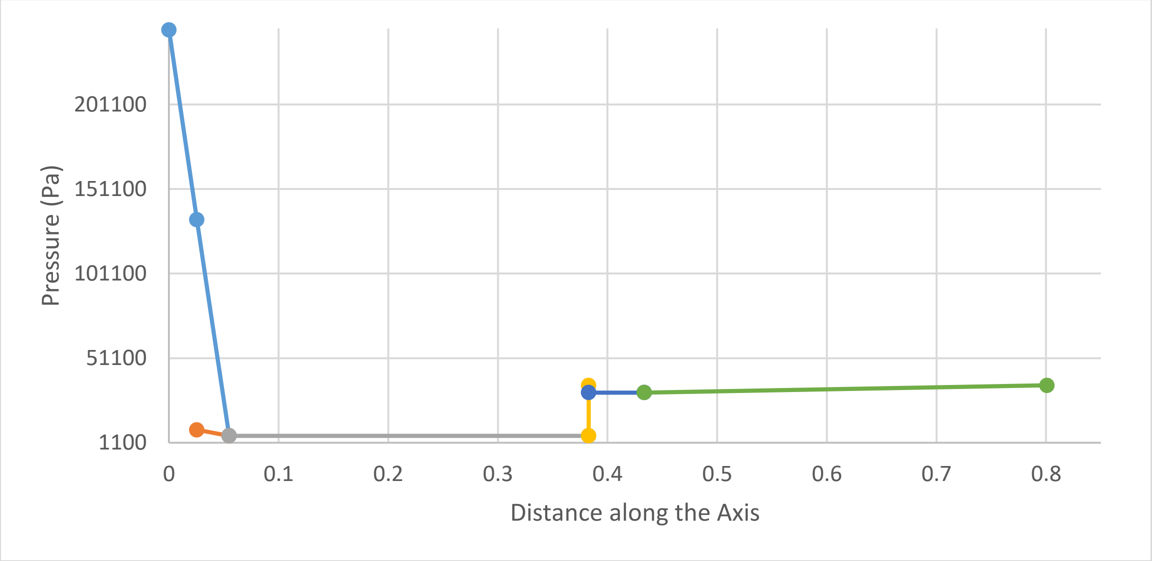


Figure gg: graph of pressure and distance along the axis

The graph displayed shows a sudden decrease in the pressure as it passes through the primary nozzle and velocity increases. The shockwave displayed in yellow shows a sudden increase in pressure and reduction in velocity.

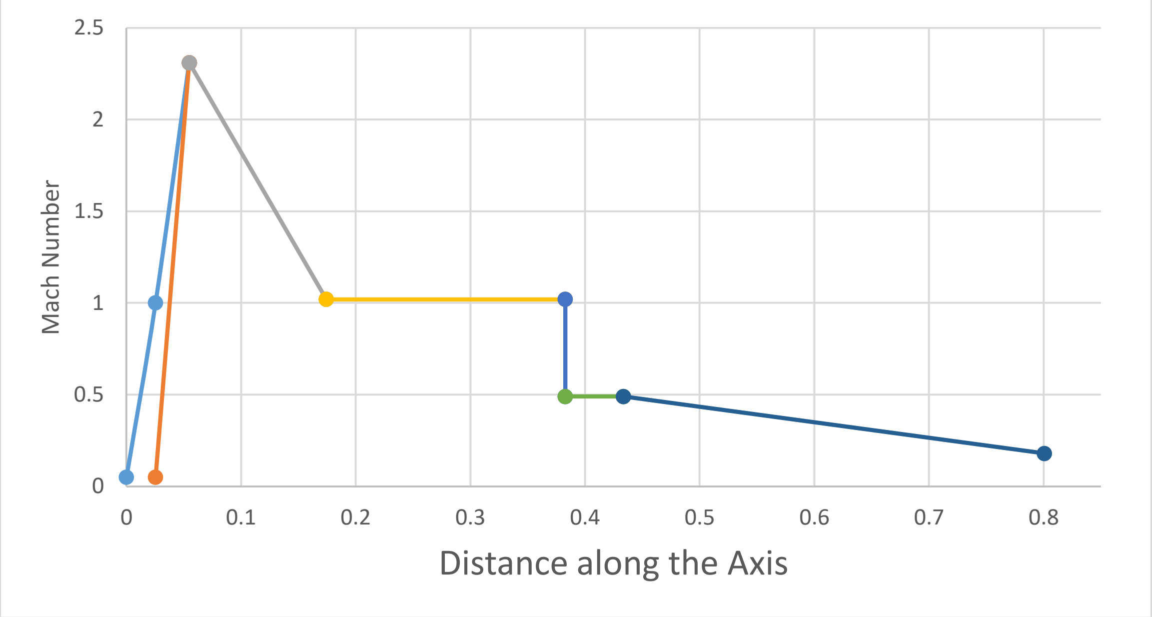


Figure hh: graph between Mach number and distance along the axis

The graph above shows the variation in Mach number along the x-axis. The Mach number increases causes a decrease in pressure and vice versa.

TESTING OF PROTOTYPE:

After the manufacturing of the prototype which was approximately done in one and a half months, it was time to test the prototype working whether it was providing us with satisfactory results. To test the prototype, the team transported the device to college of EME (electrical and mechanical) in Rawalpindi. The mechanical department is equipped with a steam lab containing a boiler able to withstand 10bar pressure before tripping. The device was installed at the exhaust pipe of the boiler, from which the steam comes out of the lab. This provided a safe environment as now the device was outside the lab and not damaging any other sophisticated equipment. The tests were run by running the boiler at 3 bar and checking the parameters of our device.

Validation of suction at secondary inlet:

To check whether suction was being created at the secondary inlet, an anemometer was used to measure the speed of air in the environment first and then the speed of air at the secondary inlet. The speed was considerably high at the inlet proving that suction was taking place.

Validation of shockwave:

Creation of shock wave is vital for the device to raise pressure to the desired output pressure. therefore, it was a must to check whether a shockwave created or not. As the system was open ended, it was rather extremely difficult to measure pressure inside the device before and after the shockwave, so what the group did was that we used a temperature gun to measure the temperature before and after the shockwave as the trend for both pressure and temperature is same i.e. they increase after the shockwave. After measuring the temperature, the pressure rise was obtained which was within the 10 percent error as compared to analytical values.

Sonic to Supersonic Validation:

Now it was time to check that the flow is being converted from sonic to supersonic and there is a significant decrease in pressure to cause suction. Again the temperature gun was used to verify this effect. Temperature gun was used to measure the temperature of the primary nozzle placed inside the mixing chamber. The readings showed a sudden decrease in temperature from 94^{o}C at the beginning of the nozzle to 33^{o}C at the end. This sudden pressure drop was verification that the flow is being converted to supersonic flow.

Primary Nozzle Validation:

The following table shows values obtained experimentally and analytically, the results obtained experimentally are within the acceptable range. Some errors that might be caused were due to the fact that the environment required for the exact results to match could not be generated. i.e. the secondary nozzle input is from the fractional distillation tower that is very difficult to simulate. Air was used as the entrained fluid (Secondary Fluid) instead of diesel fumes as the fumes at such low pressure are not available.

	Analytical Temperature C			**Experimental Temperature C**			**Percentage Error %**		
3 Bar	Inlet	Throat	Exit	Inlet	Throat	Exit	Inlet	Throat	Exit
	137	80.44	35	140	79	38	2.1	1.7	8.5
5 Bar	Inlet	Throat	Exit	Inlet	Throat	Exit	Inlet	Throat	Exit
	151	92.51	29.24	142	85	31	6.3	12.4	6

Table 13:Primary Nozzle Validation

Secondary Nozzle Validation:

The following table shows values obtained experimentally and analytically, the results obtained experimentally are within the acceptable range. Some errors that might be caused were due to the fact that the environment required for the exact results to match could not be generated. i.e. the secondary nozzle input is from the fractional distillation tower that is very difficult to simulate. Air was used as the entrained fluid (Secondary Fluid) instead of diesel fumes as the fumes at such low pressure are not available.

	Analytical Temperature C	**Experimental Temperature C**	**Percentage Error %**
3 bar	113	102	9.7
5 Bar	95	94	1

Table 14: Secondary Nozzle Validation

Conclusions and Recommendations:

Ejectors are widely being used in various industries like chemical, nuclear, refrigeration etc. because of the fact that they are highly reliable and cost less than mechanical compressors. They also have very less maintenance because of no moving parts. After going through the literature and research being performed already in the field, the group used the above mentioned method of ejector designing under methodology.

Methodology used in designing of ejector was basically the combination of isentropic relations and ESDU approach. There were parameters that had to be assumed to get the initial design. CFD analysis was done to check those parameters and bring the CFD Analysis results close to the analytical results. According to results mentioned in ESDU the length of constant portion of mixing chamber can be from 2D TO 4D where D is the diameter of constant area portion of mixing chamber. After testing this parameter in CFD 3D was selected. Similarly the length of whole mixing chamber can be from 5D to 10D. Here length of convergent portion of mixing chamber was equal to 7D. Hence in total 10D length of mixing chamber was selected.

Angles of convergence and divergence for both primay and secondary nozzle were selected using same approach. After going through the literature mentioned above it was found that for primary nozzle maximum angle of convergence is 30 degrees so after testing the design we selected 30 degrees. Study shows that maximum divergent angle is 15 degrees, we selected 9 degrees. The limits of angles of convergence and divergence in primary and secondary nozzles are different. Maximum convergence angle is 10 degrees while maximum divergence angle is 7 degrees. This information was again gathered from research papers mentioned below and ESDU 86030. We selected 8 degrees and 3 degrees respectively.

Nozzle position was kept at different position in mixing chamber and back pressure was calculated. After parametric study nozzle position 60 % placed inside mixing chamber gave promising results.

Below is graph of nozzle position with back pressure of diffuser

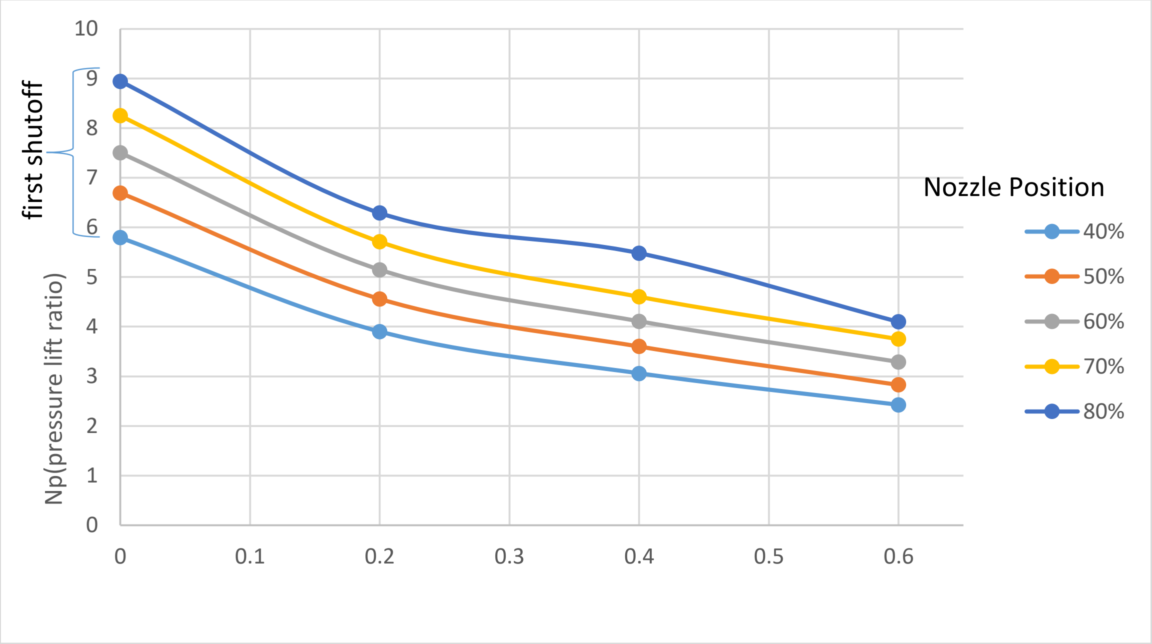


Figure ii: entrainment ratio vs pressure lift ratio

The exit pressure and temperature were the deciding parameters of nozzle position. We needed pressure around 35000 Pascal with temperature around 100 degrees. When nozzle placed 60 % inside mixing chamber satisfied both the values.

Shut off point was also important to check. It gives the range at which the given design of the ejector can be operated.

After all the above mentioned parameters, a CAD model was developed for the CFD analysis to double check our results obtained analytically via isentropic relations and ESDU approach. The CFD analysis concluded that the designing of primary nozzle was up to the mark and both are results complimented each other such that both the results were in sync. The CFD analysis of the primary nozzle alone was what we desired but things got complex when added the primary nozzle into the secondary nozzle. The CFD analysis of the primary plus secondary nozzle created a few minute problems that were the cause of hindrances faced during the analysis. one of the problems faced during the CFD analysis of the combined model was that ANSYS is sensitive to fluid interaction. That is why when our two fluids (steam and diesel air mixture) in the project got mixed in the mixing chamber, some of the parameters that were obtained after the analysis of now what was the mixed fluid were arbitrary. But in general the contours were following the general trend that was expected by the ejector under the set conditions. The ambiguities faced will be cleared and corrected in the manufacturing phase. For the manufacturing phase, the literature review has been done and mentioned above in the literature review portion of the report. The metallurgical aspects and all the forces that an ejector will face or faces during its normal operation such as fatigue load, rust that causes failure etc. have been studied in detail. The materials were shortlisted down to 10 then finally one material was selected that was SS316. The availability of the material is being checked as well as other properties.

The prototype manufacturing was done after all the simulations were performed. The material study was done firsthand, before manufacturing, but the Pakistani market limited our material selection to a mere few materials. None the less, the device was manufactured, the alignment on a major scale of the primary and secondary nozzle was taken care of. The results obtained as mentioned in the tables presented in results and discussion show that the prototype was performing well and providing accurate results. The percentage errors could be minimized by simulating an environment as close to the simulation environment as possible.

Bibliography:

[1] T. Chitkara, “Design , CFD Analysis and Performance Evaluation of the Steam Jet Ejector,” *Natl. Conv. Aerosp. Eng. (27th NCAE)*, no. November 2013, 2013.

[2] R. Verma and S. Chaudhary, “Analysis of Constant Pressure and Constant Area Mixing Ejector Expansion Refrigeration System using R-1270 as Refrigerant,” *Int. Res. J. Eng. Technol.*, vol. 4, no. 6, pp. 897–901, 2017.

[3] T. Royal and A. Society, “Esdu 86030,” no. March, 2007.

[4] K. Chavan, B. Bhingole, J. Raut, and A. B. Pandit, “Numerical Optimization of converging diverging miniature cavitating nozzles,” *J. Phys. Conf. Ser.*, vol. 656, no. 1, 2015.

[5] H. Wu, Z. Liu, B. Han, and Y. Li, “Numerical investigation of the influences of mixing chamber geometries on steam ejector performance,” *Desalination*, vol. 353, pp. 15–20, 2014.

[6] K. Zhang, X. Zhu, X. Ren, Q. Qiu, and S. Shen, “Numerical investigation on the effect of nozzle position for design of high performance ejector,” *Appl. Therm. Eng.*, vol. 126, pp. 594–601, 2017.

[7] S. Chaturvedi, “Machine Design : Selection of Materials for Design Machine Design : Selection,” no. May, 2015.

[8] T. Standard and I. Ministry, “MATERIAL AND EQUIPMENT STANDARD FOR STEAM JET EJECTORS ORIGINAL EDITION IPS-M-ME-256,” vol. 1999, no. 1, 2015.

[9] P. H. Oosthuizen and W. E. Carscallen, *Compressible Fluid Flow*. .

[10] “EJECTOR : WORKING PRINCIPLE MATERIALS USED IN.”