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Senior Design Project Report

Design of Cavitation Jet for Oil and Gas Industry

In partial fulfillment of the requirements for the Degree of Bachelor of Science in Mechanical Engineering

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Abstract

This project is to investigate the cavitation drilling jet, used in drilling technology. Cavitation consist of the formation of micro-bubbles that are rapidly expanding because of a liquid evaporation in a local low- pressure area where the pressure is less than the saturated vapor pressure at a certain temperature. Therefore, when the environmental pressure is less than the saturated vapor pressure at a certain temperature, the bubbles begin to expand, and cavitation takes place. When the environmental pressure becomes greater than the saturated pressure, the bubbles are crushed. Thus, the rate of penetration ROP, the bottom hole rock breaking and cleaning are enhanced. Moreover, this project will discuss the methods used to measure cavitation and the factors affecting the cavitation occurrence. In addition, the cavitation number is calculated and used to predict cavitation. Since the static pressure at the bottom of the well is extremely high and cavitation can only occur at the vapor pressure, the pressure in the nozzle should be decreased from the static pressure to the vapor pressure which is a challenging task. Therefore, more efforts are needed to innovate and develop a self-resonating jet geometry that would be used in such operating conditions.

Acknowledgement

First of all, we would like to express our appreciation to our advisor Dr. Mohammad El-Hassan for his continued support in our project and his sincere encouragement. Also, we express our sincere thanks to our professors in the faculty of Engineering for their expertise and guidance. We would like to extend our thanks and appreciation to Dr. Faramarz Djavanroodi, chair of the Mechanical Engineering Department at PMU, for his continuous encouragement and to believe in us and our abilities to carry out such a project that clearly tests us and challenges us to hone and use our gained knowledge through the year. Lastly, we thank our parents for the unceasing encouragement, support, and attention as because of their moral support we are able to stand tall at such a position.

List of Acronyms

P_a	**Atmospheric Pressure**
P_v	**Vapor Pressure**
P_{static}	**Static Pressure**
D_i	**Inner Diameter**
$\dot{m}$	**Mass Flow Rate**
v	**Velocity**
A	**Cross Sectional Area**
$\dot{V}$	**Volume Flow Rate**
Re	**Reynolds Number**
H_{vap}	**Enthalpy of Vapour**
ρ_w	**Density of Water**
V	**Volume Flow Rate**
T_1	**Normal Boiling Temperature**
T_2	**Localized Exact Temperature**
C	**Cavitation Number**

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Chapter # 1: Introduction

1.1 Project Definition

The senior design project that our group will be working on is based on cavitation jets and more precisely is focused in the field of drilling applications. The phenomenon of cavitation will be looked upon in quite a detail as there is a need to understand and learn how it takes place. Because, the aim is to increase the drilling effectiveness and rate of penetration. So, cavitation occurs at a localized point when the fluid leaves the nozzle of a drilling bit. At that very instance, there is an abrupt rise in temperature and a decrease in pressure which creates a void as soon as the surrounding pressure and temperature stabilizes according to atmospheric conditions. This creates a huge pressure difference which effectively creates a bubble. This bubble then implodes because of having a low pressure than the atmospheric producing a shockwave which erodes the formation and improves the overall drilling effectiveness.

1.2 Project Objectives

The main objective of this project is to design and build an experimental prototype to investigate the flow dynamics in cavitation jets encountered in well drilling application. The primary objective of our study is to enhance our knowledge of flow mechanics and how can it facilitate mechanical operations greatly, such as drilling. The present project has three main objectives:

(i) To investigate and study the process of cavitation jets in drilling technology.

(ii) Impact of cavitation on ROP (Rate of Penetration).

(iii) To measure cavitation process through various methods.

(iv) To identify the factors affecting cavitation process.

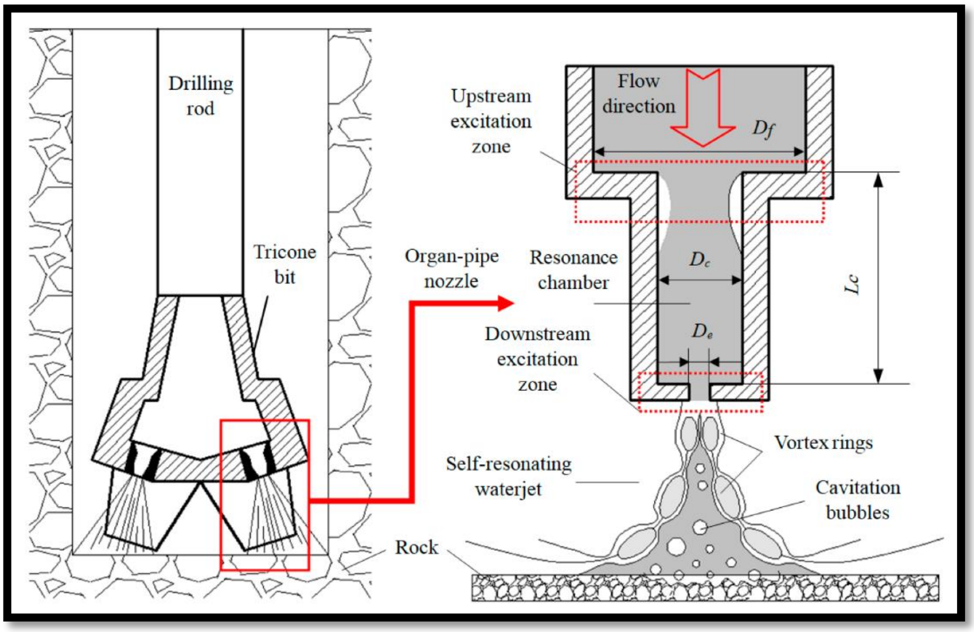


Figure # 1: Cavitation Jet Drilling

1.3 Project Specifications

The project specifications will be based entirely on parameters like Reynold's number, orifice shape, nozzle shape and also the pump pressure and output that it can deliver with very minimal perturbations.

Since, we have to achieve the phenomenon of cavitation in jets, it will solely first depend on the nozzle opening shape which should be faced like an organ pipe. Secondly, to achieve such a level of intricacy there will also be a need to have a pump which can have minimal head losses and incurs as minimum perturbations as possible to be able to achieve the Reynold's Number to facilitate the condition giving rise to cavitation process.

1.4 Project Applications

According to the design and the sophistication our project involves, it is quite usual that it will have most of its viable uses in the industrial sector at a wide range. Based on the theories and hypotheses applications in the industrial region can be:

- Effective Drilling operation.
- Abrasive Cleaning.
- Paint Removal.
- Underwater Cleaning of pipelines.

Chapter # 2: Literature Review

2.1 Project Background

Cavitation occurs mainly when the static pressure becomes smaller than the liquid's vapour pressure. So basically, when water in solid state which is ice melts to liquid water at a zero degree Celsius, keeping the pressure constant at 1 bar absolute liquid water evaporate when temperature above 100 Celsius.

The other possibility, is to keep the temperature constant and reduce the pressure below the vapour pressure, water can evaporate and condensate at temperature below 100 degrees Celsius is static pressure is low enough see the below picture for more understanding.

Details of Cavitation bubbles, if the local pressure decreases below the vapour pressure water evaporate a Cavitation bubble is forming is growing larger and is transported with the flow to the region with high pressure the bubbles stops growing if the local pressure exceeds the vapour pressure vapour condenses starting from the bubbles wall it is surface starts to break down at its weakest spot after being collapsed the micro jet continue to flow in the liquid and can hit a wall

Through its concentrated impact even a high strength material can be damaged the implosion releases energy in a very short time concentrated in a very small spot, if the micro jet hits a surface it damages the material and later material can break off.

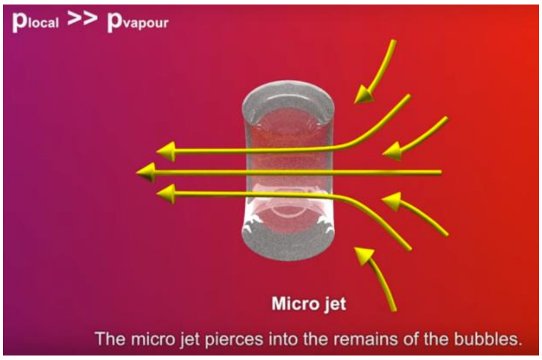


Figure # 2: Cavitation Process on a Cavitation Bubble

Moreover, Cavitation Jets on the other hand, play a similar function when in drilling mechanisms as nozzle shape is responsible for such a phenomenon to take place. An organ pipe nozzle is used basically which gives rise to the cavitation just after the fluid experiences the effects of venturi principle before existing the nozzle. Consequently, it will improve the downhole drilling efficiency and the formations will be easily removed from downhole with less effort.

2.2 Previous Work

As our project needs ideas and some consideration of the approach to the problems. Our team conducted a literature review related to cavitation jet drilling. Of course, we had to aim towards the findings and implications with respect to cavitation jets in drilling processes. For that, an extensive amount of study had to be done to be able to give our project a benchmark or a reference to work with from previously done related work. Furthermore, the projects done in the past carry a lot of intel which we can use to our benefit as discussed below.

First of all, the appearance of cavitating jet impinging on the solid wall was simultaneously measured with its impact. Quantitative estimation of collapsing behavior of cavitation cloud was tried using the image analysis. And collapsing behavior, impact and damage of cavitation cloud were related with each other. Collapsing behavior of cavitation cloud and its impact were measured simultaneously, Cavitation cloud impinges on the wall and spreads in a radial direction with the collapsing motion of clouds, Then the cavity forms a ring-like cavitation cloud accompanying with rebound motion and spreads in a radial direction, Cavitation damage can be formed on the wall by the collapse of cavitation clouds impinging and spreading on the solid wall and the bubble collapse position was evaluated using the image analysis and related to the cavitation damage [1].

Secondly, cavitation occurs or the degree of cavitation. It is more accurate to predict cavitation occurrence by directly comparing the liquid pressure to the saturated vapor pressure. The primary reason, the strong breaking capability of cavitation jets, is not attributed to the impact pressure produced by bubble bursts; instead, the primary reason is the impact pressure fluctuation caused by the density difference between the gas bubbles and the fluid when the flow acts on the rocks. It is extremely difficult to apply today's cavitation technology to a practical drilling downhole. Because the static pressure at the well bottom is extremely high and cavitation only occurs at the vapor pressure, the pressure in the nozzle must be reduced from the static pressure to the vapor pressure. It is extremely challenging to design a new nozzle that reduces the pressure in the nozzle from the static pressure to the vapor pressure and maintains the flow in the cavitation state before the flow acts on the rocks. [2].

Additionally, Offshore drilling has attracted much more attention than ever before due to the increasing worldwide energy demand especially in China. The issues challenge offshore drilling are cost control, shorter drilling cycle, and speed up the drilling process. First of all, the mechanism of pulsed and cavitating jet improving ROP had been studied in this paper [3].

Moreover, the destructive power of a continuous waterjet issuing from a nozzle can be greatly enhanced by generating self-resonance in the nozzle assembly to produce a Self-resonating pulsed waterjet (SRPW). To further improve the performance of SRPW, effects of feeding pipe diameter on the pressure characteristics were experimentally investigated by measuring and analyzing the axial pressure oscillation peaks and amplitudes. Four organ-pipe nozzles of different chamber lengths and three feeding pipes of different diameters were employed. Results show that feeding pipe diameter cannot change the feature of SRPW of having an optimum standoff distance, but it slightly changes the oscillating frequency of the jet. It is also found that feeding pipe diameter significantly affects the magnitudes of pressure oscillation peak and amplitude, largely depending on the pump pressure and standoff distance. The enhancement or attenuation of the pressure oscillation peak and amplitude can be differently affected by the same feeding pipe diameter [4].

Finally, Hydraulic pulsed cavitation jet drilling is a combined drilling technology that the hydraulic pulsed cavitation jet generator is installed on the bit. Based on modulating pulse jet and cavitating jet, a new drilling tool is designed which couples advantage of both pulse jet and cavitating jet. When drilling fluid flows through tool during drilling process, fluid is modulated to pulse and cavitate. Thus, pulse cavitating jet is formed at outlet of bit nozzle. Because of jet pulsation, cavitating erosion and local negative pressure effect, bottom-hole rock. cleaning and breaking is enhanced and penetration speed improved [5].

These previously done work has provided a sense of direction in order for our project to take a significant shape and progress. Because, what many people have done with regards to rotating discs impinging, there has been more focus towards the impinging jet on a stationary disc which really seems fine enough. However, if gone in-depth of the flow studies when the discs are rotating, there is a completely new different picture and flow visualization.

2.3 Comparative Work

For our team and the project, we are responsible to hold up our reputation as mechanical engineers in our institute and successfully pass out by achieving of the most important milestone of the whole degree plan, the senior year project. And, for that we have to ensure that the project we are pursuing as a team can be compared with the projects or some research work done in the past.

To begin with, For the purpose of enhancing the rate of penetration of deep-hole drilling for underground energy acquisition, the performances of organ-pipe nozzles with different downstream contraction ratios were studied by evaluating the axial pressure oscillations. Even though this study is preliminary, it still provides important information for improving the erosion and impact effects of SRWJs, as well as the drilling efficiency. An organ-pipe nozzle with a contraction ratio of 2.5 generates effective SRWJ at both inlet pressures, while a nozzle with the ratio of 3.5 also creates a waterjet possessing the typical feature of SRWJ when inlet pressure increased to 20 MPa [6].

Also, this paper presents results of a systematic experimental study into the effects of cavitation formation on noise and erosion characteristics, using a water jet (cavitating jet) test rig. Within this respect, the main objective of the study is to enhance the understanding of the cavitation phenomenon by conducting detailed water jet tests and investigate the relation between noise level and cavitation erosion rate. The investigation of the cavitation erosion was carried out using Cu1 (manganese-bronze) propeller material, according to ASTM G-134 standards; while the noise measurements were conducted following ITTC (1978) procedure. The tests were performed for different operating conditions and the effect of cavitation number on noise characteristics and erosion rate were examined. In this matter, the cavitation erosion tests were conducted for different cavitation numbers. Background noise due to main and auxiliary pumps inside the chamber was tried to identify. The cavitation erosion rate, which is a function of mass loss per time, was used as an indicator to evaluate the erosion damage on the material. The surfaces of the tested samples were examined by a 3D optical profilometer instrument and maximum pitting depths on the damaged surfaces over time were obtained. The results of the systematic experiments have shown that the formation of cavitation by water jets were both highly erosive and a dominant source of cavitation noise. Cavitation number was found to have the influence not only on the erosion rate but also on the level of noise. It was detected that the erosion rate become more pronounced with increasing testing duration. Besides, both erosion rate and noise level were more pronounced with decreasing cavitation number. Despite certain limitations, simultaneous investigations of noise and erosion within this study offers a significant insight into the nature of cavitation-dominated noise and cavitation erosion. The ultimate aim of the study is try to explore the similarity of the cavitation erosion and noise level between water jet tests and cavitation tunnel experiments for marine propellers. [7].

Since, these researches were conducted for the purpose of identifying new improvements and advancements in drilling operations and drilling efficiency, it focuses on the type of nozzle to be used for such a purpose. Now, these will give us some insight and ideas to clarify the objective of our project and successfully advance towards the prototype achievement.

Chapter # 3: System Design

3.1 Design Constraints and Design Methodology

3.1.1: Geometrical Constraints:

Since our project aims at flow visualization on the phenomenon of cavitation in jets during drilling operation, we have to make sure that our prototype is portable and can be easily transported for demonstration purposes. Because, the idea is to develop and design a cavitation jet that would facilitate and give rise to cavitation phenomenon which will improve the drilling rate of penetration (ROP) and would eventually effectively remove cuttings from the borehole.

3.1.2: Sustainability:

As far as sustainability is concerned for the prototype, it was made sure that selection of components, pump and nozzle material were made according to the fact that it should be durable and can sustain high pressure and high flow-rate of fluid flowing through these components. Because, if gazing towards our project, it will be based on proving and defending the concern of cavitation jets and how effectively it improves the overall drilling process. Furthermore, since corrosion is a huge concern related to these kinds of processes, it has been made sure that none of the components will be exposed to conditions where corrosion control can become a dilemma to deal with.

3.1.3: Environmental Concern:

Environmentally, our system does not require any burning of fossil fuels to power it up since it will be laboratory-based and it will be operated using an external A/C source. However, in terms of drilling, the environmental concern will arise only if the drilling fluid used is Oil-Based as it isn't environmental friendly at all but this project only aims to provide an idea and a visual evidence about the cavitation jets and their facilitation in drilling processes which pose no threat to the environment but in fact, if successful, can be implemented in the industry to save resources while and after drilling operations and in cavitation processes.

3.1.4: Social Impact:

As most of the projects are done to provide welfare to the society and to contribute in making our lives easier and efficient by using as minimum resources as possible, this project aims to provide such a idea where the drilling industry for oil and gas can save a significant amount of resources like fuel and time to benefit the society and also to reduce the environmental concerns related to it. Because, cavitation jets are designed in such a manner that they improve the formation cutting and saves time which means rate of penetration could be increased with effective borehole cleaning.

3.1.5: Economic:

According to the Kingdom's Vision 2030 objective to improve the GDP and the overall cost-effectiveness in several different projects, quite prominently in the field of oil and gas, these technological advancements can play a very supporting role for the future and well-being prosperity of our country. Since, we as a group and many other technical personnel are thriving to work hard and devise solutions to improve the quality of operations and save cost, we think our project could be a very unique initiative towards the contribution of improved and cost-effective drilling operations. Because, approximate fare for one day of operation at a typical drilling site in Kingdom can escalate to as much 200,000 U.S. Dollars, little but prominent advancements can play a very root cause for the cost savings.

3.1.6: Safety:

Safety is always kept as number one priority for us, since we will be dealing high pressure, high temperature and also fluid with a very high velocity. Additionally, since we will be utilizing a high pressure water pump for the demonstration of cavitation process through a cavitation nozzle, it would be extremely important to be at a safe distance for observing the process and the cavitation will be conducted on a material of our choice which is soft and can be used for our control parameters like aluminum or copper.

3.1.7: Ethics:

Ethically, we are bound to select a topic and a unique idea which will benefit the Kingdom and its people. Although no project or prototype or even a research cannot be conducted by a mere idea of an individual, it takes some background information, some knowledge, some exposure to the relevant topic of interest and future recommendations of previously done work. So, instead of just following an idea of our own, we are also taking some motivation, some ideas and knowledge from the work done globally relevant to our topic. This gives us more confidence and a proper insight of how we will be able to work our thing in a way we have intended it to.

3.2 Engineering Design Standards

Since our project contains components that are readily available in the market, as far as the engineering standards are concerned, they are dependent on the manufacturers producing such components. However, below is the list of components with their grade/ standards enlisted.

Components	***Engineering Standards***	***Details***
Cylinder to Accommodate the Nozzle	Stainless Steel (SS304)	Bore: 10.7 cm, Length: 50 cm
Trolley	Stainless Steel (SS304)	Bore: 1.95 cm, Length: 80 cm
Pulleys	Carbon Steel (ASTM A29)	Bore: 1.4 cm, Diameter: 10 cm
Cavitation Nozzle	Bronze (ASTM B505)	OD: 1.191 cm, ID: 0.12 cm, L: 2.5 cm

Table # 1: Engineering Standards

3.3 Theory and Theoretical Calculations

In order to properly carry out successful calculations of our system design, some theoretical aspect has been taken into consideration to come up the necessary requirement with which our system could work and produce outcomes such as power, torque of drilling bit, etc. Following calculation carried out in the bottom would surely be necessary in order to help identify the specifications and working requirements for our prototype.

3.3.1 Cavitation Number:

The critical state at which the first tiny cavity randomly appears in a small area of the flow field when the flow velocity is fixed and the pressure decreases (or the pressure is fixed and flow velocity increases) is denoted as a cavitation occurrence. In actual applications, whether to prevent or to use cavitation, the conditions of cavitation must be given attention. Although there are many factors that influence cavitation, the absolute pressure and flow velocity are the most dominant factors.

Thus, absolute pressure and flow velocity are used to define the cavitation parameter. In classical cavitation theory, the saturated vapor pressure is regarded as the critical pressure at which cavitation occurs in a liquid system. The cavitation number is defined as;

$$\sigma = \frac{(2)p_{atm} - p_v}{\rho V_c^2}$$

where σ is the cavitation number, pv the saturated vapor pressure of the liquid at the current temperature and ρ is the liquid density. For a submersed jet with a high environmental pressure, because P_2 is much greater than P_v in Eq. (1), pv can be neglected. Using the expression, $\rho V_c^2 /2 = p_1 - p_2$, the cavitation number can be expressed as

$$\sigma = \frac{Downstream\ Pressure}{Total\ Pressure\ Drop\ of\ Nozzle} = \frac{p_2}{p_1 - p_2} \qquad (2)$$

Cavitation should occur if $\sigma \leq 1$ and should be steady when $\sigma \leq 0.5$. Even if the environmental pressure is on the order of several dozens of MPa, if the jet-velocity is large enough, cavitation should occur.

Temperature (^oC) (deg F)	**Vapor Pressure (kPa, kN/m^2)** (psi)
0	0.6
5	0.9
10	1.2
15	1.7
20	2.3
25	3.2
30	4.3
35	5.6
40	7.7
45	9.6
50	12.5
55	15.7
60	20
65	25
70	32.1
75	38.6
80	47.5
85	57.8
90	70
95	84.5
100	101.33

Table # 2: Water Vapor Pressure for Different Temperature

Given:

P_v = 3.2 kPa (from Table # 2 at T = 25^{O}C)

ρ_w = 1000 kg/m^3

$\dot{V}$ = 12.9 L/min = $2.15 \text{ x } 10^{-4} \ \frac{m^3}{s}$

D_i = 1.7 mm = 0.0017 m

Formula used:

Velocity of water at the exit of the nozzle:

$$\text{v} = \frac{\dot{V}}{A} = \frac{\dot{V}}{(\frac{\pi}{4})D^2_{exit\ of\ nozzle}}$$

$$\text{v} = \frac{\dot{V}}{A} = \frac{\dot{V}}{(\frac{\pi}{4})D_i^2} = \frac{2.15 \text{ x } 10^{-4}}{\left(\frac{\pi}{4}\right)(0.0017)^2}$$

$$v = 94.72\ m/s$$

Velocity of water through the pipes:

$$\text{v} = \frac{\dot{V}}{A} = \frac{\dot{V}}{(\frac{\pi}{4})D^2_{hose}}$$

$$\text{v} = \frac{2.15 \text{ x } 10^{-4}}{\left(\frac{\pi}{4}\right)(0.008)^2} = 4.3\ \frac{m}{s}$$

Mass flow rate:

$$\dot{\boldsymbol{m}} = \boldsymbol{Q\rho} = (2.15 \text{ x } 10^{-4})(1000) = 0.215\ \frac{\boldsymbol{kg}}{\boldsymbol{s}}$$

Reynolds Number:

$$\boldsymbol{Re} = \frac{\boldsymbol{\rho VD}}{\boldsymbol{\mu}} = \frac{\boldsymbol{4\dot{m}}}{\boldsymbol{\pi D_{avg}\mu}} = \frac{\boldsymbol{4(0.215)}}{\boldsymbol{\pi(0.0044)(0.00089)}} = \boldsymbol{69119.17}$$

Pump work:

$$\left(W_{pump}\right) = \dot{m}g\mathrm{h} = (0,215)(9.81)(2100) = 4.4\ \mathrm{kw}$$

Major losses:

$$h_L = f\frac{L}{D}\frac{V^2}{2g} = (0.0199)\frac{10}{(0.008)}\frac{4.3^2}{2(9.81)} = 23.4m$$

Minor losses:

$$h_L = K_L\frac{V^2}{2g} = (0.27)\frac{(4.3)^2}{2(9.81)} = 0.26m$$

Cavitation Number calculations:

$$\sigma = \frac{2(Patm - P_v)}{\rho * v^2} = \frac{2(101325 - 3200)}{(1000) * 94.72^2} 0.02$$

Optimized nozzle length calculations:

$$Mach\ nymber \quad M_a = \frac{V}{speed\ of\ sound} = \frac{66.1}{1470} = 0.0445$$

$$strouhal\ number \quad S_d = \frac{F.d}{V} = \frac{(19411.76)(0.0017)}{66.1} = 0.5$$

$$\text{optimized nozzle length} \qquad L = \frac{K_N\ d}{M.S_d} = \frac{(0.25)(1.7)}{(0.0445)(0.5)} = 19\ mm$$

3.4 Product Subsystems and selection of Components

3.4.1 Base (Trolley)

Since we are designing and manufacturing a prototype for lab testing purposes solely for the sake of fluid flow visualization in the water cavitating jets of a drilling bit, the whole system should be mounted on a base that can withstand a considerable amount of load and can secure motors and other moveable components effectively

3.4.2 Water Pump

We have selected a centrifugal type water pump which will be pump water from a reservoir in order to successfully simulate fluid flow and can maintain a proper flow rate. Although we would be facing some head loss in the fluid flow, it is possible that such an anomaly could cause perturbations while achieving the Cavitation Number we desire.

3.4.3 Cylinder

In order to keep a safety enclosure around the cavitation operation where the nozzle will be delivering fluid at high-pressure, a transparent cylinder will be used, most probably of light weight polycarbonate glass which is impact resistant and better than any glass or plastic grade.

3.4.4 Cavitation Nozzle

The whole prototype will be based in support to the nozzle that has been intended to design based according to the idea of producing cavitation phenomenon and after conducting research and surveys related to the nozzle shape and size, it has been finalized that the nozzle will be manufactured from bronze and the internals will have such dimensions to properly facilitate the cavitation phenomenon.

Moreover, figure # 2, shown below, illustrates a CAD drawing of the nozzle since it is the most vital component in our system and will be successful to produce cavitation phenomenon.

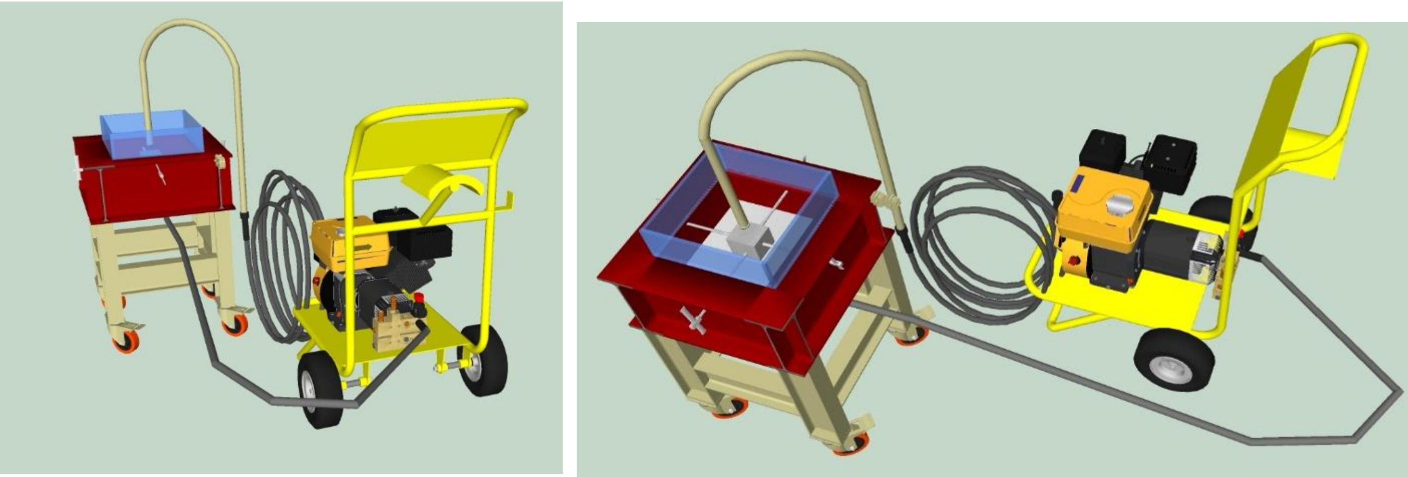


Figure # 3: CAD Model for Prototype System

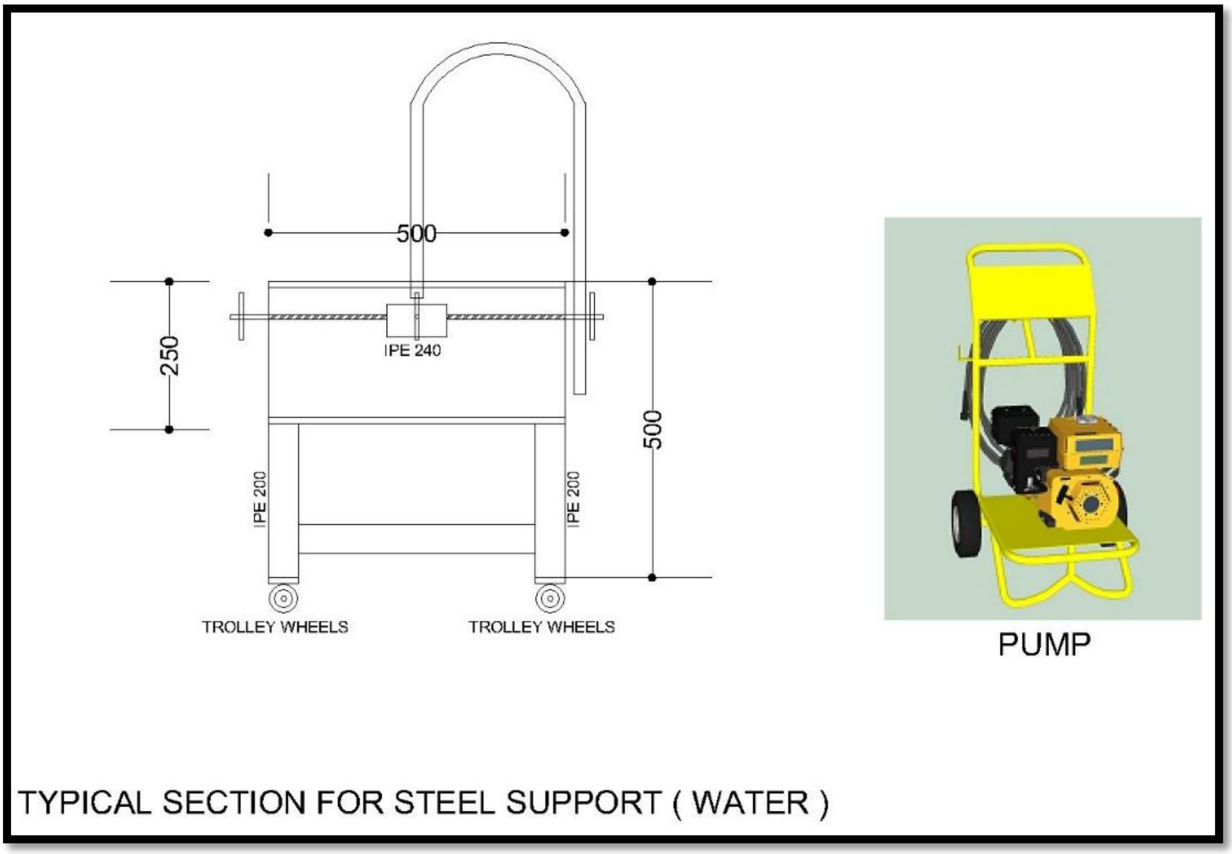


Figure # 4: 2D Drawing of Steel Trolley for Pump Support

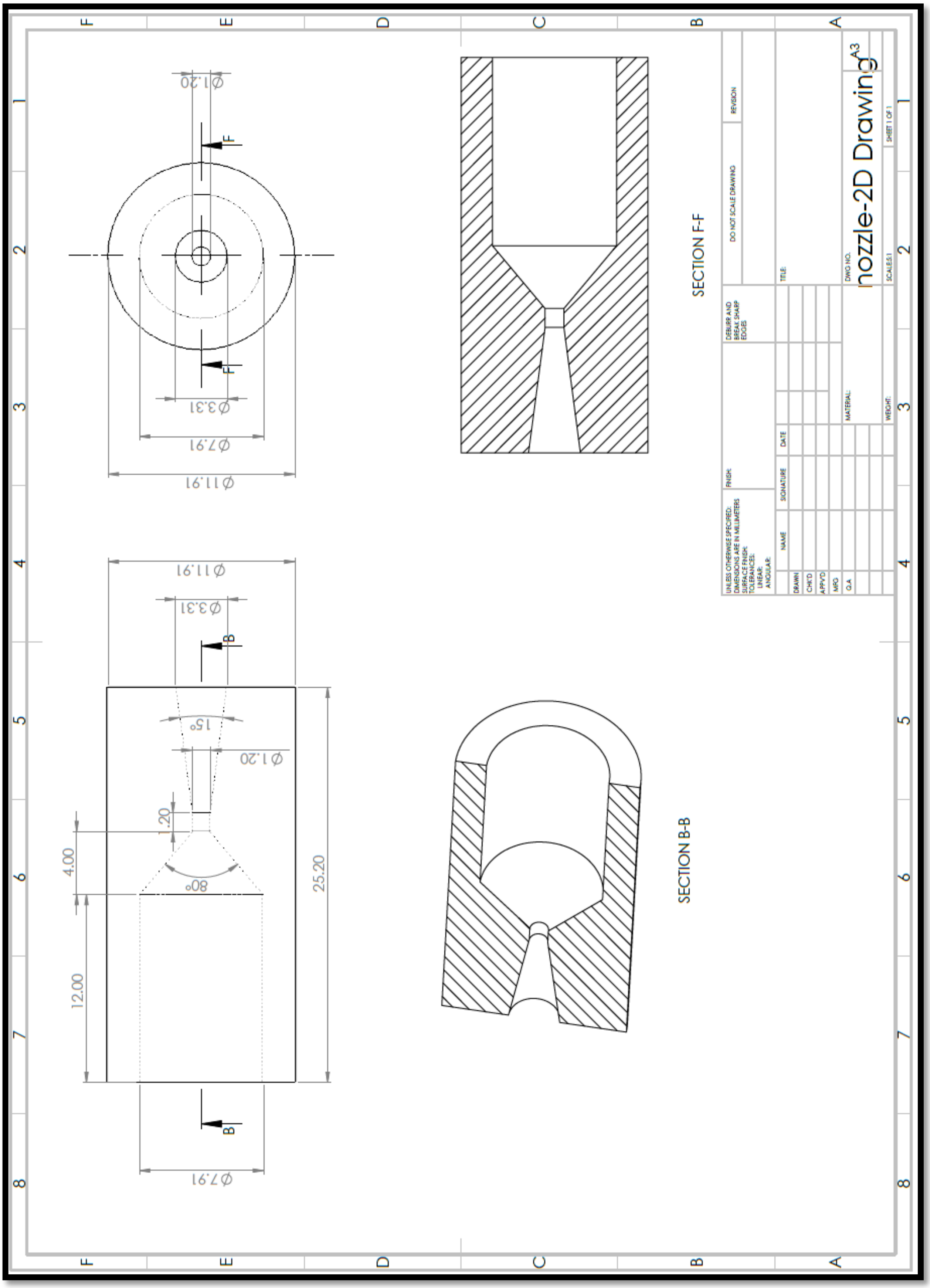


Figure # 5: Nozzle CAD Drawing

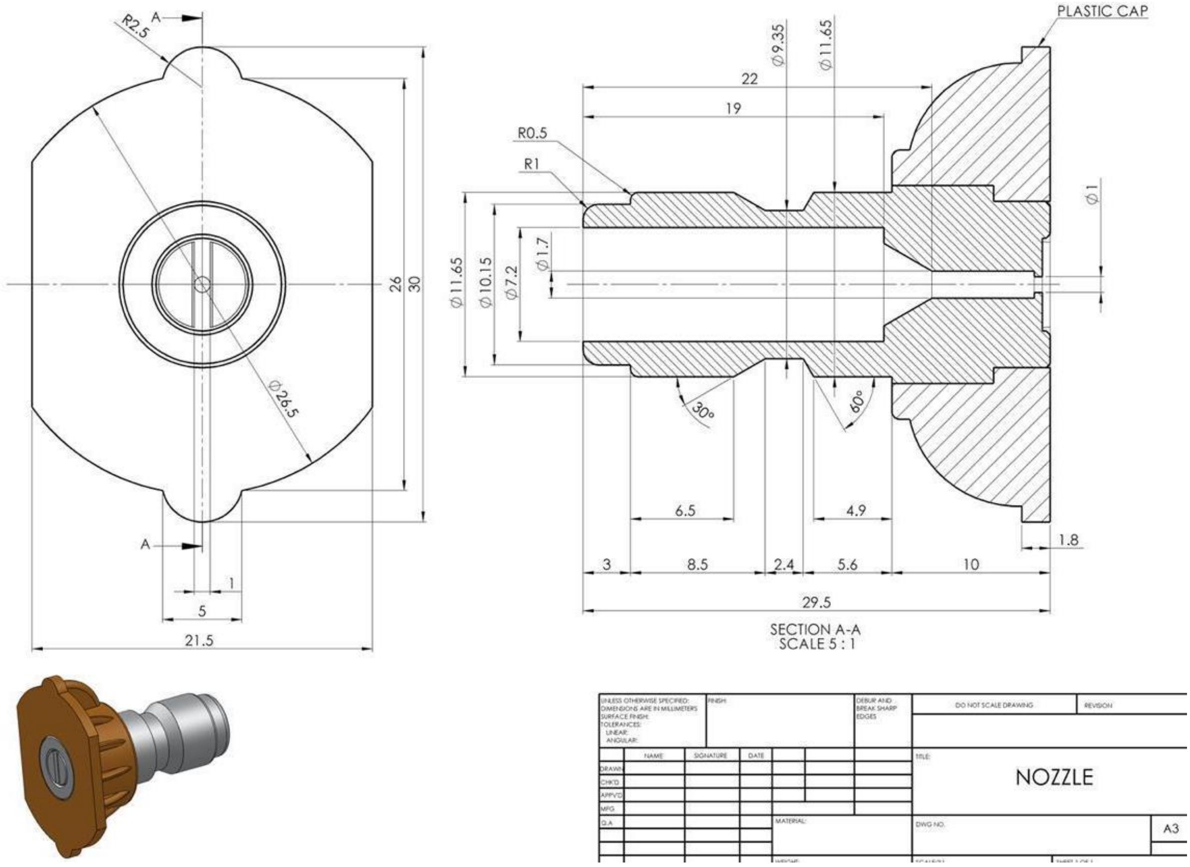
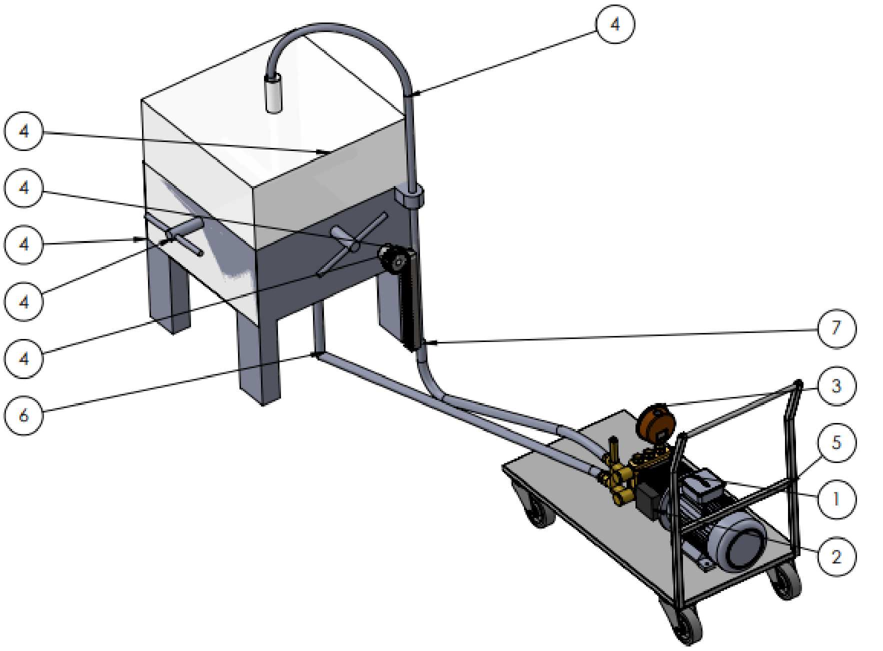


Figure # 6: Optimized nozzle CAD Drawing



ITEM NO.	PART NUMBER	QTY.
1	Motor	1
2	PRESSURE WASHER PUMP	1
3	Pressure Gauge	1
4	Assem1	1
5	plate form trolley	1
6	hose	1
7	hose2	1

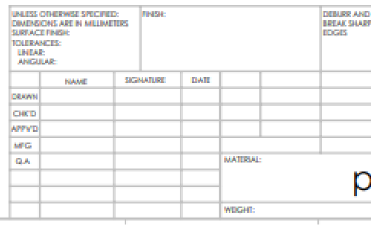


Figure # 7: prototype CAD Drawing

3.5 Manufacturing and Assembling (Implementation)

As engineering students attending the final year project, time always can get too limited if we some delays are encountered while the assembling and manufacturing of the prototype. So, in order to be free from hassles and dilemmas, we have been gathering and purchasing the required components which would be assembled and bolted down with each other in a timely fashion however, it will all be carried out at a third party fabrication workshop where availability of tools are in reach as well as we can also have some assistance from some of the skilled technical personnel in order for us to achieve the required and desired product. To maintain the prototype's basic functionality and the ease of operation and maintenance, it has been ensured to use as minimum components and resources to achieve the objective concerning cavitation process. Since, our main concern is to design a nozzle that will facilitate and give rise to the cavitation process, it would be extremely important to get all the dimensions right and get it manufactured from a machining shop.

Chapter 4: System Testing and Analysis

4.1 Experimental Setup, Sensors and data acquisition system

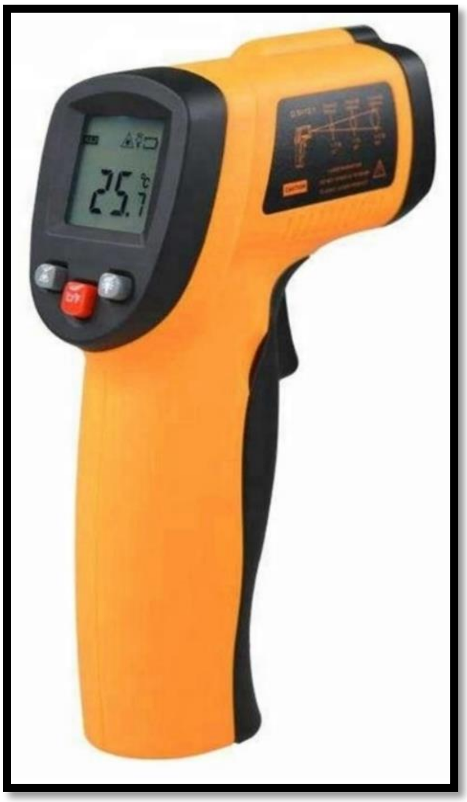
4.1.1: Infrared Thermometer:

Looking towards our prototype and the parameters which are effective in giving rise to cavitation phenomenon, temperature is one of the fundamental parameters which is crucial in determining whether or not cavitation state of fluid is achievable at the state of exit from the nozzle since at such an instance there happens a pressure deviation which subsequently affects the fluid's boiling point. Therefore, in order to get temperatures at those specific instances, an infrared thermometer was used.

Additionally, the infrared thermometer used had the following specifications;

Specifications:

- Temperature range：-50 ~ 380℃ (-58~716℉)
- Accuracy：±1.5% or ±1.5℃
- Repeatability：±1% or ±1℃
- Distance Spot Ratio：12:1
- Emissivity：0.95 preset
- Resolution：0.1℃/℉
- Response Time：500ms
- Wavelength：8-14μm
- ℃/℉ Selection
- Data Hold function
- Laser Target Pointer selection
- Backlight ON/OFF selection
- Auto Power Shut Off
- Power supply：2 x 1.5V AAA battery
- Weight：115.1g（Including battery）
- Dimension：144.5 x 38 x 93 mm



igure # 8: IR Thermometer

4.1.2: **Pressure Gauge**:

Pressure gauge is a mandatory piece of data acquisition system which is required in our prototype to determine the outlet pressure of the fluid from the plunger pump which will be delivering fluid towards the targeting material through our nozzle. This pressure gauge is necessary to take note of the pressure values at which cavitation which be taking place and for that the following pressure gauge has been used which has the following specifications:

Specifications:

- Standard 3/4 GHT (Garden Hose Thread) for all standard outdoor Patio Fixtures, RV Lines, Garden Hoses, Spigots, Faucets And Washing Machine Outlets, Plus 5 Adapters so you can measure in multiple possible settings and locations.
- Quick Connect Adapter for Snap Fit quick Release Systems: Meter Regular and pressure Water Hoses, Sprinkler Systems, Irrigation, Garden Hose Tools, Watering Devices (guns and wands) and Spray Nozzles.
- All Purpose 1/2" Standard Pipe Adapter for testing threaded House, Building, Shower, Water Tank, Hot Water Heater, Pump, Booster, Well, Boiler, Rv Water, Waterer, Sprinkler Irrigation System or Bathtub, piping outlets and supply lines.
- Measure at Sinks, Toilets, Basins, Dishwashers and Angle Valves. TWO TUBIN ADAPTERS. (1/4" and 3/8") for outlets that feed the Refrigerator Water Filter, Aquarium, Ice Maker, Drinking Water Purifier Filters, Water Treatment, Drinking Water Fountain, RV Filter, Plant Watering System, Drip Irrigation Tubing, Pc Cooler, Needle Valve and Tubular Connection, use any common T adapter (Not Supplied) for Dynamic Pressure Measurement on those systems.
- Black Steel Casing with All Copper Attachment. Easy to Read Double Dial. Precise Markings. Four-unit Readout.

Figure # 9: Pressure Gauge

Testing Parameters	
IR Thermometer	**To obtain the operating temperatures**
Pressure Gauge	**To Obtain the pressure of fluid at exit from pump.**

Table # 3: Testing Parameters

4.2 Results, Analysis and Discussion

In order to obtain expect the cavitation phenomenon, cavitation formula can be used several times with varying parameters in which we will be fine tuning the water pressure and velocity of water at the nozzle exit. The results can be displayed as follows:

$$\sigma = \frac{p_2 - p_v}{\rho V_c^2/2}$$

The above given formula will be used to get numerous data to be presented in a graphical form.

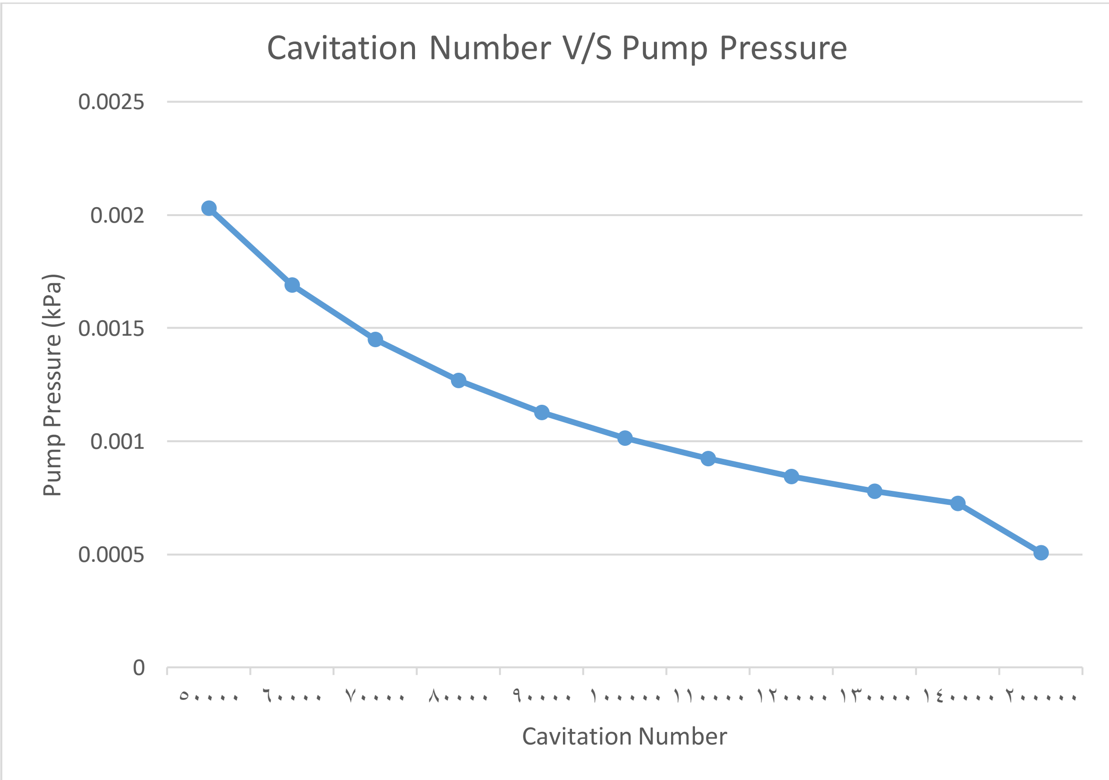


Figure # 10: Graph of Pump Pressure versus Cavitation Number

As visible from the graph above, we can observe a very prominent relation between the pump pressure and the cavitation number that is subsequently affected from its variation. As the pressure of the pump is increased, there is a very prominent decrease in the cavitation number.

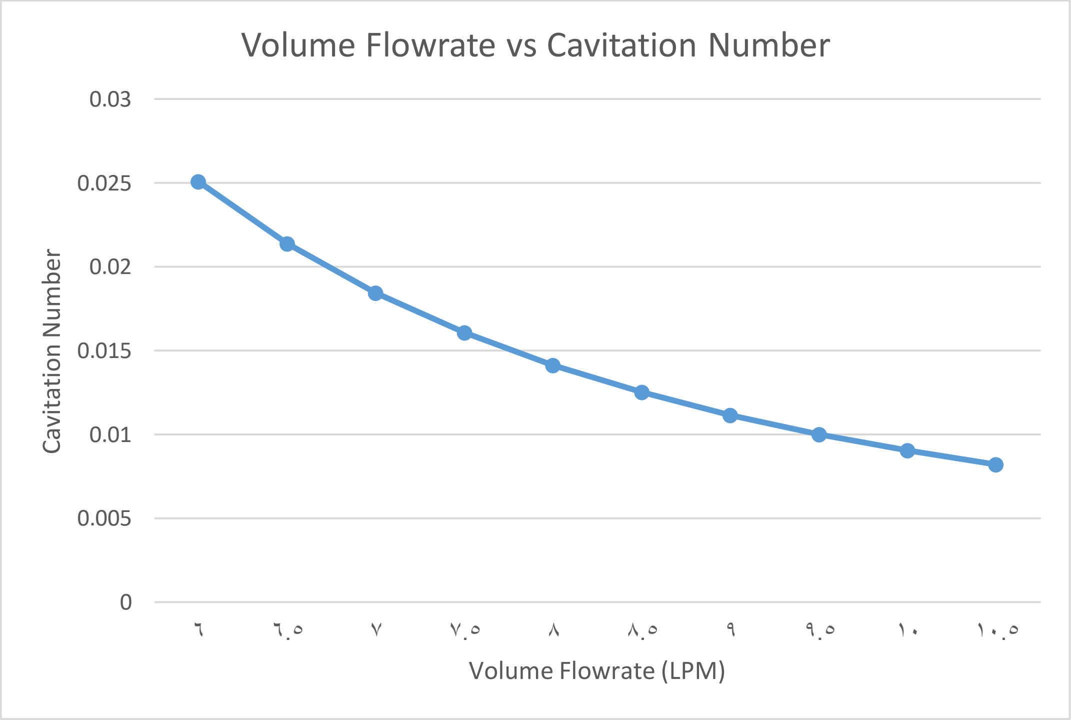


Figure # 11: Graph of Volume Flowrate versus Cavitation Number

For the graph displayed above, we can see a prominent relation between the volume flowrate and the cavitation number that we have experienced and that if the volume flowrate increases, the cavitation number decreases which is quite visible in the graphical data given in figure # 10 above.

Figure # 12: Cavitating a Concrete Block

As visible from the figure given above, the cavitation phenomenon is being tested on a concrete block of certain thickness and after just targeting the nozzle at the surface of the block, it can be seen that a significant amount of material has been removed.

Figure # 13: Cavitating a Brick

Similarly, looking at the pictures in above given figure, a very prominent indentation is seen after directing the cavitating jet on towards the surface of a brick which clearly left a shallow yet visible indentation depicting that our nozzle is extremely effect.

Chapter 5: Project Management

5.1 Project Plan

The project comprises of various tasks that are assigned to each group member in an equal manner, to ensure fairness between the members. Each member was given a specific task that needed to be completed within a certain amount of time.

The times and dates listed in the Gantt Chart were followed to ensure consistency and quality of the work done by the group members.

Table 3 displays the number of tasks done alongside with the number of days it took for that specific task to be completed.

<table>
<tr><th>S. No.</th><th colspan="2">Tasks</th><th>Start</th><th>End</th><th>Duration</th></tr>
<tr><td>1</td><td colspan="2">Ch. 1: Introduction</td><td>3/09/2019</td><td>6/09/2019</td><td>4</td></tr>
<tr><td rowspan="3">2</td><td rowspan="3">Ch. 2: Literature Review</td><td>Project Background</td><td rowspan="3">7/09/2019</td><td rowspan="3">11/09/2019</td><td rowspan="3">5</td></tr>
<tr><td>Previous Work</td></tr>
<tr><td>Comparative Study</td></tr>
<tr><td rowspan="5">3</td><td rowspan="5">Ch. 3: System Design</td><td>Design Constraints & Methodology</td><td rowspan="5">21/09/2019</td><td rowspan="5">1//09/2019</td><td rowspan="5">11</td></tr>
<tr><td>Engineering Design Standards</td></tr>
<tr><td>Theory & Theoretical Calculations</td></tr>
<tr><td>Product Subsystems & Component Selection</td></tr>
<tr><td>Manufacturing & Assembly</td></tr>
<tr><td rowspan="2">4</td><td rowspan="2">Ch. 4: System Testing & Analysis</td><td>Experimental Setup, Sensors & Data</td><td rowspan="2">28/11/2019</td><td rowspan="2">30/11/2019</td><td rowspan="2">3</td></tr>
<tr><td>Results, Analysis & Discussion</td></tr>
</table>

5	Ch. 5: Project Management	Contribution of Team Members	22/09/2019	24/09/2019	2
		Project Execution Monitoring			
		Challenges & Decision Making			
		Project Bill of Materials & Budget			
6	Ch. 6: Project Analysis	Impact of Engineering Solution	11/11/2019	13/11/2019	2
		Contemporary Issues Addressed			
7	Ch. 7: Conclusion & Recommendation	Conclusion	2/12/2019	3/12/2019	1
		Future Recommendation			
8	Design of Prototype		05/10/2019	15/11/2019	45
9	Parts Purchased		8/11/2019	18/2019	10
10	Manufacturing		12/11/2019	22/11/2019	12
11	Testing		28/11/2019	30/11/2019	3

Table # 4: Tasks and their Duration

Table 4 identifies the team members responsible for their respected tasks.

S. No.	Task	Assigned Members
1	Introduction	Sultan & Naif
2	Literature Review	Yazeed & Abdullah
3	System Design	Yazeed & Abdullah
4	Testing and Analysis	Abdullah, Yazeed & Sultan

5	Project Management	Naif & Yazeed
6	Project Analysis	Abdullah & Sultan
7	Conclusion and Recommendation	Naif, Sultan & Abdullah
8	Design	Yazeed
9	Parts Purchased	Sultan & Abdullah
10	Manufacturing	Yazeed & Naif
11	Testing	Everyone

Table # 5: Assigned Members for Each Task

5.2 Contribution of Team Members

Each member's contribution and their willingness to work was discussed in our first meeting as a team, and the tasks were divided and agreed upon by each member.

Table # 5 shows how much work each group member contributed, as a rough percentage.

S. No.	Tasks		Assigned Member	Contribution
1	Ch. 1: Introduction		Naif & Sultan	100%
2	Ch. 2: Literature Review	Project Background	Abdullah & Yazeed	33%
		Previous Work	Abdullah	33%
		Comparative Study	Yazeed	34%
3	Ch. 3: System Design	Design Constraints & Methodology	Yazeed, Sultan & Naif	20%
		Engineering Design Standards	Abdullah	20%
		Theory & Theoretical Calculations	Abdullah, Yazeed & Naif	20%

		Product Subsystems & Component Selection	Sultan	20%
		Manufacturing & Assembly	Yazeed	20%
4	Ch. 4: System Testing & Analysis	Experimental Setup, Sensors & Data	Yazeed	40%
		Results, Analysis & Discussion	Abdullah	60%
5	Ch. 5: Project Management	Contribution of Team Members	Naif & Sultain	100%
		Project Execution Monitoring		
		Challenges & Decision Making		
		Project Bill of Materials & Budget		
6	Ch. 6: Project Analysis	Impact of Engineering Solution	Yazeed	100%
		Contemporary Issues Addressed		
7	Ch. 7: Conclusion & Recommendation	Conclusion	Abdullah, Yazeed & Sultan	100%
		Future Recommendation		
8	Design of Prototype		Yazeed	50%
			Abdullah	50%
9	Parts Purchased		Sultan	20%

		Yazeed	30%
		Abdullah	30%
		Naif	20%
10	Manufacturing	Naif	60%
		Sultan	40%
11	Testing	Yazeed & Abdullah	100%

Table # 6: Contribution of Tasks

5.3 Project Execution Monitoring

To ensure the continuous progress of the project, regular meetings between the group members, to discuss the next step, and between the group members and the advisor, to take approval for said step, needed to be done on a regular basis. In addition to these meeting, we were asked to hand in progress reports and perform a presentation to explain what we have done in the project till the date of the presentation. All the dates are listed in table 6 below

Activities and/or Events	Time and Date
Assessment Class	Once a week
Meeting with the group members	Weekly
Meeting with the Advisor	Bi-Weekly
Midterm Presentation	28th November, 2019
Finishing Final Prototype	2nd December, 2019
Test of the System	2nd December, 2019
Final Submission of Report	19th December, 2019
Final Presentation	19th December, 2019

Table # 7: Dates of Activities and Events

5.4 Challenges and Decision Making

While working in developing our project to its final stages, we incurred some problems which effected the progress of our project and acted as a hurdle to overcome. However, after successions of different suggestions and review, they were eventually rectified. The problems we faced were some of the following:

5.4.1: <u>Equipment and Device Problems</u>

- **Plunger Pump**

  In order to achieve cavitation phenomenon and to successfully simulate the conditions on a pilot test scale, we were to select a plunger pump which works on a mechanical principle of suction and to find a suitable one which had the most modest specifications was becoming a problem since it was not very commonly available in the market and required an extensive amount of research and survey.

- **Nozzle Manufacturing**

  As the project object relies heavily on how we design our nozzle so it can give rise to the cavitation phenomenon, the manufacturing was becoming quite a problem since the nozzle's overall dimension was intricate and small, it required some very precise machining and specialized machining shops were a problem to find. Moreover, we also had to make sure that the design which we agreed on should actually work in the experimental application for demonstration and testing purposes.

5.4.2: <u>Testing & Safety Issues</u>

Since our project aims to demonstrate the phenomenon of cavitation which could have a very significant impact in the drilling operations, we were to make sure that safety is kept as a number one priority since equipment with high pressure applications will be used constantly and we had to make sure that we take as extra safety precautions and measures as possible. However, since the cavitation process will be applied on a targeting material for the sake of demonstration, a proper selection of material and its mounting was very important as we did not want the pressure from the nozzle to displace or ricochet any material to the spectators or onlookers.

5.4.3: <u>Design Problems</u>

The most basic and prominent design problems we had were with the selection and designing of a proper nozzle that could facilitate the cavitation phenomenon and in order to achieve that we took consideration from many research papers, forums and journals so we can initiate the designing phase of our nozzle and give it away for manufacturing as soon as possible. This created a wide range of problems in dimension optimization that in the end after consultations and simulations we agreed on a proper design for the nozzle to be used for demonstration and production of cavitation.

5.5 Project Bill of Materials & Budget

The table below illustrates the parts we purchased and the amount given to the third party for manufacturing some of the intricate parts for us. It includes the total amount spent in our project in Saudi Riyals (SAR).

Table 7 shows the amount of money paid for each part in Saudi Riyals (SAR).

Materials	**Cost (SAR)**
Plunger Pump	3060
Nozzle Manufacturing	1000
Pressure Gauge	66
Hoses	60
Custom Adapter to Nozzle	250
Acrylic Compartment	600
Trolley	300
Clamps	100
Total Sum	**5436**

Table # 7: Bill of Materials

Chapter 6: Project Analysis

6.1 Life-Long Learning

Since we were working as a team in the progress of our project, we had one aim completely firm in our minds and that was to achieve all the goals we had set in the beginning of project. Of course, in order to achieve that, we were prone to use and utilize some software and hardware by using our time in a very efficient manner and also to manage all of these things, we had to setup and prescribe a pre-planned schedule which really gave us a boost in every aspect we worked on and we would like to share some of that experience.

6.1.1: Software Skills:

When designing our prototype, we first referred to some websites online and then test out the constraints on Solid-Works Simulation. We designed and simulated the necessary components for our project to guarantee suitable procedure concurring to our needs of materials that are sufficient enough to withstand our system so that it can run efficiently. It all went extremely well by the group's contribution and support since each member was able to solve an obstacle more rapidly depending on the way they thought. Correspondingly, we utilized Microsoft Excel to exhibit the charts and graphs displaying our experimentation data.

6.1.2: Hardware Skills:

To conduct a performance test of our system, we had to interact with some of the facilities provided in our Laboratories which included an IR Thermometer. Having sufficient background knowledge on using an IR Thermometer we were able to successfully without additional help. This hardware equipment helped to obtain the experimental data that was necessary to demonstrate the performance of our system as a whole. Moreover, using measuring devices like a pressure gauge and flowmeter was also a plus in our project as we were able to keep track of important parameters like flow-rate and pressure.

6.1.3: Time Management:

Since we had about 3 months of total time to be given to the project, we really needed to manage time in an efficient manner in order to be ahead of time for predicted problems and hurdles we thought we would face. Although, we were still falling short of that as days were passing by, our team really worked on it in every spare time they had available in order to accomplish a heap of milestone that was set for us.

6.1.4: Project Management:

To carry out the whole schedule of developing our project, we needed a plan to execute and follow it step by step. By conducting weekly meetings with our team mates, we were able to assign tasks based on the time one is comfortable and available. This mutual communication and understanding led to a properly managed progress flow related to our project which we are proud of.

6.2 Impact of Engineering Solutions

6.2.1: <u>Society</u>:

Any project that is for the well fare of the industry that will surely benefit the society of it. Since, the project will always be aimed towards the betterment of operational efficiency, effectivity or cost saving without compromising on the quality of the outcome, claims can be made with pure intention that it would open an opportunity for investors to step in the field to sponsor such projects which can reach the prosperous stages of development. These investments will provide a very clear social impact proving the ideas and the skillful youth which are striving to contribute in achieving one of the objectives of Vision 2030 which is to increase the public's investment funds so the people of Saudi Arabia can get benefit and the needs that any prosperous and developed country would need to survive and compete.

6.2.2: <u>Economy</u>:

0According to the Kingdom's Vision 2030 objective to improve the GDP and the overall cost-effectiveness in several different projects, quite prominently in the field of oil and gas, these technological advancements can play a very supporting role for the future and well-being prosperity of our country. Since, we as a group and many other technical personnel are thriving to work hard and devise solutions to improve the quality of operations and save cost, we think our project could be a very unique initiative towards the contribution of improved and cost-effective drilling operations. Because, approximate fare for one day of operation at a typical drilling site in Kingdom can escalate to as much 200,000 U.S. Dollars, little but prominent advancements can play a very root cause for the cost savings.

6.2.3: <u>Environment</u>:

If we consider our prototype of how it will benefit on an environmental basis, to give an insight in terms of indirect perspective. It would decrease the cost of fuel used and eventually lower the pollutants beings produced by the powering up the whole unit when in a drilling operation. Furthermore, it would serve as a very basic solution in order to decrease bit balling which effectively improves drilling efficiency when down below the borehole subsequently lowering the power consumption and fuel burnt. These aspects were considered when we decided to design a cavitation jet nozzle system for drilling bits as it will improve number associated parameters.

6.3 Contemporary Issues Addressed

Since our prototype or project is still in a condition where many things can go wrong or may even be a hazard in terms of safety perspective, we ensured that proper precautionary measures were taken in order to properly operate our mechanism without causing harm to the environment and operators. Also, some optimization may be required in order to properly function our mechanism without any pump perturbations and that can resolve quite a number of problems which will be optimization based if all things are considered where we have to make sure that a specific range of Reynold's Number is maintained for a flow to be turbulent enough to avoid bit balling and improving the drilling operations and to keep the fluid flow in the cavitation phenomenon range.

Chapter 7: Conclusion & Future Recommendations

7.1 Conclusion

In a nutshell, the senior design project that our team was involved into was accomplished successfully. However, we did face some problems related to the manufacturing and designing aspect of the nozzle we agreed and intended to work on but it was tackled with professionalism and technical knowledge. Moreover, the whole project was an experience which gave us a lot of knowledge, information, abilities and skills which we used and also had a chance to enhance them while working on our objective. In the end, we were able to illustrate and represent the cavitation phenomenon by the nozzle we designed specifically for the purpose of increased rate of penetration which was experimentally tested on a targeting material.

7.2 Future Recommendations

There have been myriad studies related to cavitation. This research focused on one particular aspect related to clouds of cavitation bubbles and its impact on the rate of penetration ROP. The hope is that this work forms a foundation for future research using a cavitating water jet to erode solid materials at a distance in underwater environments.

The previous research shows that cavitation erosion has the potential to be an effective cutting mechanism. If a cavitation device that can remotely cut submerged solids without polluting its surroundings is developed many underwater environments will become safer for commercial and private use.

Additionally, the cavitation number formula presented in this paper really helps to predict cavitation occurrence, but it is highly recommended to directly compare the liquid pressure to the saturated vapor pressure for better and accurate results.

Moreover, we recommend future researchers seeking answers to the following questions:

1. What are the fluid properties of drilling fluid which affect the cavitation phenomena, and how can cavitating nozzles be designed for optimum performance in these fluids?

2. What are the detailed flow field characteristics of self-resonating cavitating jets, and how can improved understanding of the jet fluid dynamics be used to develop improved bit nozzle systems for both existing and higher pressure drilling equipment?

3. How can self-resonating jets be adapted to improve the hole-bottom cleaning action?

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