CERTIFICATION OF APPROVAL

Design of a New Centrifugal Pump Impeller

by

Muhammad Naim bin Ariffin

A project dissertation submitted to the
Mechanical Engineering Programme
Universiti Teknologi PETRONAS
in partial fulfilment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(MECHANICAL ENGINEERING)

Approved by.

____

(Ir Idris Ibrahim)
Main Supervisor

Universiti Teknologi PETRONAS
Tronoh, Perak
January 2008

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

____

MUHAMMAD NAIM B ARIFFIN

ABSTRACT

Nowadays, the usage of computer software to assist designer for designing equipment has been highly regarded. The objective of this project is to understand the basic principle of centrifugal pump and also the procedure to design the centrifugal pump impeller. Besides that, other objective of this project is to construct the designed impeller in 2D and 3D model. The problem identified for this project is the challenge for the pump designer to design the new centrifugal pump impeller with best possible performance. Besides that, pump designer can only rely to the previous data to design the impeller and also based on the past experience. Basically, there are various stages required to complete the project within the timeline. After the project has been defined, the detailed research is performed. The next phase of the project is the designing stage which is when the impeller is designed by using the Computer Aided Design (CAD). Each parts of the centrifugal pump impeller should be designed according to the research and calculation obtained. As the result, the data had been obtained according to the basic specification of the new centrifugal pump. Based on the data, the impeller has been constructed in 2D and 3D model. Besides that, the right material selection of the centrifugal pump impeller has been identified. As the conclusion, this project is successful and the objectives have been completed within the time frame.

ACKNOWLEDGEMENT

I would like to take this opportunity to acknowledge and thank everyone that has given me all the supports and guidance throughout the whole period of completing the final year project. Firstly, many thanks to the university and the Final Year Project coordinators that have coordinated and made the necessary arrangements for this project.

I must also acknowledge the endless help and support received from my supervisor, Ir Idris Ibrahim throughout the whole period of completing the final year project. His guidance and advices are very much appreciated. Apart from that, I would like showing my gratitude to my previous supervisors, Mr. Mior Azman and Mr Shariza Nisha, which are currently proceeding their study abroad.

Finally, many thanks to my fellow colleagues for their help and ideas throughout the completion of this study. Thank you all.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES **PAGE**

ABBREVIATIONS AND NOMENCLATURES

K_u	=	Speed constant
U_2	=	Impeller peripheral velocity (ft/sec)
g	=	Gravitational constant
H	=	Impeller head (ft)
D_2	=	Impeller outside diameter
D_1	=	Impeller eye diameter
K_{m2}	=	Capacity constant
C_{m2}	=	Radial velocity at impeller discharge
D_3	=	Volute cutwater diameter
A_2	=	Impeller discharge area
S_u	=	Vane thickness at D_2
Z	=	Number impeller vanes
b_2	=	Inside impeller width at D_2
Q	=	Pump flow rate
K_3	=	Volute velocity constant
C_3	=	Volute velocity
A_8	=	Volute throat area
C_{m1}	=	Average meridional velocity at blade inlet
A_e	=	Impeller eye area at blade entry
U_t	=	Peripheral velocity of impeller blade

CHAPTER 1

INTRODUCTION

1.1 Background of Study

The main function of pump is to increase the pressure of the fluid flow. Basically, the main part of the pump is the impeller itself. This part makes the most contact with the medium flow and will compress it in order to transfer it to other area or equipment for further process. The pump will rotate to provide enough compression ratios for compression purpose. Generally, the rotation of the pump is due to the power transmitted from the prime movers equipment such as motor or steam turbine.

Pump is a highly important and widely use equipment in Malaysia with various requirement and parameter involved. Basically, pump is design according to the operating standard with an optimized performance. A lot of time and work should be carried out until the single pump is constructed. Certain things such as cost, time and quality of the pump should be taken into account to design the centrifugal pump. One of the ways to design and analyze the impeller is by using the computer software.

The project title is to design the new centrifugal pump impeller. The designed centrifugal pump must provide sufficient pressure to a liquid so that the liquid will arrive at the particular point with required flow rate and pressure according to the requirement needed. Certain consideration should be followed to ensure the performance of the centrifugal pump which are:

- The friction of the system the pump is working with
- The pressure to overcome this friction and the pressure required for the process
- The flow rate of the fluid to satisfy the requirement

In order to design centrifugal pump impeller with an optimized performance, the procedure to construct the impeller should be done carefully based on the study conducted.

1.2 Problem Statement

1.2.1 Problem Identification

The main problem faced by the pump designer is to design the centrifugal pump with the best performance possible. The main question is how to design such a pump but at the same time the pump designer should satisfy the customer requirement. The truth is, there is no exact procedure and step to design the centrifugal pump impeller. The only reference is based on the past experience and by using the previous data to design a new pump. It should realize that the improvement has been incorporated in today’s centrifugal pump and that a few harder ones will be a fact in another ten years. As example, there is various type of liquid to be pumped in the current industry. Different liquid has its own characteristic and properties. Due to that reason, there is a major change to design the centrifugal just based on the liquid being pumping. This is just one factor that should be considered, and generally there are lots more factors and limitations faced by the pump designer.

According to Val S Lobanoff and Robert R Ross (1992)

> From the information applied on the data sheet, a pump can normally be selected from the pump manufacturer’s sales book. If the pump requirements fall within the performances shown in the sales book, the process of selection is simple. When the required pumping conditions, however, are outside the existing range of performance, selection is no longer simple and becomes the responsibility of the pump designer. (p.10)

1.2.2 Significant of the Project

Nowadays, there is rapid development on the technology especially regarding the usage of computer software. The Computer Aided Design (CAD), Computer Aided Engineering (CAE) and Computer Aided Manufacturing (CAM) techniques can be applied through the usage of software design namely CATIA or other product which is available. There is no need to design the parts using hand sketching because the usage of that computer software is much easier, accurate and can save a lot of time.

1.3 Objective and Scope of Study

This Final Year Project course plays a very important role in achieving UTP's vision which is to produce a well rounded graduate. The course also gives very great opportunity for students to relate the theoretical knowledge from class, exploring new knowledge and applying it in the project. Despite that, students will develop skills in work ethics, communication, management and interpersonal skills. The objectives of this Final Year Project are:

i. Understand the basic principle of pump
ii. Designed the new centrifugal pump impeller
iii. Analyze the impeller using CFD techniques to determine the pump performance
iv. Familiar with the engineering software used in this project

Background study is done on the design and parameters involved in designing the impeller for centrifugal pump. Detail study and analysis on the design of impeller is implemented before transferring the designs into a geometrical modeling format using computer-aided design (CAD) software, namely CATIA V5. Then, Computational Fluid Dynamics (CFD) analysis is performed onto this design using FLUENT software to determine the centrifugal pump performance.

Knowledge based design are vital for the application of the right impeller. However, in order to reach the stage of knowledge-based design, it required an intensive effort of research and study on the basic design of impeller. A lot of thing should be considered during the pump construction such as cavitation, pump head, customer requirement and many more.

1.4 The Relevancy of the Project

Since this project is more on analysis and designing the part of pump, it is very suitable for Mechanical Engineering student. The courses taken before and internship experience is a very useful tool to do this project. The project involves mechanical knowledge in terms of fluid dynamics, computational aided design and mechanical engineering design. Besides that, centrifugal pump is the equipment which is very much helpful to the industrial field in this country.

1.5 Feasibility of the Project

Basically, this project is very complicated but it surely can be done within the time frame. Since there is two semester or approximately nine months of period given, it is enough time to complete the project (refer APPENDIX). The first semester will be focus on research and design the centrifugal pump impeller profile using the computer software. The simulation and the improvement of work from previous work will be done on the second semester. After drafting the methodology of the project, the project's objectives are considered achievable within the given time frame.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction to Centrifugal Pump

Centrifugal pumps employ centrifugal force and velocity to create pressure. The mechanical element is an impeller, which is a rotating disc with vanes. The inlet flow to the pump is directed into the center of the spinning impeller and centrifugal force throws the liquid at high velocity into the surrounding casing. The special shape of the volute converts high velocity into pressure.

The purpose is to increase the pressure of a liquid to ensure the flow at required rate. The impeller and volute form the heart of the pump and help determine its flow, pressure and solid handling capability. Figure 2.1 below shows the basic parts of the centrifugal pump.

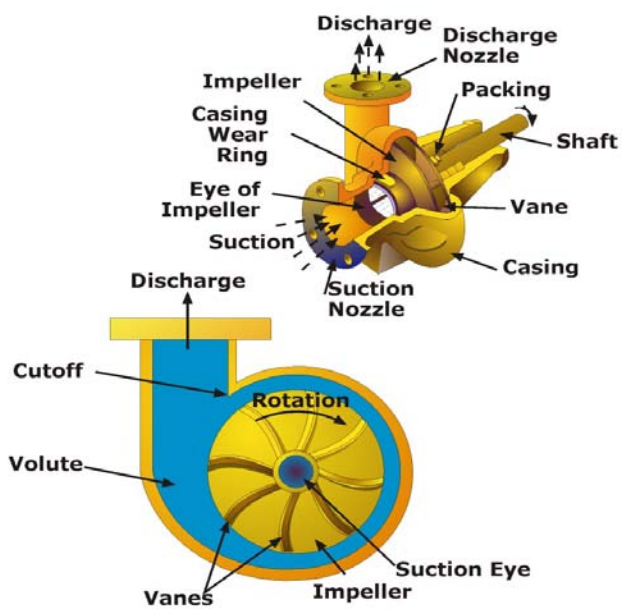


Figure 2.1: Important Parts of Centrifugal Pump [12]

2.2 Pump Performance

Generally, there are lots of considerations that will contribute to the centrifugal pump performance. The important factors that should be considered can be narrowed down to these aspects:

i. System head
ii. Net Positive Suction Head (NPSH)
iii. Pump characteristic curve
iv. Affinity Law

2.2.1 System head

The total head of a system against which a pump must operate is made up of the following components

i. Static head
ii. Differences in pressure existing on the liquid
iii. Friction head
iv. Entrance and exit losses
v. Velocity head

Total static head of a system is the difference in elevation between the discharge liquid level and the suction liquid level shown in Figure 2.2.

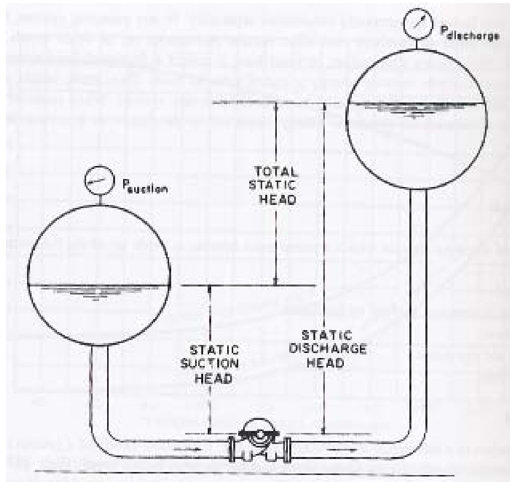


Figure 2.2: Static Head [10]

Friction head is the equivalent head of the liquid pumped that is necessary to overcome the friction losses caused by the flow of the liquid through the piping including all the fittings. The friction head varies with

i. Quantity of flow
ii. Size, type and condition of the pipe and fittings
iii. Characteristics of the liquid pumped

The friction head losses, pressure differences and static heads can be graphically related. The resulting curve is called the system head curve as shown in Figure 2.3. It is possible to construct curves for minimum and maximum static heads for system with varying static heads or pressure difference.

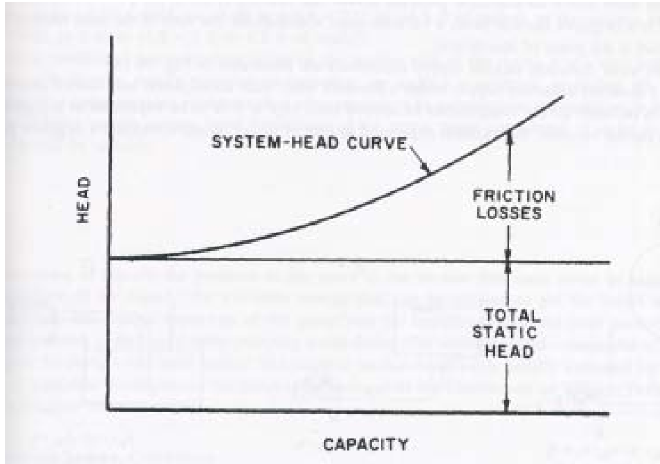


Figure 2.3: System Head Curve [10]

2.2.2 NPSH

During liquid pumping, the pressure at any point in the suction line must never be reduced to the vapor pressure of the liquid. When the pressure at that point is more than the vapor pressure of the liquid, cavitation would be occurred. One of the affect of cavitation is it will badly affect the performance of the centrifugal pump.Net Positive Suction Head is the suction pressure of the pump. A pump will be unable to meet its design capacity condition unless the suction head can provide enough energy to get the liquid into the pump. For liquids, information on the pumping temperature and vapour pressure is necessary. All expected or probable variations in suction conditions should also be specified.

2.2.3 Pump characteristic curve

A centrifugal pump operating at constant speed can deliver any capacity from zero to a maximum value dependent upon the pump size, design and suction conditions. The total head developed by the pump, the power required driving it and the resulting effiency vary with the capacity. The interrelations of capacity, head, power and effiency are called the pump characteristic. These interrelations are best shown graphically and the resulting graph is called as the characteristics curve of the pump. The head, power and effiency are usually plotted against capacity at a constant speed as shown in Figure 2.4.

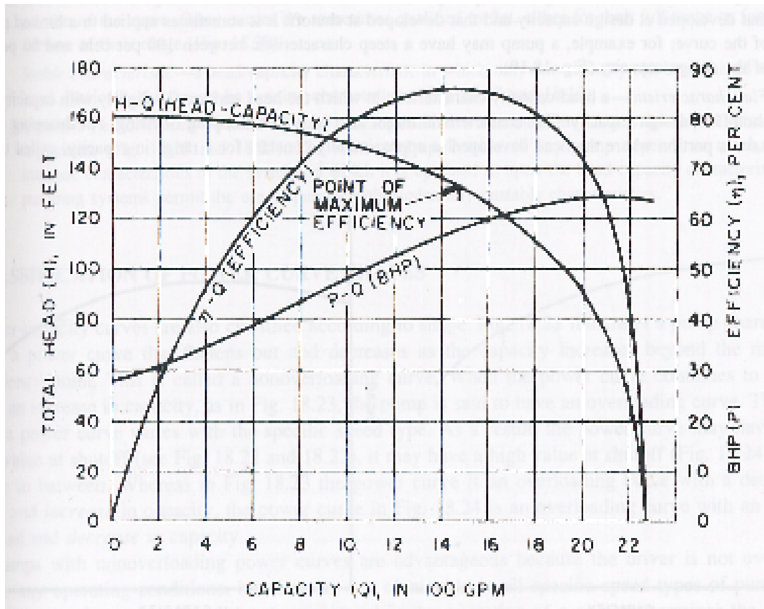


Figure 2.4: Pump Characteristic Curve [10]

2.2.4 The Affinity Law

This law states for similar condition of flow, the capacity will vary directly with the ratio of speed and/or impeller diameter and the head with the square of this ratio at the best effiency point. Other point to the left or right of the best effiency point will correspond similarly from this definition, the rules in Table 2.1 can be used to refigure centrifugal pump performance with impeller diameter or speed change**.**

Table 2.1: Formulas for Refiguring Pump Performance with Impeller Diameter or Speed Change [6]

Diameter Change Only	Speed Change Only	Diameter and Speed Change
$Q_2 = Q_1 \left(\frac{D_2}{D_1}\right)$	$Q_2 = Q_1 \left(\frac{N_2}{N_1}\right)$	$Q_2 = Q_1 \left(\frac{D_2}{D_1} \times \frac{N_2}{N_1}\right)$
$H_2 = H_1 \left(\frac{D_2}{D_1}\right)^2$	$H_2 = H_1 \left(\frac{N_2}{N_1}\right)^2$	$H_2 = H_1 \left(\frac{D_2}{D_1} \times \frac{N_2}{N_1}\right)^2$
$bhp_2 = bhp_1 \left(\frac{D_2}{D_1}\right)^3$	$bhp_2 = bhp_1 \left(\frac{N_2}{N_1}\right)^3$	$bhp_2 = bhp_1 \left(\frac{D_2}{D_1} \times \frac{N_2}{N_1}\right)^3$

Q_1, H_1, bhp_1, D_1, and N_1 = Initial capacity, head, brake horsepower, diameter, and speed.
Q_2, H_2, bhp_2, D_2, and N_2 = New capacity, head, brake horsepower, diameter, and speed.

2.3 Reviewed Paper

2.2.1 Paper/article Reviewed

The paper that had been reviewed are:

- Hydraulic Engineering : Design and Construction
- Simulation Helps TESMA Reduce Water Pump Manufacturing Cost

The detail of the paper reviewed can be refer to APPENDIX 3. Both of the project had been highly utilized the used of CAD techniques to design the pump impeller. However, the CFD software that has been used is different. This is due to different approach used by both designers to design the pump impeller. For the paper *Hydraulic Engineering : Design and Construction,* the designer manage to design three different design and each of the design will be justify the performance by using the CFD techniques. As for the article *Simulation Helps TESMA Reduce Water Pump Manufacturing Cost*, the designer objective is to design a new automotive water pump that met all design requirements while being considerably less expensive to build rather than the initial concept design.

3 main designs have been chosen for the paper *Hydraulic Engineering: Design and Construction* to be analyzed. The designs are as follows:

i. Design I: Basic design of turbine compressor blade of turbomachinery industry
ii. Design II:A typical 4 blades submersible propeller selected based on the design of existing propeller design in marine industry
iii. Design II:A typical 4 blades submersible propeller selected based on the design of existing propeller design in marine industry

Design from CATIA V5 was converted into '.igs' format so that is could be transferred into ANSYS program. For the analyzing stage,

i. Design I: CFD analysis conducted in a 2-d FLOTRAN analysis
ii. Design II and III: CFD analysis conducted in 3-d

The results obtained from the work done are different for each type of design.

i. Design I: a basic design of turbine compressor blade was created
ii. Design II: the design that is similar to Kaplan propeller with several limitation when designing exact replication
iii. Design III: the modification made on the propeller does effect the performance

As for the paper *Simulation Helps TESMA Reduce Water Pump Manufacturing Cost,* the methodologies are as follows:

i. Design the pump using computer aided system (CAD)
ii. The design exported to the FLUENT software in FTL format
iii. GAMBIT preprocessor from FLUENT used to generate surface mesh over the problem domain

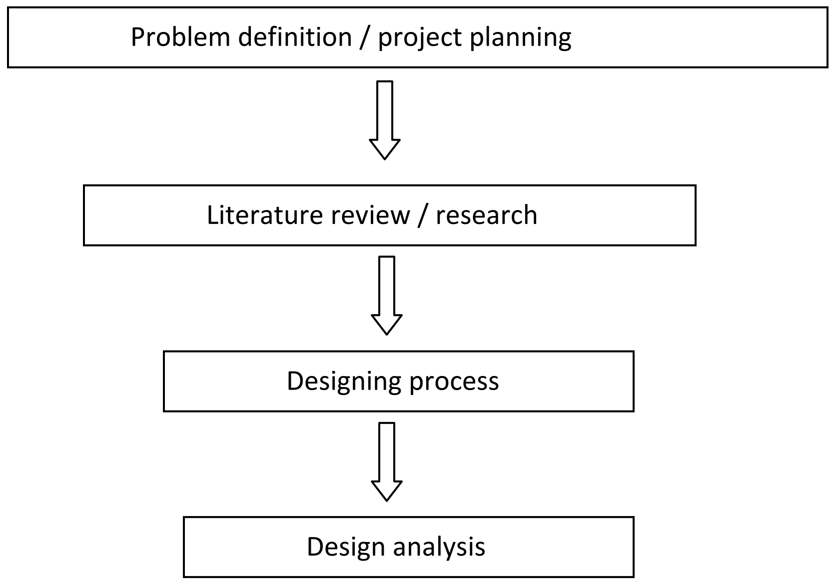
iv. The mesh exported to another FLUENT program known as TGrid, where the quality of surface mesh checked and made correction where necessary
v. Volume mesh generated and check the its quality afterwards
vi. To rotate the impeller, multiple reference frames (MRF) model used where the impeller is at rest in a rotating frame and the shroud is in stationery frame
vii. A steady transfer of information across a pre-defined interface between the two frames
viii. Boundary condition for the model is mass flow inlet and pressure outlet. k-e turbulence model used with a standard wall function
ix. The model solved and the results particularly pump head and hydraulic effiency

Testing results match the analysis predictions very closely. The difference between analysis and testing is between 5% and 10%. The difference is stable enough that it is possible to predict the performance of proposed design with even higher levels of accuracy.

Based on the research done on the previous papers, the objective, methodology and expected result for this project also has been indentify. The detail of the methodology and flow of work will be discussed briefly in methodology section. The expected result of the pump impeller is done in 2D and 3D model. Then analysis is performed on the designed centrifugal pump impeller. Based on the result on the simulation, the expected conclusion is the impeller design met all performance requirements.

CHAPTER 3

METHODOLOGY



3.1 Project flow

There are four major stages included in this project which are:

I. Problem definition / project planning
II. Literature review / research
III. Designing process
IV. Design analysis

I. Problem definition / project planning

The initial phase of the project focuses on the problem definition and the planning for the future work. The topic should be defined at this stage and analyzed carefully to avoid problem especially for the time management, equipment involve and the difficulty of the project. The planning of the project was carefully outlined to ensure the project can be implemented systematically.

II. Literature review / research

The phase involves literature review and research activities on the topics at hand. This phase requires an extensive amount of work and analysis as there is a lot of engineering principles to be covered. Thorough concepts project researches on the design of the impeller and factors that influence their performance have been undertaken. Most of these literature review researches are mainly focused on the impeller design and the methods available to avoid centrifugal pump problem in the future.

III. Designing process

The third phase of the designing process can be done by designing a 2-dimensional design and 3-dimensional impeller design. The software used to draw the 2-dimensional impeller is AUTOCAD 2007. The CATIA V5 is used to design the 3-dimensional centrifugal pump impeller.

IV. Design analysis

FLUENT software will be used to perform the simulation on the design impeller. The main task during the testing and simulation is to verify the performance of the design pump impeller. The impeller should be modeled and meshed first in GAMBIT software. the model of the impeller will be solved using Computational Fluid Dynamics (CFD) technique.

3.2 Procedure to design centrifugal pump impeller

The first step to design each part of the impeller is the most crucial one. Every step and calculation must be determine and carefully examine. This is because the understanding and correct procedure to construct the impeller are the reference for further design by using Computational Aided Design (CAD).

In this part, detailed information for designing a centrifugal pump impeller will be presented. The design factors shown are based on a theoretical approach and many years of collecting thousands of performance test in various specific speeds.

Based on Figure 3.1, the requirement for the new pump can be determined. The parameters for the centrifugal pump are as follows:

Capacity	=	2000 gpm
Head	=	460 ft
Speed	=	3600 rpm

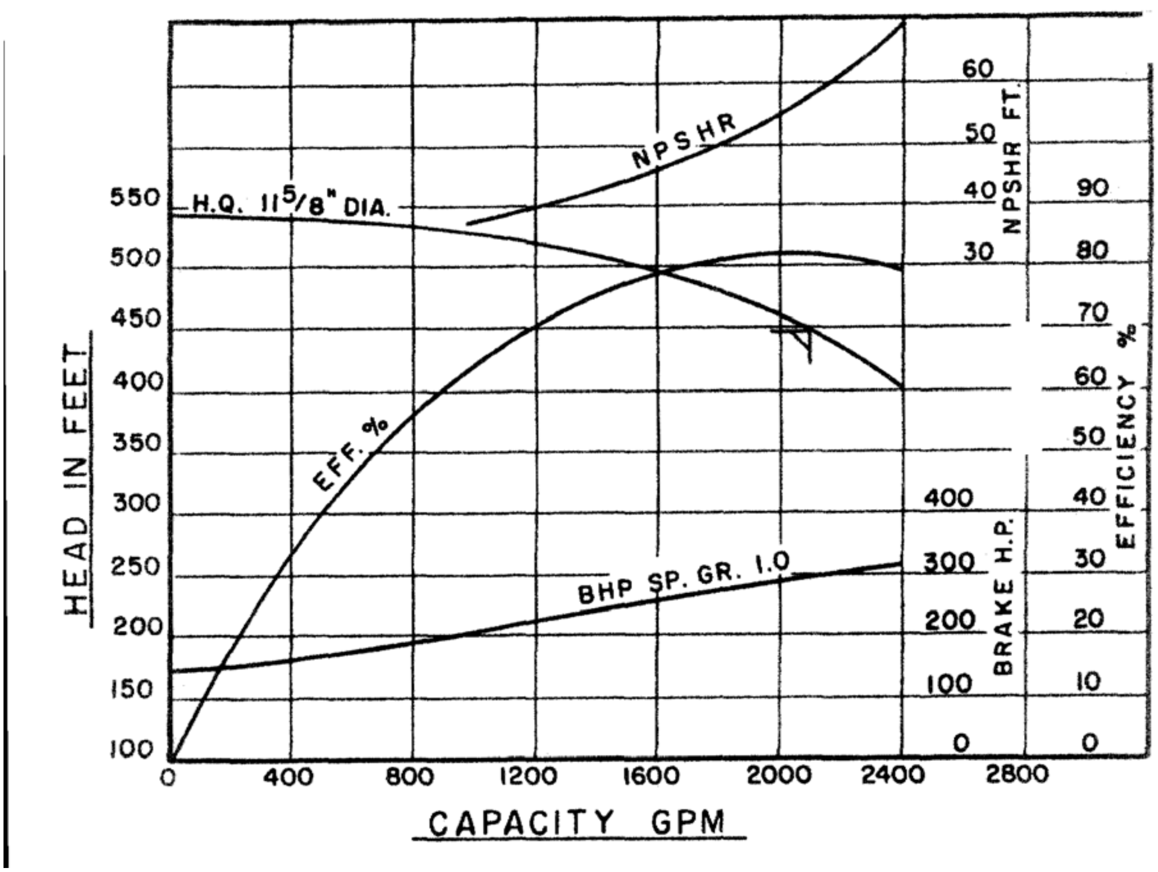


Figure 3.1: Required Performance of New Pump [6]

Step 1 : Calculate pump specific speed, N_s

$$N_s = \frac{\text{pump speed x (pump capacity)}^{0.5}}{H^{0.75}} \quad \text{………………..….Equation 1}$$

$$= 1620$$

Step 2 : Select vane number and discharge angle

The desired head rise from best effiency point (BEP) to zero pump capacity is 20% continuously rising. In order to produce this head rise, the impeller should be designed with six equally spaced vanes having 25^0 discharge angle as shown in Figure 3.2.

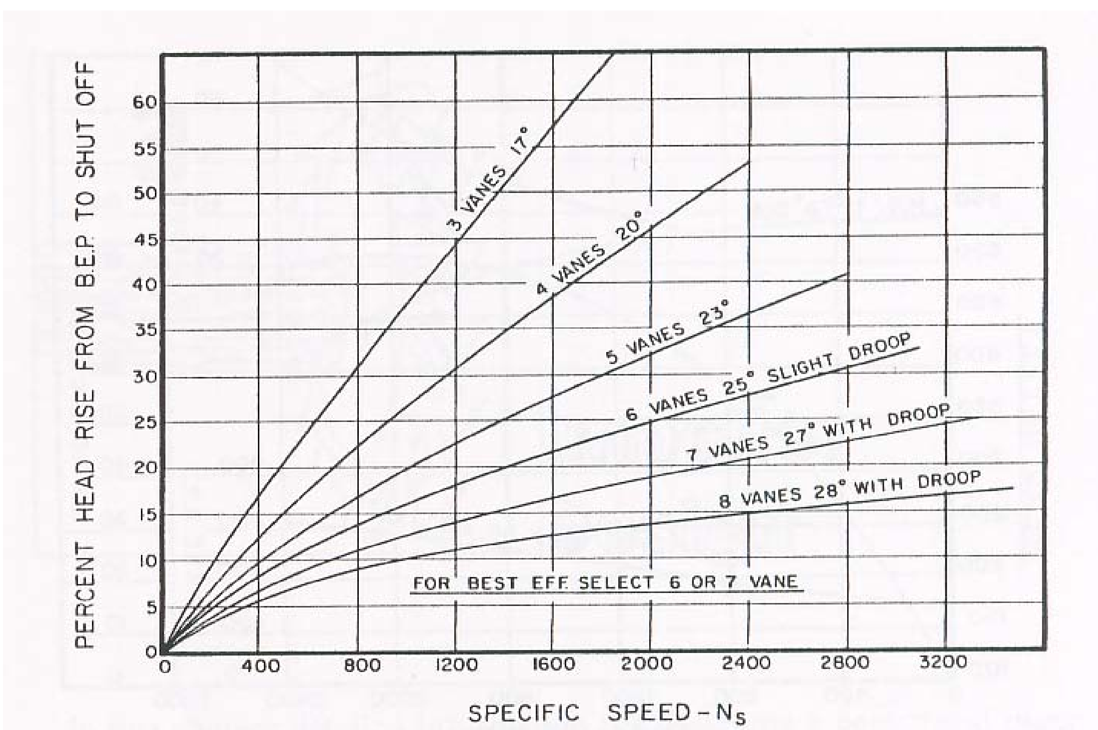


Figure 3.2: Percent Head Rise [6]

Step 3 : Calculate impeller diameter, D_2

In order to determine the impeller diameter, the unknown value which is Head Constant, K_υ should be obtained first.

Based on Figure 2.4, the value of the Head Constant can be determine:

Head constant K_υ = 1.06

After the Head Constant has been obtained, the value will be inserted into this equation

$$D_2 = \frac{1840 \times K_u \times H^{0.5}}{pump\ speed} \qquad \text{.........Equation 2}$$

$$= \frac{1840 \times 1.06 \times 460^{0.5}}{3600} = 11.62$$

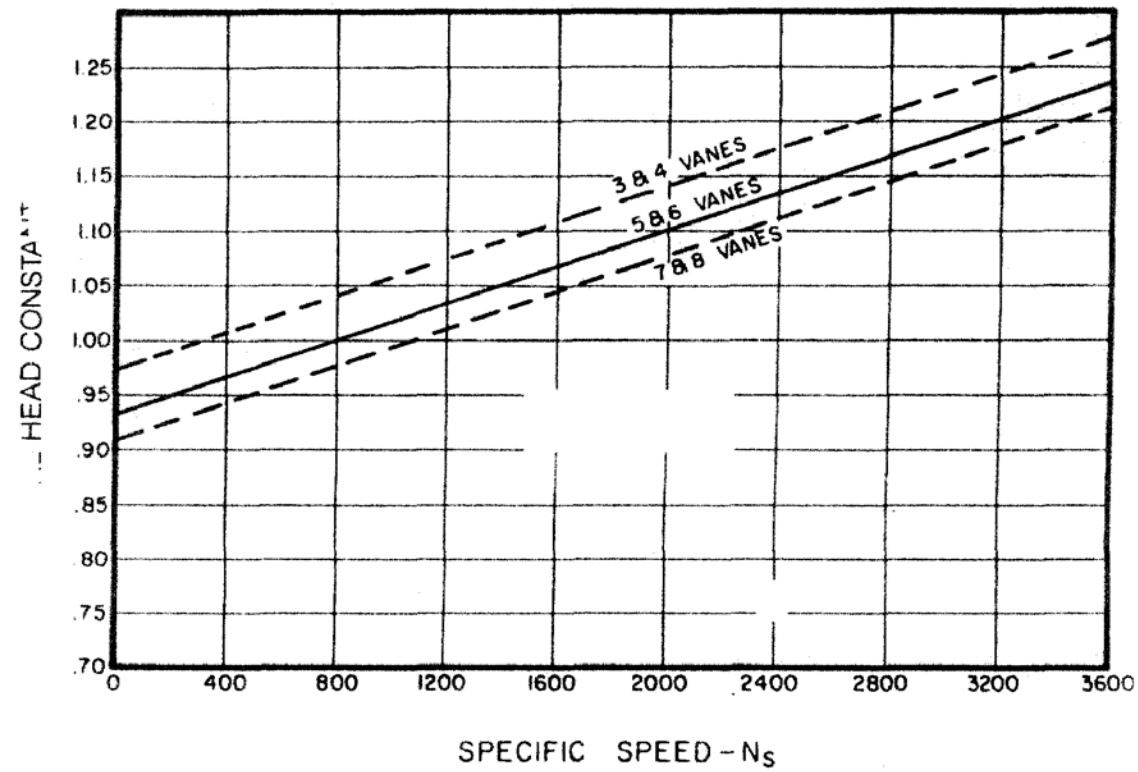


Figure 3.3: Head Constant [6]

Step 4 : Calculate impeller width, b_2

From Figure 3.4:

$K_{m2} = 0.12$

The value of K_{m2} will then be used for the Equation 3 as stated below:

$C_{m2} = K_{m2} \times (2gH)^{0.5}$ …………………………………………………… Equation 3

$= 0.12 \times (2 \times 32.1 \times 460)^{0.5}$

$= 20.63 ft/sec$

Where,

K_{m2}	=	Capacity constant
C_{m2}	=	Radial velocity at impeller discharge (ft/sec)
g	=	Gravitational constant

The next step is to calculate the impeller width after all the unknown parameter has been solved. Equation 4 shows the way to obtain the impeller width value.

$$Impeller\ width, b_2 = \frac{pump\ capacity \times 0.321}{C_{m2}(D_2\pi - no\ of\ vane \times 0.5)} \quad \text{……………………..Equation 4}$$

$$= \frac{2100 \times 0.321}{20.63 \times (11.62\pi - 6 \times 0.5)}$$

$$= 0.93\ inch$$

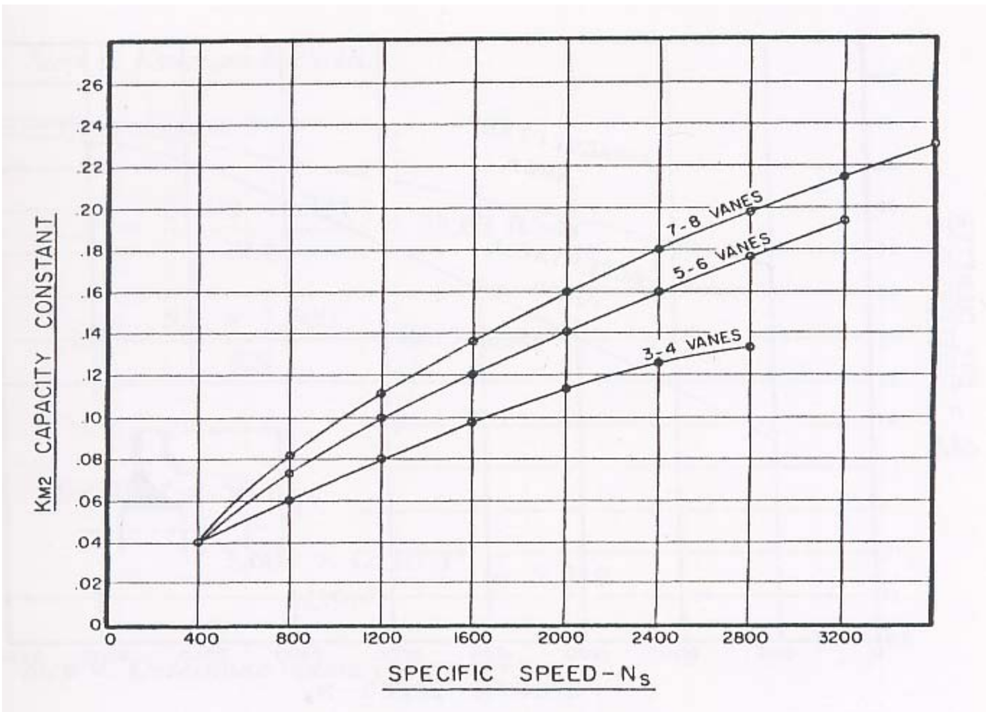


Figure 3.4: Capacity Constant [6]

Step 5 = Determine eye diameter, D_1

As shown in Figure 3.5, the impeller eye diameter over impeller diameter can be obtained by referring the acceptable area curve.

$$\frac{D_1}{D_2} = 0.46 \quad \text{.........................Equation 5}$$

$$D_1 = 11.62 \times 0.46$$

$$= 5.35\ inch$$

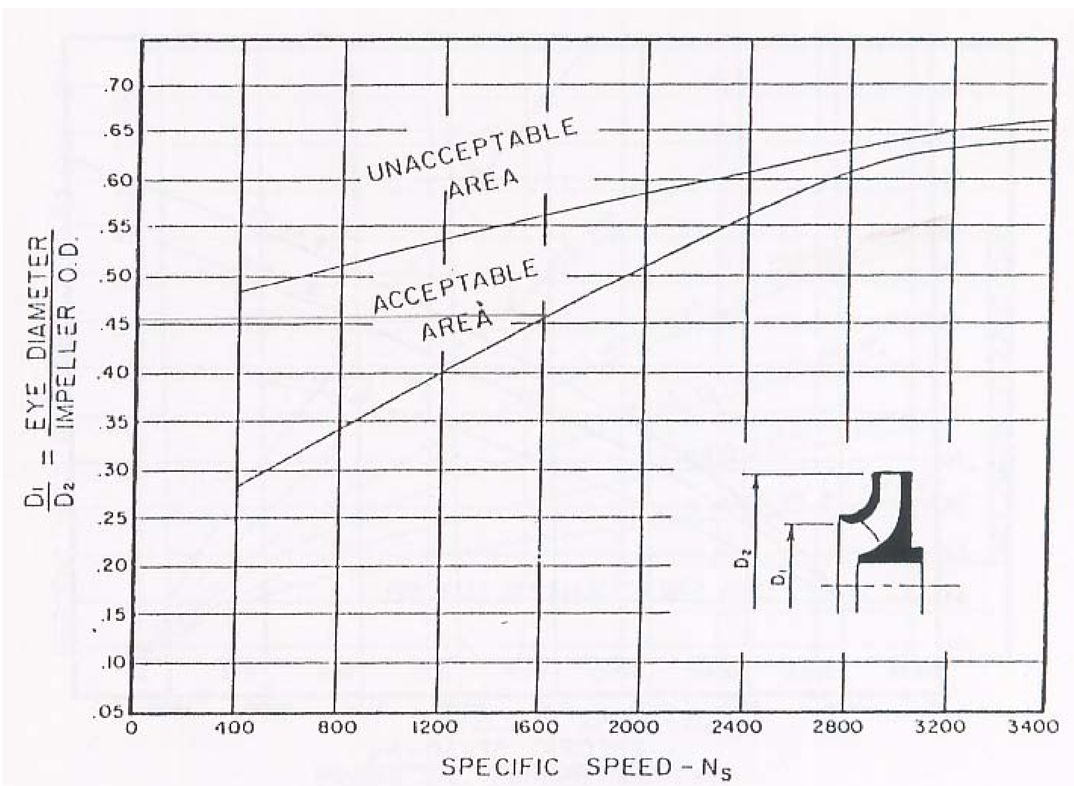


Figure 3.5: Impeller Eye Diameter/ Outside Diameter Ratio [6]

Step 6 : Determine shaft diameter under impeller eye

The shaft diameter under the impeller eye is assumed to be 2 in. The reason of choosing it will be discussed furthermore in Result and Discussion part.

Step 7 : Estimate impeller eye area

$$Eye\ area = Area\ at\ impeller\ area - shaft\ area$$ ……………………….Equation 6

$$= 23.76 - 3.1$$

$$= 20.66\ inch^2$$

Step 8 : Estimate Net Pressure Suction Head Required (NPSHR)

The value of C_{m1} and U_t should be determined first before obtaining the NPSHR value. The parameter of C_{m1} and U_t will be used in Figure 3.6.

$$C_{m1} = \frac{pump\ capacity \times 0.321}{eye\ area}$$ ……………………………………………Equation 7

$$= \frac{2000 \times 0.321}{20.66}$$

$$= 31.07\ ft/sec$$

Where,

C_{m1} = Average meridional velocity at blade inlet (ft/sec)

$$U_t = \frac{D_1 \times pump\ speed}{229}$$ ……………………………..………………………..Equation 8

$$= \frac{5.35 \times 3600}{229}$$

$$= 84.1\ ft/sec$$

Where,

U_t = Peripheral velocity of impeller blade (ft/sec)

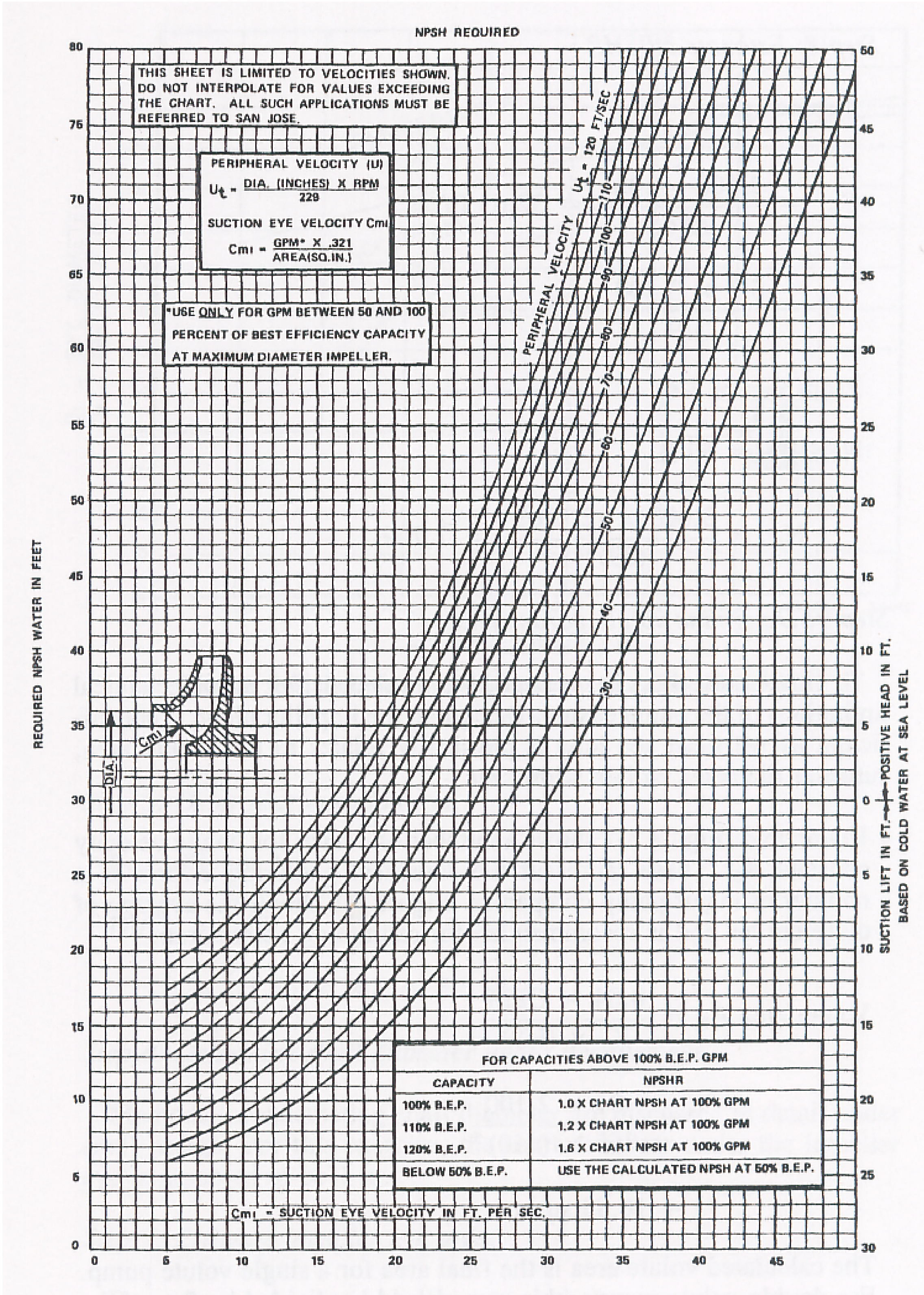


Figure 3.6: NPSHR Predicted Chart [6]

From Figure 3.6, the value of NPSHR can be figured out.

$NPSHR = 55\ ft$

$$N_{ss} = \frac{pump\ speed \times (pump\ capacity)^{0.5}}{(NPSHR)^{0.5}}$$ ……………………………Equation 9

$$= \frac{3600 \times 2000^{0.5}}{55^{0.75}}$$

$$= 7971.6$$

Where,

N_{ss} = Pump suction specific speed

Step 9 : Determine volute parameter

i. Volute area, A_8

Figure 3.7 shows the average curves estimating for volute velocity constant K_3

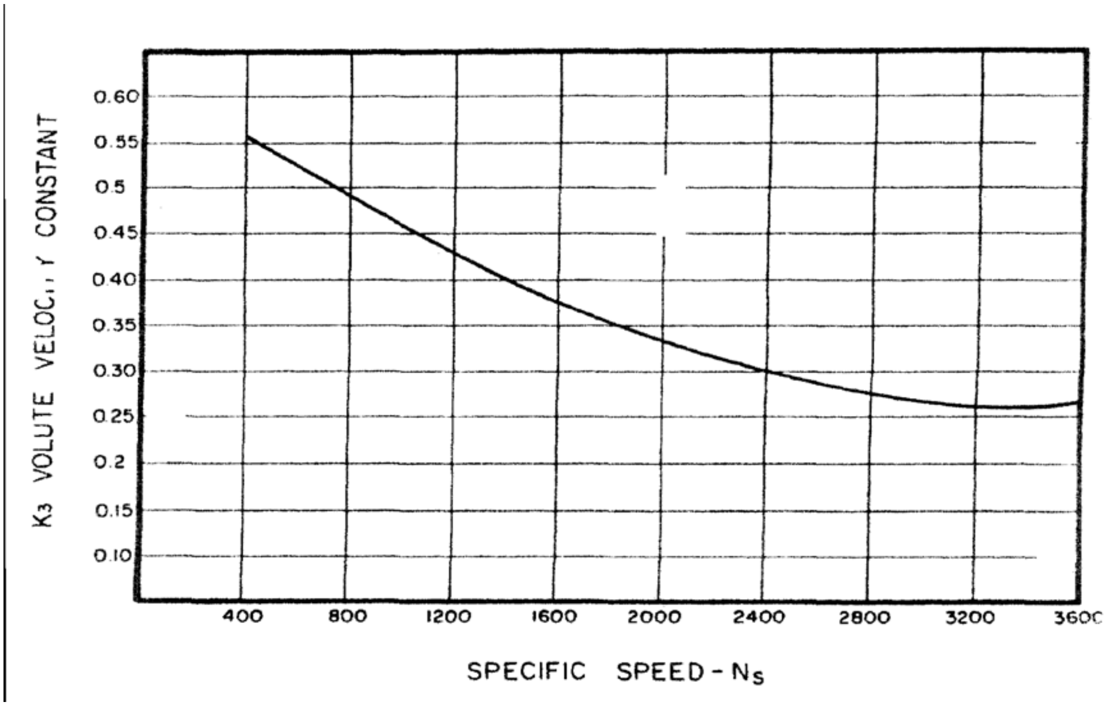


Figure 3.7: Volute Velocity Constant [6]

$$Volute\ area\ A_8 = \frac{0.04 \times pump\ capacity}{K_3 \times H^{0.5}}$$ …………………………..Equation 10

$$= \frac{0.04 \times 2000}{0.365 \times 460^{0.5}}$$

$$= 10.22\ inch^2$$

*the calculated volute area is the final area for a single volute pump

ii. Establish volute width

To determine the width of the volute, the need to accommodate impellers of different diameter and impeller width must be considered. Distance from the impeller shroud to the stationary casing should be sufficient to allow for casting inaccuracies yet still maintain a satisfactory minimum end play. The values in Table 3.1 are reasonable guideline for volute width.

Table 3.1: Guidelines for Volute Width [6]

Volute Width b_3	Specific Speed N_s
2.0 b_2	< 1,000
1.75 b_2	1,000–3,000
1.6 b_2	> 3,000

$Volute\ width = 1.75 \times b_2$ ....Equation 11

$$= 1.75 \times 0.93 = 1.63\ inch$$

iii. Establish cutwater diameter, D_3

A minimum gap must be maintained between the impeller diameter and volute lip to prevent noise, pulsation and vibration. By referring to Table 3.2;

Table 3.2: Guidelines for Cutwater Diameter [6]

Specific Speed N_s	Cutwater Diameter D_3
600–1000	$D_2 \times 1.05$
1000–1500	$D_2 \times 1.06$
1500–2500	$D_2 \times 1.07$
2500–4000	$D_2 \times 1.09$

$Cutwater\ diamater\ D_3 = D_2 \times 1.0$ …………….……………………...Equation 12

$$= 11.62 \times 1.07 = 12.43\ inch$$

After that, based on the data obtained the information will be used to design each parts of the impeller. The parts of the centrifugal pump impeller are:

- Blade
- Shaft
- Volute

The modeling or design of the impeller will be using computer software. AUTOCAD and CATIA V5 are used to design each part of the impeller. The layout drawing and two dimensional designs, the software used is AUTOCAD. Three dimensional model will be designed by using CATIA V5. This computer software is important to design a complex shape of the centrifugal pump impeller

3.3 Methods for Meshing and Modeling the Centrifugal Pump Impeller

This methodology demonstrates the use of the GAMBIT turbo modeling operation as applied to the centrifugal pump impeller. In this stage, 3-D boundary layers were applied to the impeller faces and the bulk of the turbo volume was meshed using tetrahedral elements.

In general, the GAMBIT turbo modeling procedure includes seven steps:

i. Creating or importing edge data that describes the turbo profile
ii. Creating the turbo profile
iii. Creating the turbo volume
iv. Assigning zone types to regions of the turbo volume
v. Decomposing the turbo volume
vi. Meshing the turbo volume
vii. Viewing the turbo volume

As a result, the meshed turbo volume contained three volume element types which are hexahedral (in the region adjacent to the impeller blade), pyramidal (a single transition layer) and tetrahedral (in the bulk of the turbo volume)

3.4 Methods to Solve Model Using Multiple Rotating Frames

Many engineering problems involve rotating flow domains. For problems where all moving parts are rotating at a prescribed angular velocity and the stationary wall are surfaces revolution at with respect to the axis of rotation, the entire domain can be referred to as a single rotating frame of reference.

The flow features associated with multiple rotating parts can be analyzed using the multiple reference frame (MFR) capability. This model is powerful in that multiple rotating frames can be included in single domain. The resulting flow field is representative of a snapshot of the transient flow field in which the rotating parts are moving.

<u>Setup and solution</u>

Step 1: Grid

The grid will be checked from the initial drawing of the centrifugal impeller. Node smoothing and face swapping perform on it to improve mesh quality. This step is recommended for triangular and tetrahedral mesh.

Step 2: Models

The solver for the model is set. The standard k-ε turbulence model is used for this model.

Step 3: Materials

The fluid for this project is water. So water is been set as the material. The density and viscosity is already in the data base along with the selection of water as material.

Step 4: Boundary condition

The boundary condition selected is pressure inlet and pressure outlet. Besides that, the boundary condition will be separated between the fluids which are fluid in rotating zone and also the fluid outside the rotating zone.

Step 5: Solution

The second order discretization scheme is selected for the governing equation. The plot of residual is enabled during the calculation. The solution initialized using the boundary condition selected. The file will be saved and start the calculation by requesting 400 iterations. Then, once again, the case and data file saved.

Step 6: Postprocessing

The contours of total pressure and velocity can be displayed

3.5 Tools

The project will highly utilized the computer assistance upon the completion of this project. All the documentation, designing stage and analyzing phase will be using the computer software. The tools used for this project are as follows:

3.5.1 AutoCAD

AutoCAD main function is to draw the impeller design in 2D design. AutoCAD is a CAD software application for 2D and 3D design, developed and sold by Autodesk, Inc. AutoCAD used primitive entities such as lines, polylines, circles, arcs, and text as the foundation for more complex objects. Modern AutoCAD includes a full set of basic solid modeling and 3D tools, but lacks some of the more advanced capabilities of solid modeling applications. AutoCAD is a vector based drawing application intended for engineering purposes. Commands can be entered at a command line or through toolbars and menus.

3.5.2 CATIA

CATIA Version 5 is an integrated suite of Computer Aided Design (CAD), Computer Aided Engineering (CAE), and Computer Aided Manufacturing (CAM) applications for digital product definition and simulation. CATIA Version 5 is the cornerstone of a true integration of people, tools, methodologies and resources within an enterprise. CATIA Version 5 provides advanced 3D Product Lifecycle Management (PLM) solutions for collaborative product development. Its unique underlying product process resources model and workplace approach provide a truly collaborative environment that fosters creativity, sharing, and communication of 3D product and process-centric definitions, providing businesses a competitive advantage with improved time-to-market and cost reductions.

CATIA has a built-in capacity to capture and reuse know-how that will drive the implementation of corporate design best practices and free end-users to focus on creativity and innovation. The open CATIA Version 5 application architecture allows an ever-growing number of third-party vendors to create specialized applications to meet specific needs in the same user environment.

3.5.3 FLUENT

FLUENT software is a powerful and flexible general-purpose Computational Fluid Dynamics (CFD) package used for engineering simulations of all levels of complexity. It offers a comprehensive range of physical models that can be applied to a broad range of industries and applications.

3.5.4 Microsoft Words

Microsoft Words is used for documentation for every work done. Microsoft Words is easy to use, friendly features and can save a lot of time. Microsoft Office Word helps user by providing a comprehensive set of tools for creating and formatting the document in a new interface. Rich review, commenting, and comparison capabilities help to quickly gather and manage feedback from colleagues. Advanced data integration ensures that documents stay connected to important sources of project information.

3.5.5 GAMBIT

GAMBIT is Fluent’s geometry and mesh generation software. GAMBIT's single interface for geometry creation and meshing brings together most of Fluent's preprocessing technologies in one environment. Advanced tools for journaling to edit and conveniently replay model building sessions for parametric studies. GAMBIT's combination of CAD interoperability, geometry cleanup, decomposition and meshing tools results in one of the easiest, fastest, and most straightforward preprocessing paths from CAD to quality CFD meshes.

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Data for Designed Centrifugal Pump Impeller

The specifications of the new centrifugal pump impeller are shown in Table 4.1 below.

Table 4.1: Specification of the centrifugal pump

Pump specification	**Value**
Pump capacity, Q	2000 gpm
Head required, H	460 ft
Pump speed	3600 rpm
Liquid pumping	Water
Pump specific speed	1620

Throughout the project, a lot of parameters and unknown values have been encountered. Since the process to design the impeller is complicated, therefore many data should be obtained first before proceeding to the design stage. A detail discussion have been explained in the literature review section regarding the understanding and calculation required to gain important parameters to design centrifugal pump impeller. The results from the research done have been summarized in Table 4.2 below.

Table 4.2: Parameter Value of Impeller Parts

Parameter of Impeller	Value
Number of vanes	6
Impeller diameter, D_2	11.62 inch
Impeller width	0.93 inch
Impeller eye diameter, D_1	5.35 inch
Shaft diameter	2 inch
Net Positive Suction Head Required (NPSHR)	55 ft
Volute area	10.22 $inch^2$
Volute width	1.63 inch
Cutwater diameter	12.43 inch

4.2 Material Selection for Designed Centrifugal Pump Impeller

The material selection for pump is different for each parts of it. The material selection is selected based on the liquid pumping, temperature and many more factors. There are lots of liquid pumping that will affect the material selection for pump parts (refer to APPENDIX for further detail on material selection). The material chosen for the designed pump are shown in Table 4.3 below.

Table 4.3: Material Selection of Impeller Parts

PART	MATERIAL
Casing	Carbon steel casting (ASTM A 216)
Impeller	Gray iron casting (ASTM A 48 No. 40)
Shaft	Carbon steel

4.3 Designed Centrifugal Pump Impeller

i. Impeller layout

Figure 4.1 below shows the impeller layout of the centrifugal pump impeller. The designed centrifugal pump impeller has six vanes. From the figure the diameter of the impeller and eye diameter also has been shown clearly.

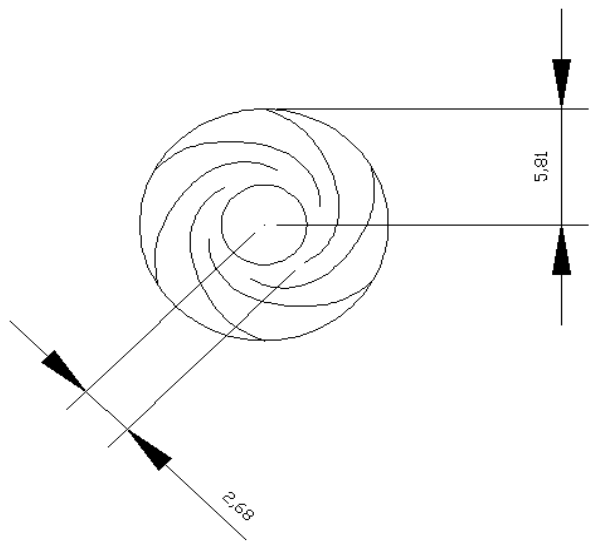


Figure 4.1: Impeller Layout (End View)

The impeller layout is the first important step to design the centrifugal pump impeller. The drawing is obtained according to the calculation mentioned in the previous part of the project report. The vane layout should be design with an equal space with each other. This is because it can affect the H-Q pump performance. Standardization as shown will lead to more accurate performance prediction.

ii. Blade

From Figure 4.2, it can be seen that the single three dimensional blade has been constructed. There are all together six same blades should be constructed to design the required centrifugal pump impeller.

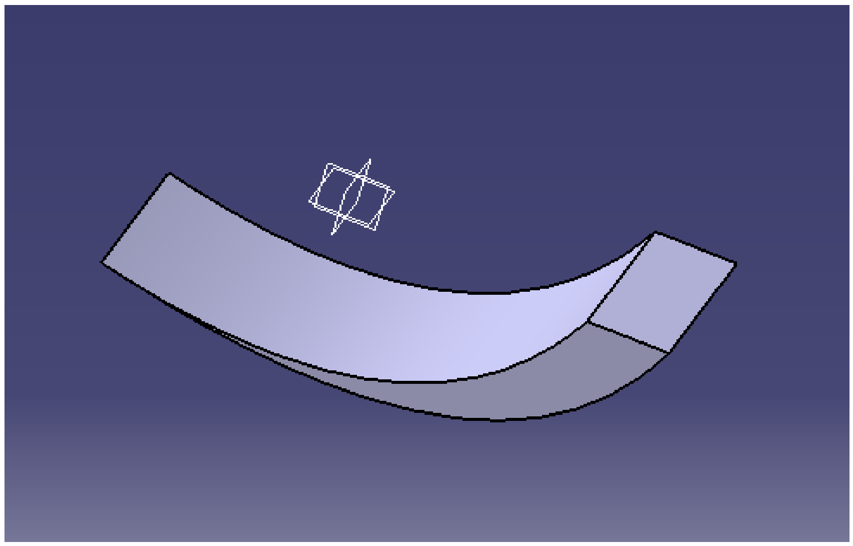


Figure 4.2: Blade

The blade profile is the most important parts of impeller should be designed with a careful estimation. The blade may look very simple but lots of estimation should be done to design the blade profile. A lot of parameter should be taken into account such as the minimum cutwater diameter, suction eye area, blade discharge angle and other parameters involved.

iii. Volute

Figure 4.3 shows the volute layout for the centrifugal pump impeller. From the figure it can be seen that two important parameters in centrifugal pump design which are the cutwater diameter and the throat area of the volute.

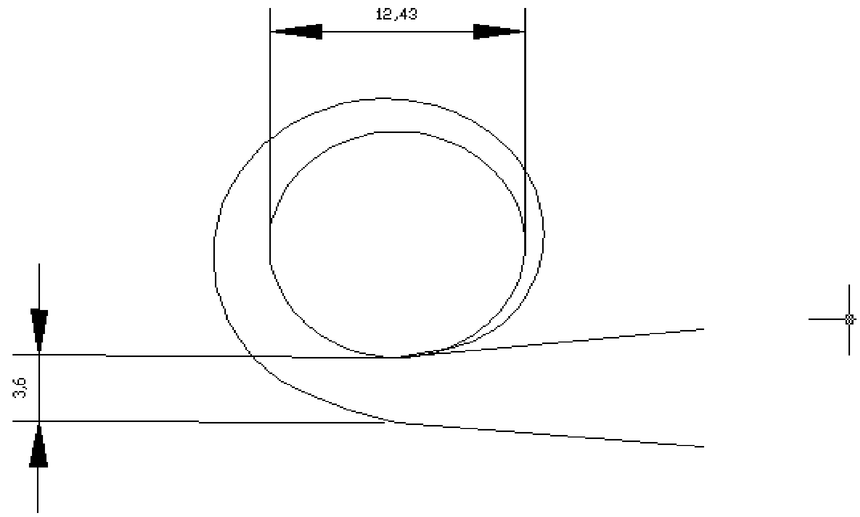


Figure 4.3: Volute Layout

Volute is the area of impeller parts which the conversion of energy occurred. The kinetic energy will be converting to pressure energy. The hydraulic characteristics of a volute casing are a function of the following design elements:

- Impeller diameter
- Cutwater diameter – A minimum gap must be maintained between the impeller diameter and the volute lip to prevent noise, pulsation and vibration.
- Volute areas – Areas increase gradually from the cutwater diameter towards the discharge nozzle
- Throat area – This area is the most important factor in determining the pump capacity at best effiency point.

Figure 4.4 below demonstrate a more detailed drawing of the designed pump volute.

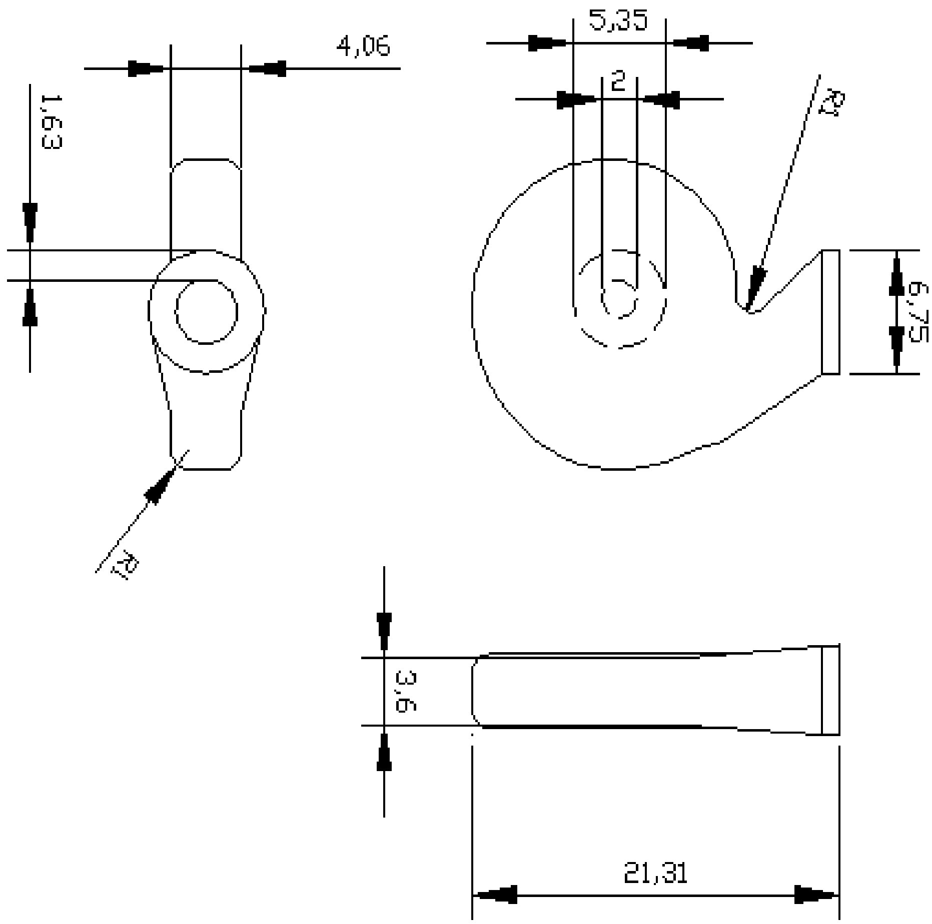


Figure 4.4: Technical Drawing of Volute

This centrifugal pump is the single volute type. This is because single volute design is more efficient than those using more complicated volute design. They are also less difficult to cast and more economical to produce because the open areas around the impeller periphery. Theoretically, the single volute pump can be used on large as well as small pumps of all specific speeds.

iv. Shaft

Figure 4.4 shows the layout of the designed shaft and from figure 4.5, it shows the model of shaft in three dimensional view.

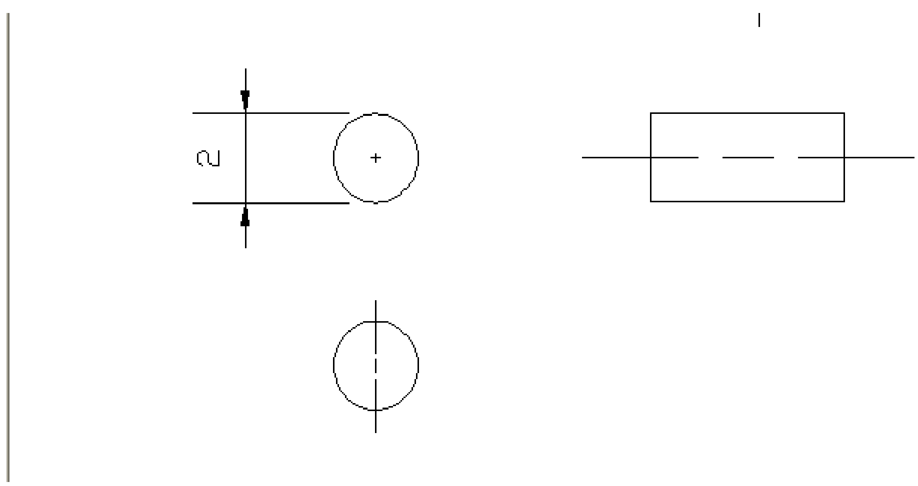


Figure 4.5: Technical Drawing of Shaft

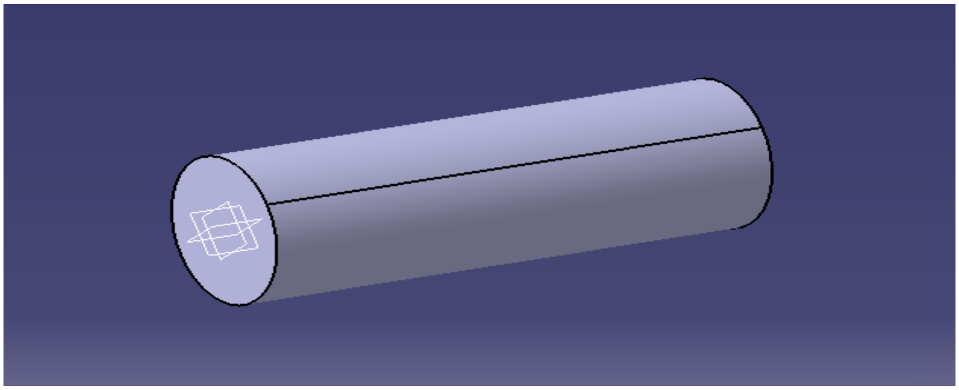


Figure 4.5: 3D Model of Shaft

The shaft should be design to sustain combined effects of tension, compression, bending and torsion. The diameter of the shaft is 2 inch. Since the size of the pump is not big, so the selection of shaft size is acceptable. The designed shaft should be able to resist those effects and at the same time rotating the impeller at optimum performance.

v. Impeller

The technical drawing of the centrifugal pump impeller is illustrated as shown in Figure 4.6.

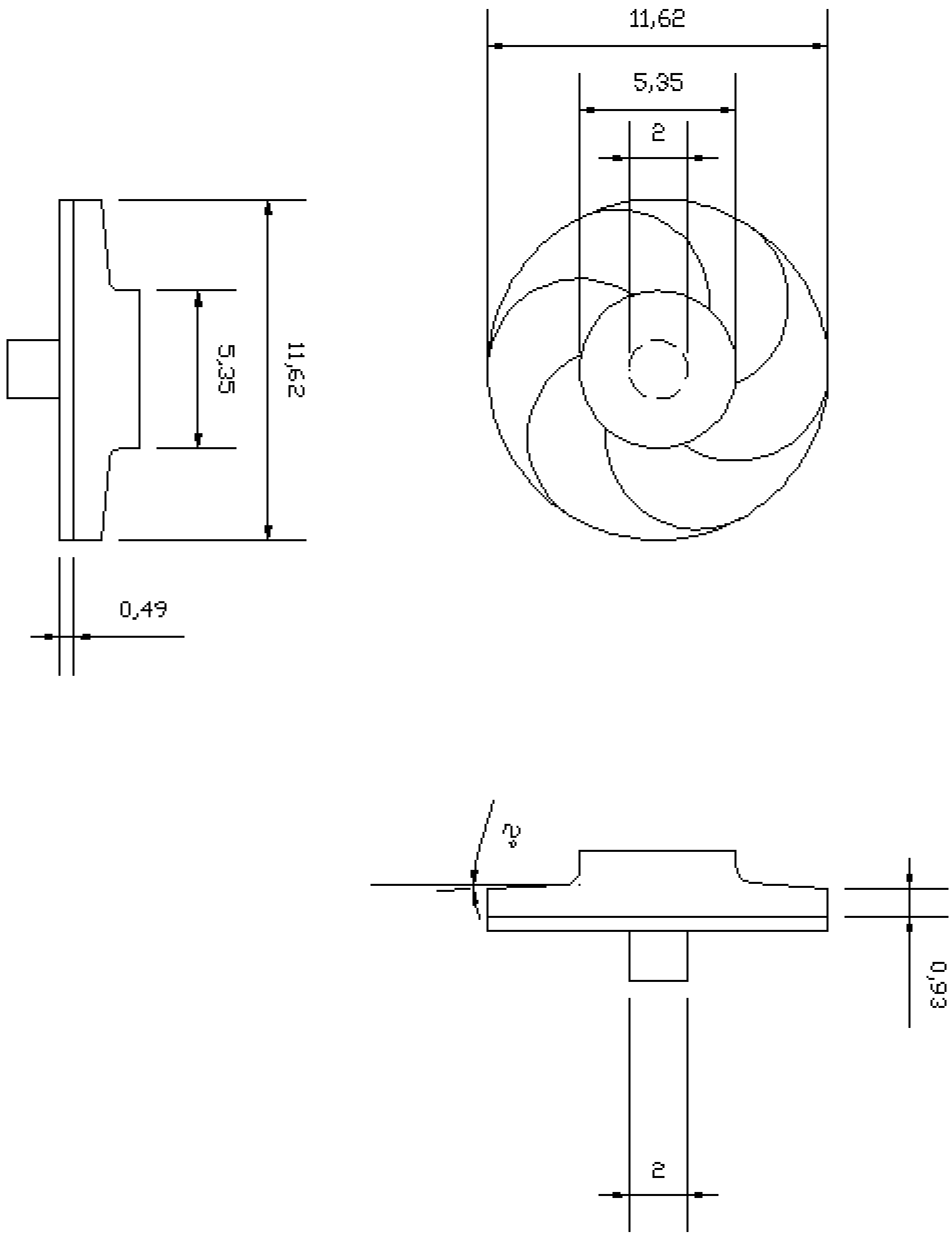


Figure 4.6: Technical Drawing of Impeller

Figure 4.6 shows the impeller in three dimensional view..

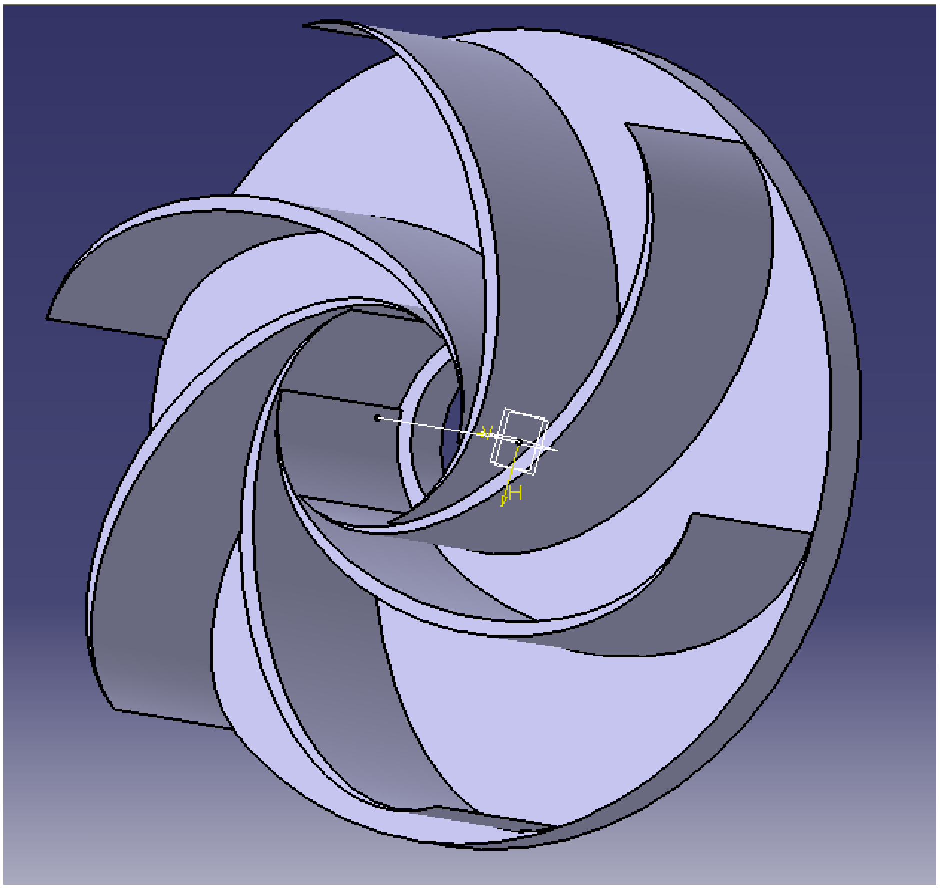


Figure 4.7: 3D Model of Impeller

vi. Assembly drawing of centrifugal pump

Figure 4.8 below shows the assembly drawing of the centrifugal pump impeller.

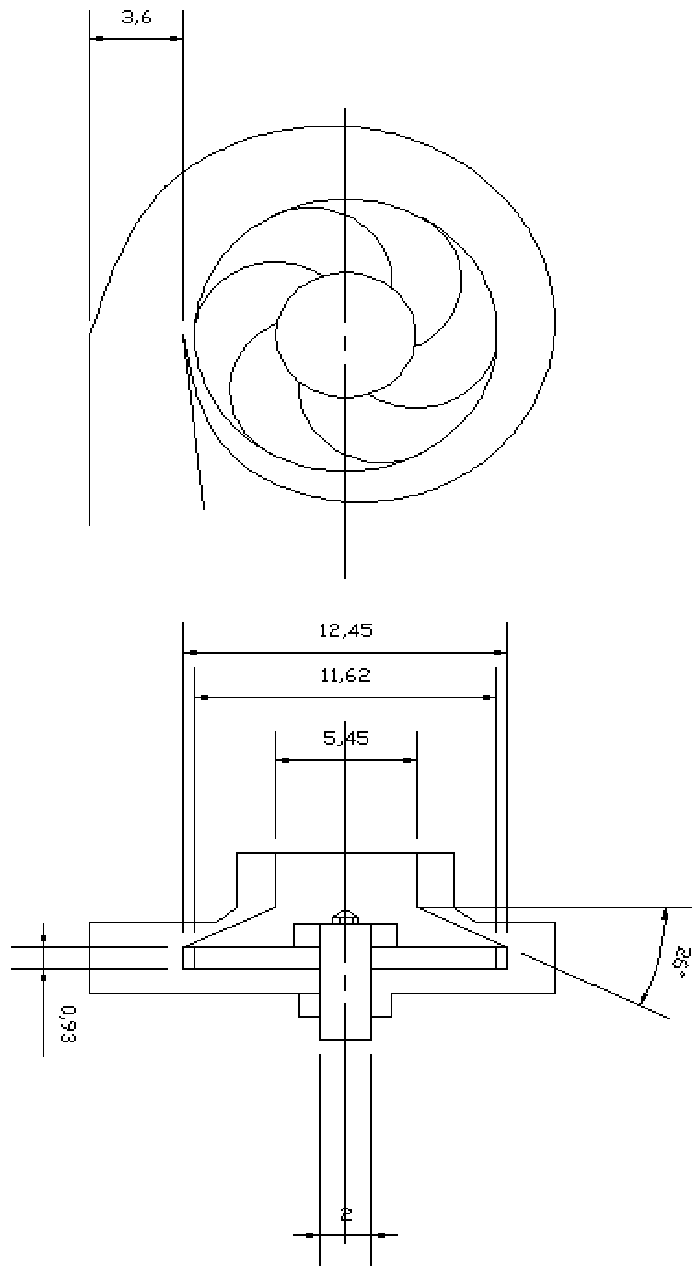


Figure 4.8: Assembly Drawing of the Centrifugal Pump

4.4 Modeling and Meshing of the Centrifugal Pump Impeller

GAMBIT reads the information contained in the data file and constructs the set of edges shown in Figure 4.9. The five sets of curved edges constitute cross sections of a single impeller blade

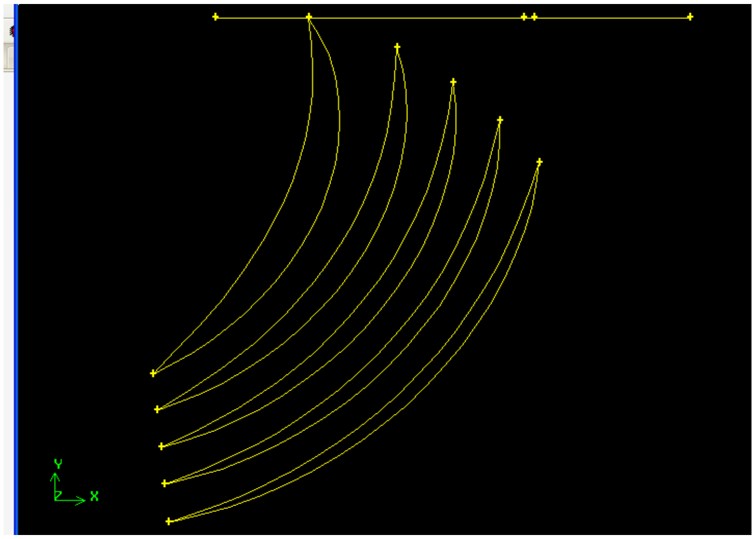


Figure 4.9: Imported impeller geometry

The turbo profile shown in Figure 4.10 includes 10 real edges and five medial edges, each of which corresponds to one of the blade cross sections.

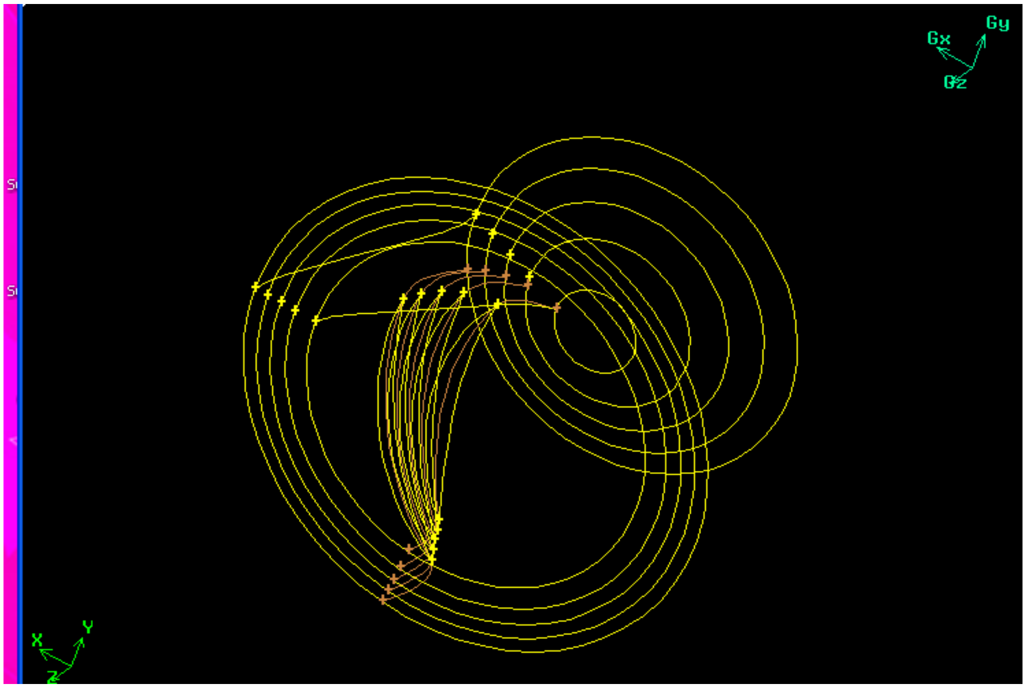


Figure 4.10: Turbo profile

Figure 4.11 shows the turbo volume of the pump impeller. The turbo volume characteristics are determined by the turbo profile and by the specification of blades on the rotor, the tip clearance and the number of spanwise sections.

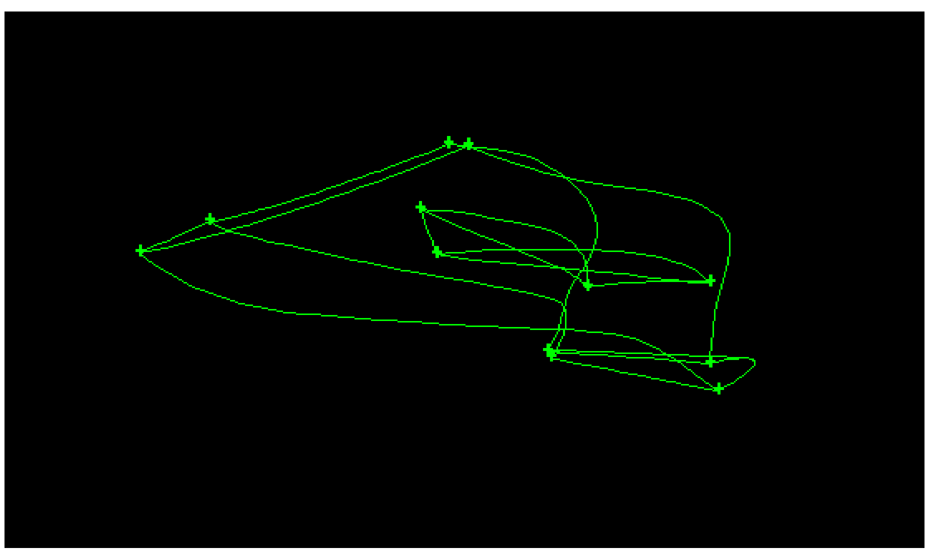


Figure 4.11: Turbo volume for pump impeller

Figure 4.12 shows the 3-D boundary layers projected onto the casing surfaces of the turbo volumes. For this model, 3-D boundary layers allow the user to ensure the creation of high quality mesh elements in regions adjacent to the turbo blade surfaces.

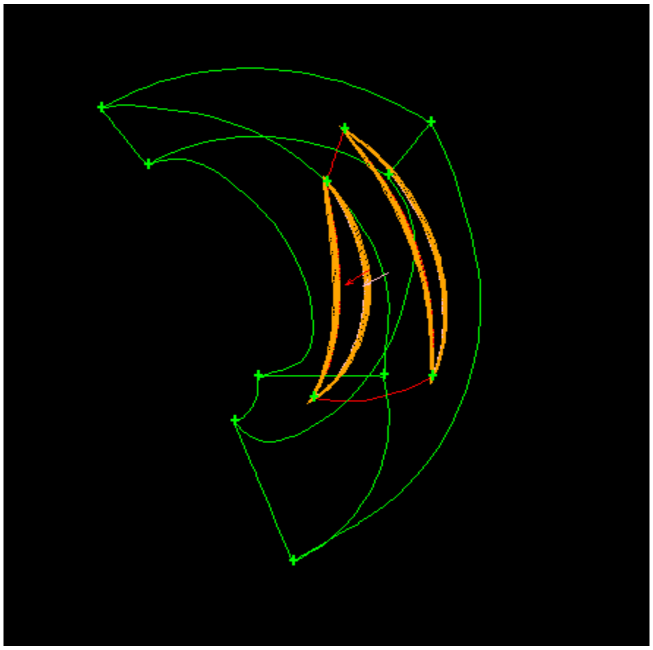


Figure 4.12: Turbo volume with 3-D boundary layer

GAMBIT meshes the pressure and suction faces on impeller blade as shown in Figure 4.13

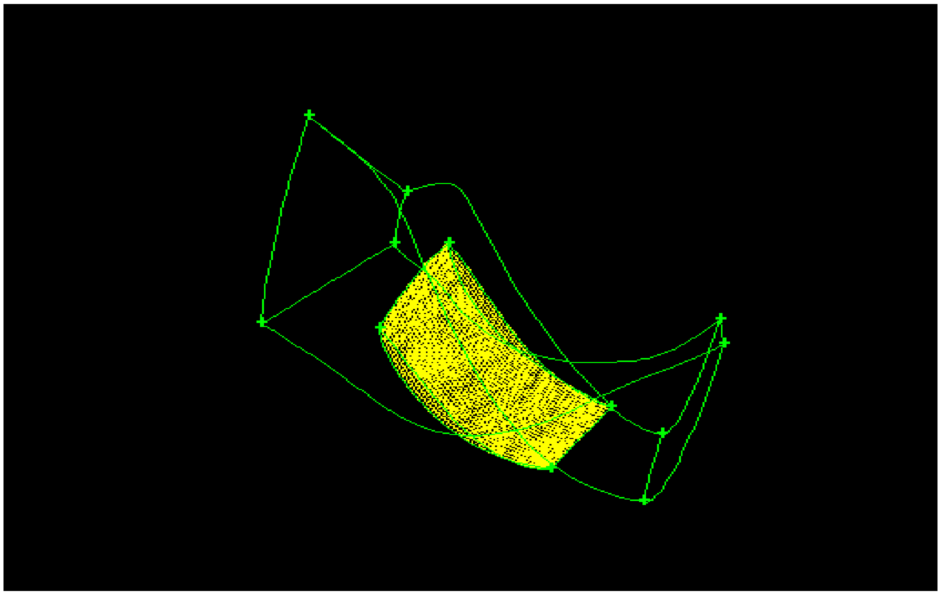


Figure 4.13: Meshed faces of the impeller blade

Figure 4.14 below shows the meshed turbo volume for the impeller blade

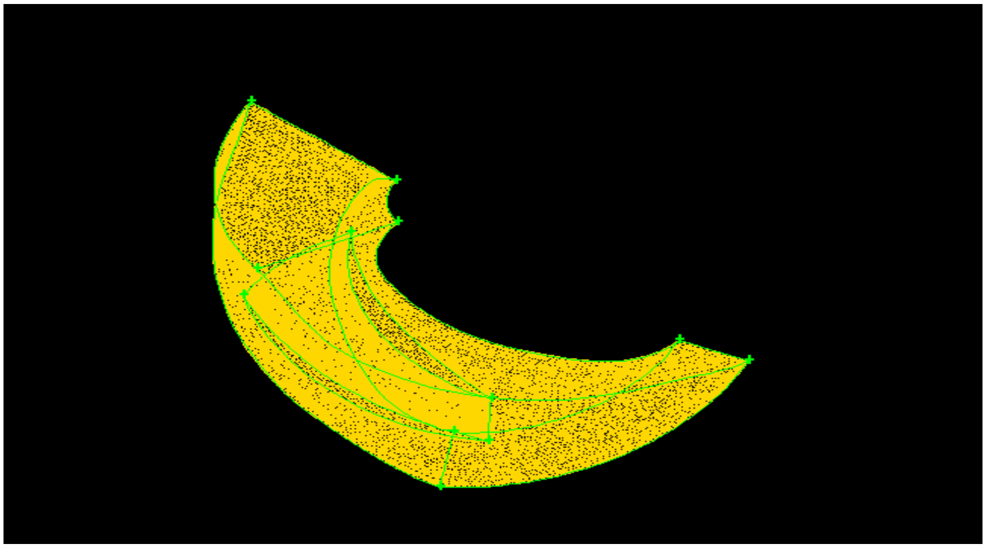


Figure 4.14: Meshed turbo volume for impeller blade

The examine mesh form in GAMBIT allows the user to view various mesh characteristics for 3-D mesh. Figure 4.15, Figure 4.16 and Figure 4.17 display hexahedral, pyramidal and tetrahedral mesh elements, respectively which the EquiAngle Skew parameter is between 0.2 and 0.3.

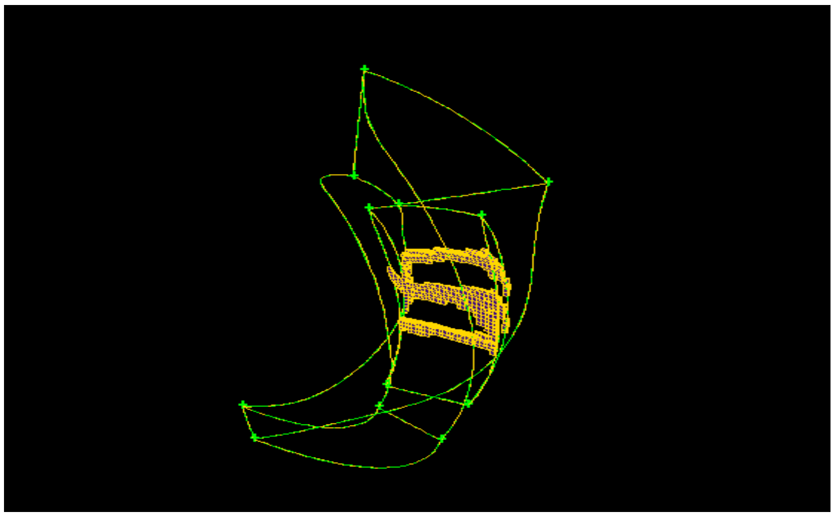


Figure 4.15: Hexahedral mesh element

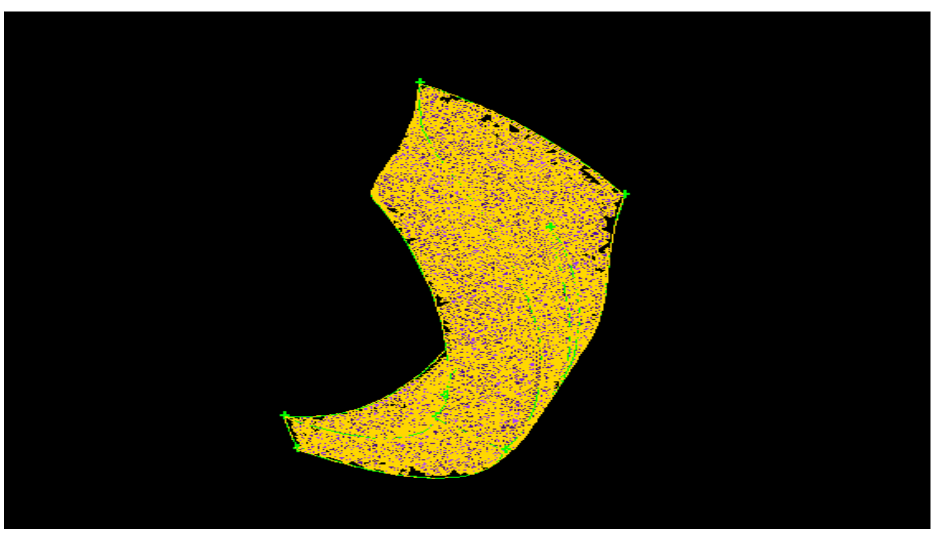


Figure 4.16: Tetrahedral mesh element

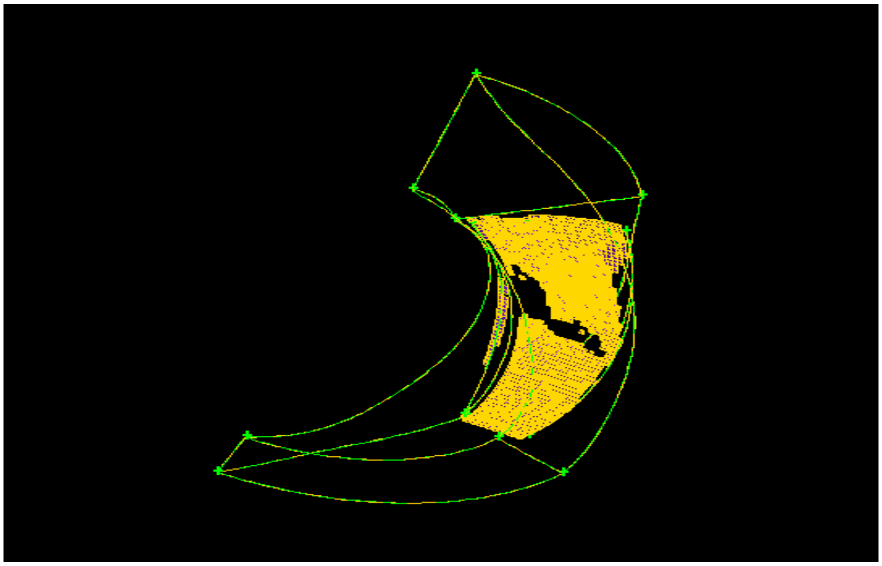


Figure 4.17: Pyramidal mesh element

4.5 Solving the Model

After the model has been completely meshed, the designed centrifugal pump impeller will be transferred to FLUENT software to solve the model. A lot of uncertainty occurred during the postprocessing of the designed impeller. Since the simulation of the model is in 3-D model, the solution using CFD will be very difficult. Although the model has been successfully meshed previously in GAMBIT, certain thing such as topology of the model cannot be defined. Hence, the model cannot be solved. In order to successfully solve the model, many things should be repaired and changed to avoid the error during the postprocessing stage. Although certain modifications had been made to overcome the error, the model still cannot be solved.

CHAPTER 5
CONCLUSIONS AND RECOMMENDATION

5.1 Conclusions

As the conclusion, the author managed to understand the basic principle of centrifugal pump and completed one of the objectives in this project. Basically, the main purpose of the centrifugal pump is to increase the pressure and to ensure the liquid pumping to flow at the particular point with required flow rate and pressure. Besides that, one of the stages in this project also had been completed. The particular stage is the design stage of the centrifugal pump impeller. The impeller parts such as volute, impeller blade and shaft are designed and viewed using 2D and 3D model. All those parts are designed carefully based on detailed research and calculation as discussed in previous part. Another objective of the project is to ensure the author familiar with the usage of the engineering software in this project. The engineering softwares used in this project are AutoCAD 2007, CATIA, FLUENT and also GAMBIT. The last stage of the project is to analyze the new centrifugal pump impeller by using CFD technique. However due to certain technical problem, the impeller could not be tested using the computer simulation.

5.2 Recommendations

Throughout the project duration, certain matters can be made for further development of the project. The approaches suggested are as follows:

1. **Blade structure**

In order to get more accurate and better result during simulation, the characteristic of the blade profile should be more unique and suitable with the requirement for the fluid flow.

The design of a unique blade profile requires very detailed knowledge in CAD especially involving CATIA or other applicable software.

2. Pump design software

The software used in this project are AutoCAD, CATIA, GAMBIT and FLUENT to design and analyze the centrifugal pump impeller. However, there is other software that has been built and specialized to design the pump such as Pump Design Code software. That special software can be purchased but it is very expensive.

3. Usage of actual centrifugal pump

The actual centrifugal pump can be used to improve the understanding in pump construction and design. In this project, the actual pump cannot be used due to limitation for the centrifugal pump that can be built based on the calculation and procedure to design centrifugal pump impeller. As example the limitation for the project is applicable for pump specific speed ranging from 400 to 3600. Besides that, the data obtained from the actual pump can be compared to the data from CFD analysis.

4. Use software to deal with the equation

In order to design the centrifugal pump impeller, too much equation involves throughout the process. It is suggested that the equation can be calculated using the software programming to make things more easy and systematic. It is more important when the pump designer have to deal with the equations frequently.

CHAPTER 6
REFERENCES

[1] http://www.sciencedirect.com

[2] http://www.cfd-online.com/Forum/fluent_archive_2004.cgi

[3] Val S. Lobanoff, Robert R. Ross; *CENTRIFUGAL PUMP: Design &Application*, Gulf Professional PublishingHouston, 1992

[4] Slade, S; *Designing a Propeller*, article, 1999

[5] Bleier, F; Fan Handbook; *Selection, Application & Design*, McGraw-Hill International, New York USA, 1998

[6] Tuzson, J; *Centrifugal Pump Design*, Wiley-Interscience publication, 2000

[7] www.fluent.com

[8] R L Elder, A Tourlidakis, M K Yates; *Advances of CFD in Fluid Machinery Design*, Professional Edition Engineering Publishing, 2003

[9] Igor J Karassik, *Centrifugal Pump Clinic*; Marcel Dekker Inc., 1989

[10] Igor J Karasik, Terry McGuire; *CENTRIFUGAL PUMPS*, Kluwer Academic Publisher, 1996

[11] Harold H Anderson; *Centrifugal Pumps and Allied Machinery*, Elsevier Advance Technology, 1994

[12] Training manual titled *Kertih Terminal: Pump Training*

APPENDICES

APPENDIX 1 – First Semester Gantt chart

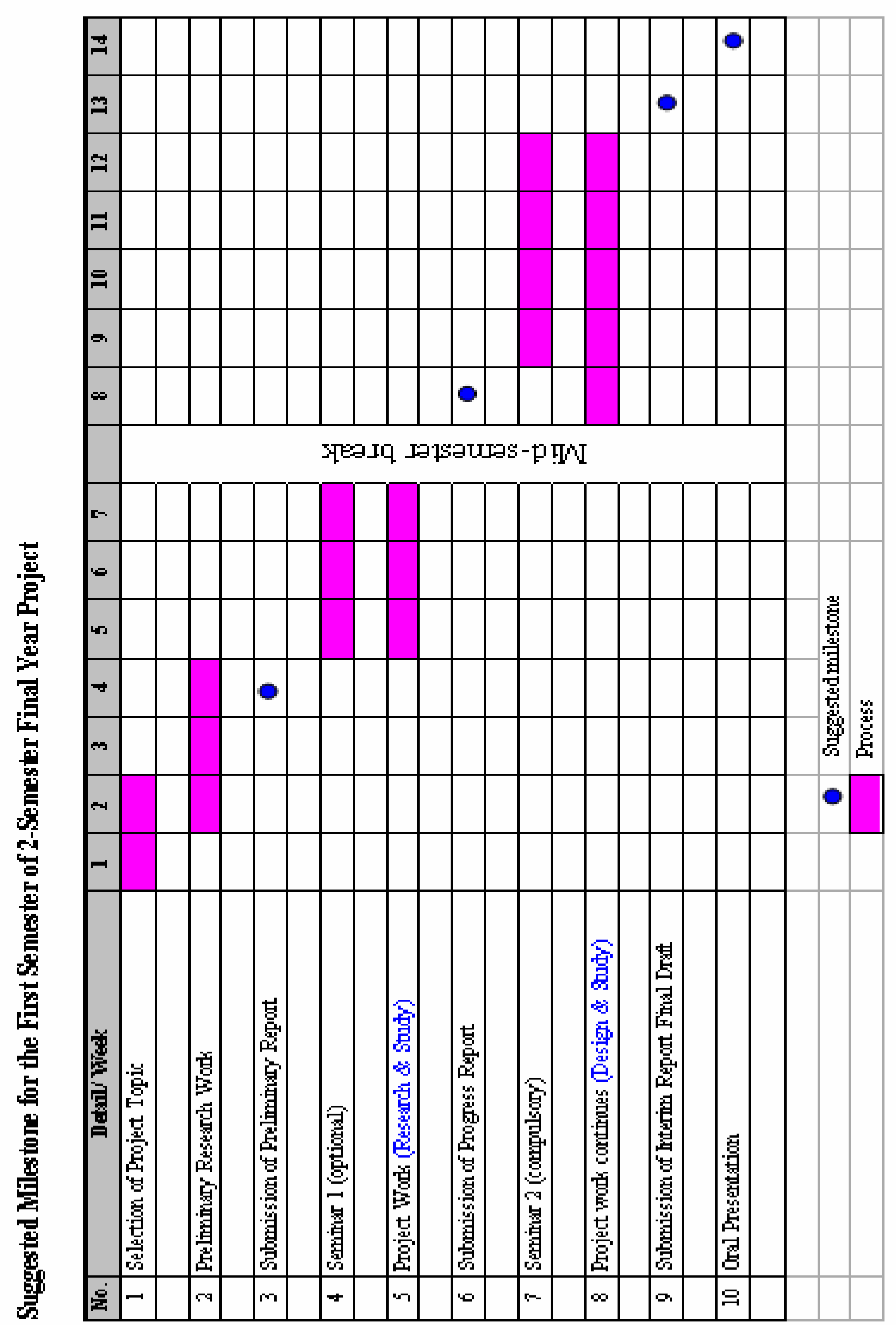


Figure 1: Suggested Milestone for Final Year Project – Semester 1

APPENDIX 2 – Second Semester Gantt chart

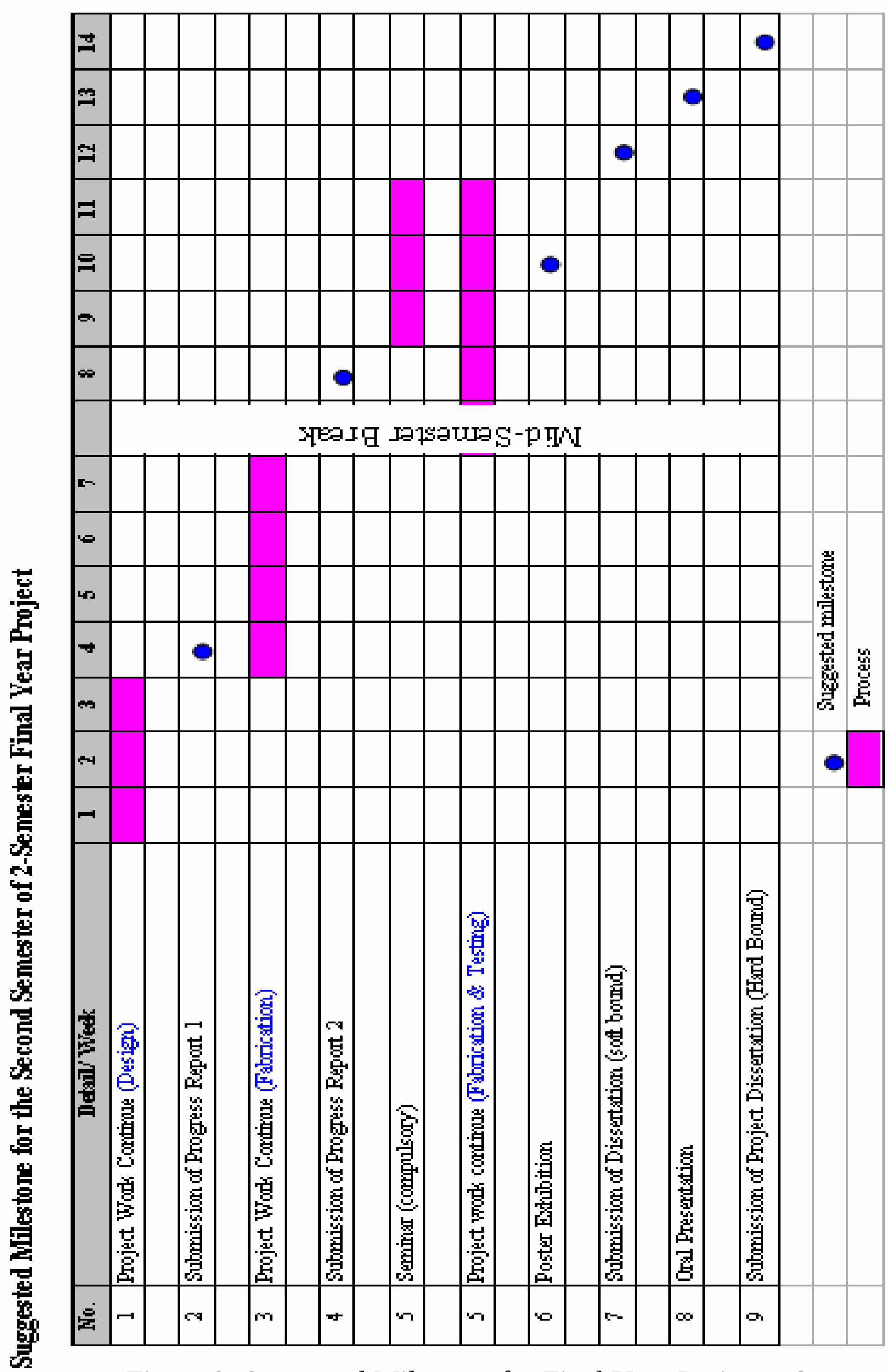


Figure 2: Suggested Milestone for Final Year Project – Semester 2

APPENDIX 3 – Reviewed Paper

Table 1: Reviewed Papers

PAPER/ ARTICLE TITLE	Hydraulic Engineering : Design and Construction	Simulation Helps TESMA Reduce Water Pump Manufacturing Cost
OBJECTIVE	Design and analyze the designs of submersible vehicle propeller for optimization of its performance	To design a new automotive water pump that met all design requirement while being considerably less expensive to build rather than the initial concept design
METHOD	(1) Design the propeller using CATIA V5. 3 main designs have been chosen to be analyzed which are: -Design I: basic design of turbine compressor blade of turbomachinery industry -Design II:A typical 4 blades submersible propeller selected based on the design of existing propeller design in marine industry -Design III: Modified design based on the Design II (2) Design from CATIA V5 were converted into '.igs' format so that is could be transferred into ANSYS program (3) Analyzing stage: - Design I: CFD analysis conducted in a 2-d FLOTRAN analysis -Design II and III: CFD analysis conducted in 3-d	(1) Design the pump using computer aided system (CAD) (2) The design exported to the FLUENT software in FTL format (3) GAMBIT preprocessor from FLUENT used to generate surface mesh over the problem domain - Tetrahedral elements selected for fast mesh setup - Hexahedral elements were chosen for critical areas such as the gap between the teeth of impeller and the shroud (4) The mesh exported to another FLUENT program known as TGrid, where the quality of surface mesh checked and made correction where necessary (5) Volume mesh generated and check the its quality afterwards (6) To rotate the impeller, multiple reference frames (MRF) model used where the impeller is at rest in a rotating frame and the

		shroud is in stationery frame (7) A steady transfer of information across a pre-defined interface between the two frames (8) Boundary condition for the model is mass flow inlet and pressure outlet. k-e turbulence model used with a standard wall function (9) the model solved and the results particularly pump head and hydraulic effiency
RESULT	Design I: a basic design of turbine compressor blade was created Design II: the design that is similar to Kaplan propeller with several limitation when designing exact replication Design III: the modification made on the propeller does effect the performance	Testing results match the analysis predictions very closely. The difference between analysis and testing is between 5% and 10%. The difference is stable enough that it is possible to predict the performance of proposed design with even higher levels of accuracy
CONCLUSION	The application of CFD used in this project to the analysis of flow through propeller blades can provide very detailed qualitative information about 3D flow field	Analysis show that the initial design met the performance requirement of the application

APPENDIX 4 – Suggested Methods

Table 2: Suggested Methods

TITLE	Design of The New Pump Impeller With An Optimize Pump Performance
OBJECTIVE	-Design the new centrifugal pump impeller -Analyze the impeller using computer simulation to determine the pump performance
METHODS	a) Define the topic and plan for future work b) Make research regarding the topic selected c) Design the centrifugal pump impeller - AUTOCAD used to design 2D impeller - CATIA used to generate 3D design impeller d) The design exported to the FLUENT program e) Surface mesh and volume mesh will be done using FLUENT program f) MRF used to rotate the impeller while the shroud is in the stationary state g) The operating parameter will be set h) Run the simulation i) The result will be taken before, during and after simulation test
EXPECTED RESULT	The design of the pump impeller has been done in 2D and 3D model. The analysis performed on the design impeller. Based on the result on the simulation, the impeller design met all performance requirement
CONCLUSION	The application of CFD techniques used in this project to the analysis of the flow through impeller parts can provide very detailed qualitative information about 3D flow field.

APPENDIX 5 – Centrifugal Pumps - Material and Gasket Groups Relative to Pumped Media

Table 3: Pumps - Material and Gasket Groups Relative to Pumped Media

SERVICE GROUP		PUMPED MEDIUM	TEMP (°C)	PUMP MATERIAL GROUP	GASKET MATERIAL GROUP	REMARKS/ NOTES
a	1	All oil and chemical products, non-corrosive	0 to 450	2	G10, G11	
	2	All oil products, non-corrosive	> 450	9	G10, G11	-
	3	Oil products containing napthenic acids (acid number above 0.5 mg KOH/g) except short residue	240 to 400	12	G8, G11	Note 13
	4	Short residue containing napthenic acids (acid number above 0.5 mg KOH/g)	> 300	9, 12	G7, G8, G11	Note 13
	5	Oil products containing sulphur compounds	> 300	9, 12	G7, G8, G11	Note 13
	6	Oil products containing a corrosive aqueous phase		10, 11, 15	G11	Note 1
	7	Crude distilling unit reflux	≤ 240	2	G10, G11	
b	1	Fresh water		1, 2	G11	Note 2
	2	Fresh cooling water, air-free closed circuit or inhibited open circuit		2	G11	
	3	Condensate, non-aerated		2	G11	Note 12
	4	Condensate, aerated		9, 12	G11	
	5	Brackish water		1, 16, 17, 18, 19	G11	Note 3
	6	Seawater, brine (seawater distiller)		13, 16, 17, 18, 19	G11	Note 10
	7	Boiler feed water, aerated		9, 12	G11	
	8	Boiler feed water, de-aerated		3, 12	G11	Note 12
	9	Sour water, pH ≤ 7		15	G11	Note 4
	10	Sour water, pH> 7		10	G11	Note 4
	11	Drain water, slightly acidic, non-aerated		15	G11	
c	2	All products, non-corrosive, low temperatures	-55 to -105	8	G7, G11	Note 5
	3		-105 to -200	14	G7, G11	Note 5, 6, 7
d	1	Caustic solutions, all concentrations	≤ 40	2	G7	
	2		40 to 100	12	G7	
	3		> 100	10, 20, 21	G6, G12	
e	1	ADOS	300 to 350	12	G8, G11	
f	1	Toxic or lethal liquids, non - cprrosive	0 to 45	7	G11	Ref DEP 30.10.02.31-Gen

APPENDIX 6 – Centrifugal Pumps - Material selection relative to pump material group

Table 4: Pumps - Material and Gasket Groups Relative to Pumped Media

Pump Material Group	Casing	Impeller	Shaft	Casing Wear Ring	Impeller Wear Ring	Inter-stage Bushings	Inter-stage Sleeves	Wet Bolting	Remarks
1	ASTM A 395	ASTM B 584-C90500 or ASTM B 148-C95800	ASTM A 276-Tp316 or **suitable ferritic stainless steel	ASTM A 48-No. 40	ASTM B 584-C90500 or ASTM B 148-C95800	ASTM A 48-No. 40	ASTM B 584-C90500 or ASTM B 148-C95800	*ASTM B 150-C63200 for impeller and A 193-B6 for casing	*Impeller and flange bolts for vertical submerged pumps. **Principal's approval required
2	ASTM A 216-WCA or WCC or ASTM A 516-Gr 55, welded and PWHT'd or ASTM A 395	ASTM A 48 No. 40 (max. tip speed 55 m/s, max. temp. 200°C) or ASTM A 216-WCA or WCC above 200 °C	Carbon steel up to 300°C' ASTM A 322-Gr 4140 above 300°C	AISI 420 (225-275 HB)	AISI 420 (325-375 HB)	ASTM A 48-No. 60	AISI 420 (325-375 HB)	ASTM A 193-B6	
3	ASTM A 216-WCA or WCC or ASTM A 516-Gr 55, welded and PWHT'd or ASTM A 395	*ASTM A 743-CA15	Carbon steel	**AISI 420 (225-275 HB)	**AISI 420 (325-375 HB)	**AISI 420 (225-275 HB)	**AISI 420 (325-375 HB)	ASTM A 193-B6	*Diffusers also ASTM A 743-CA15. **or manufacturer's standard, subject to Principal's approval
4	ASTM A 352-LCB	ASTM A 494-M-35-1	Carbon steel (suitably protected)	Monel 400	Monel 400, overlaid with Colmonoy 6	Monel 400	Monel 400, overlaid with Colmonoy 6	ASTM F 467/468-N05500	
5	ASTM A 352-LCB	ASTM A 743-CA15	Carbon steel	AISI 420 (225-275 HB)	AISI 420 (325-375 HB)	AISI 420 (225-275 HB)	AISI 420 (325-375 HB)	ASTM A 193-B6	-Refer to DEP 30.10.02.31-Gen. -For pumps without a stuffing box.

APPENDIX 7 – Impeller Layout (Plan View of Impeller Profile)

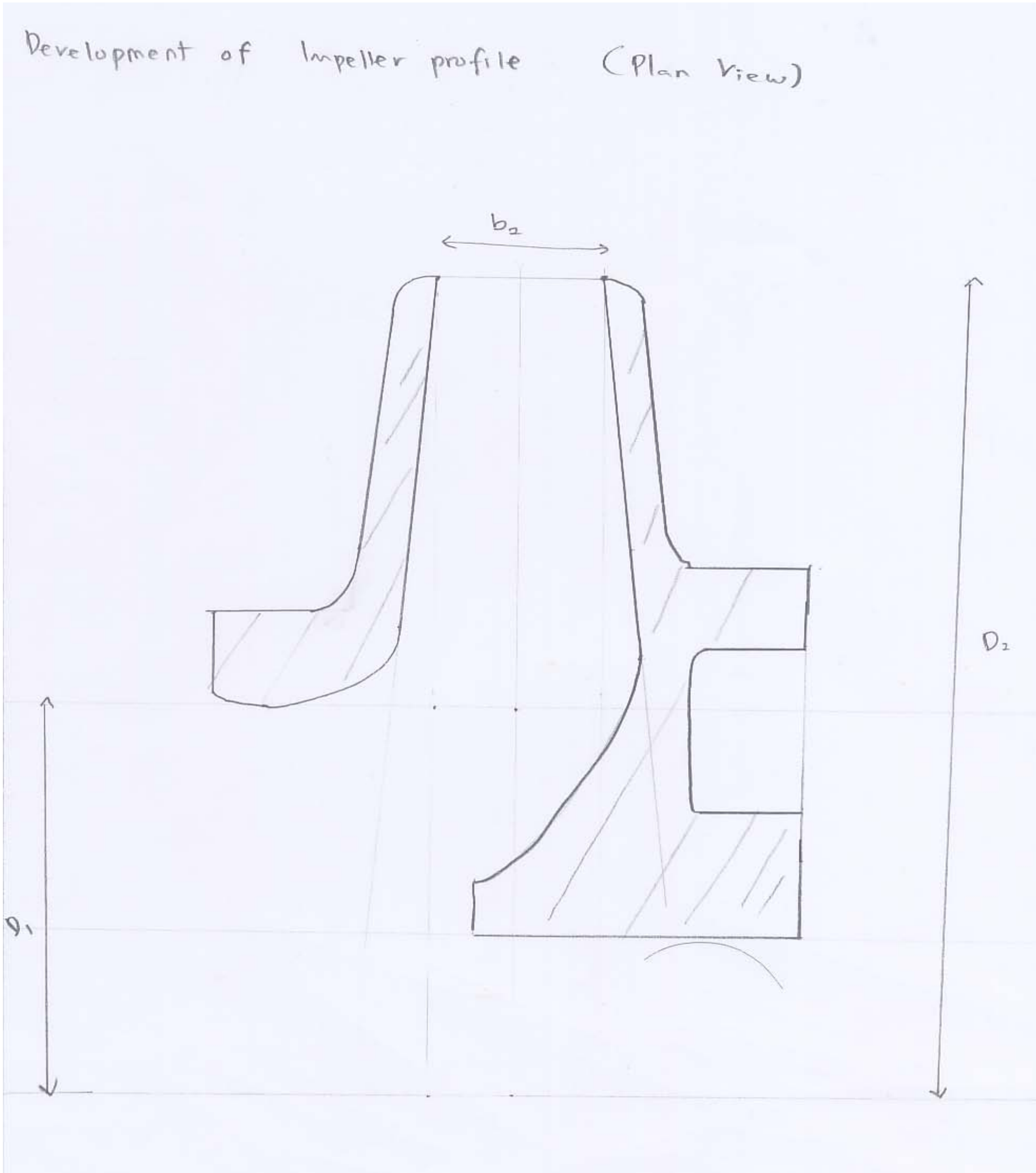


Figure 3: Impeller Layout (Plan View of Impeller Profile)

APPENDIX 8 – Impeller Layout Construction

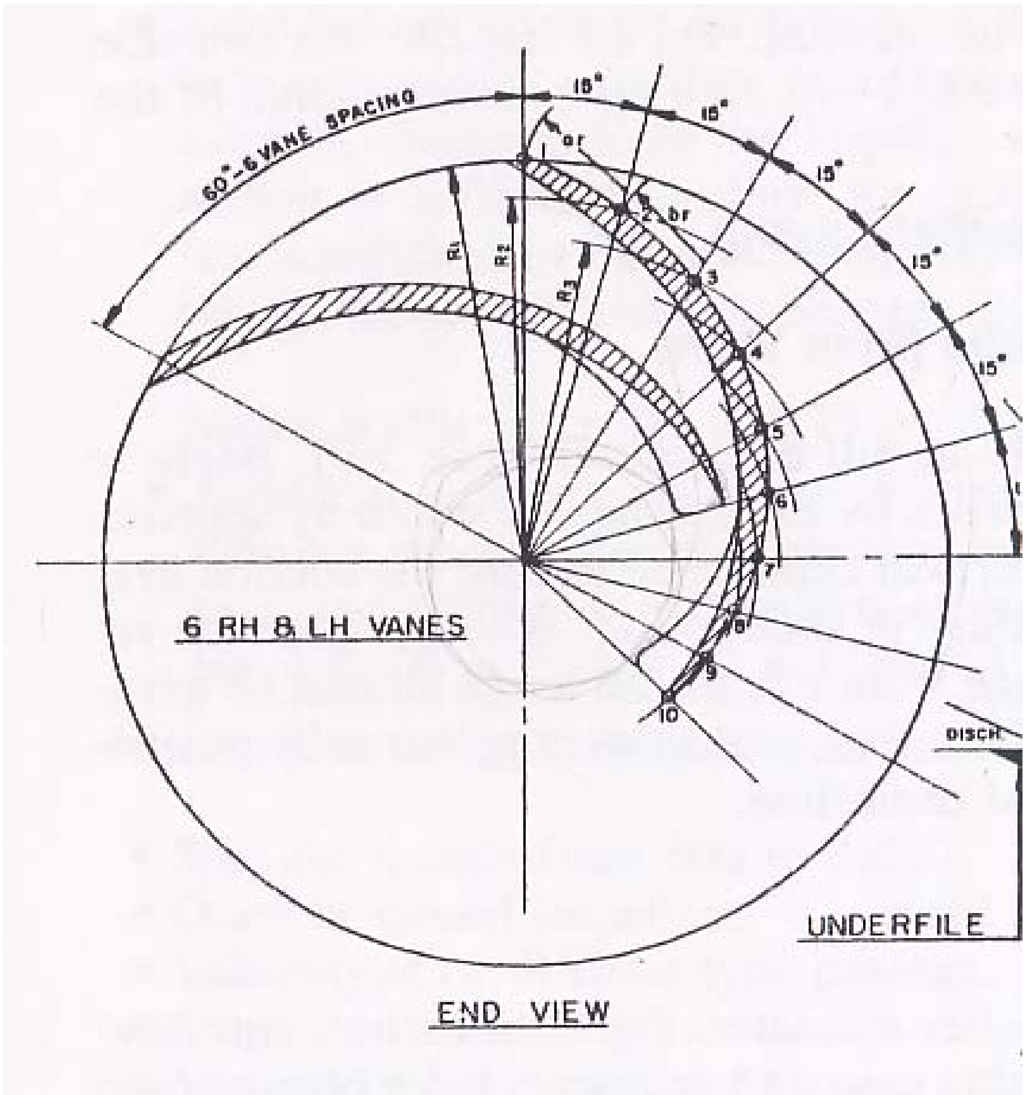


Figure 4: Impeller Layout Construction

APPENDIX 9 – Basic Design of Volute

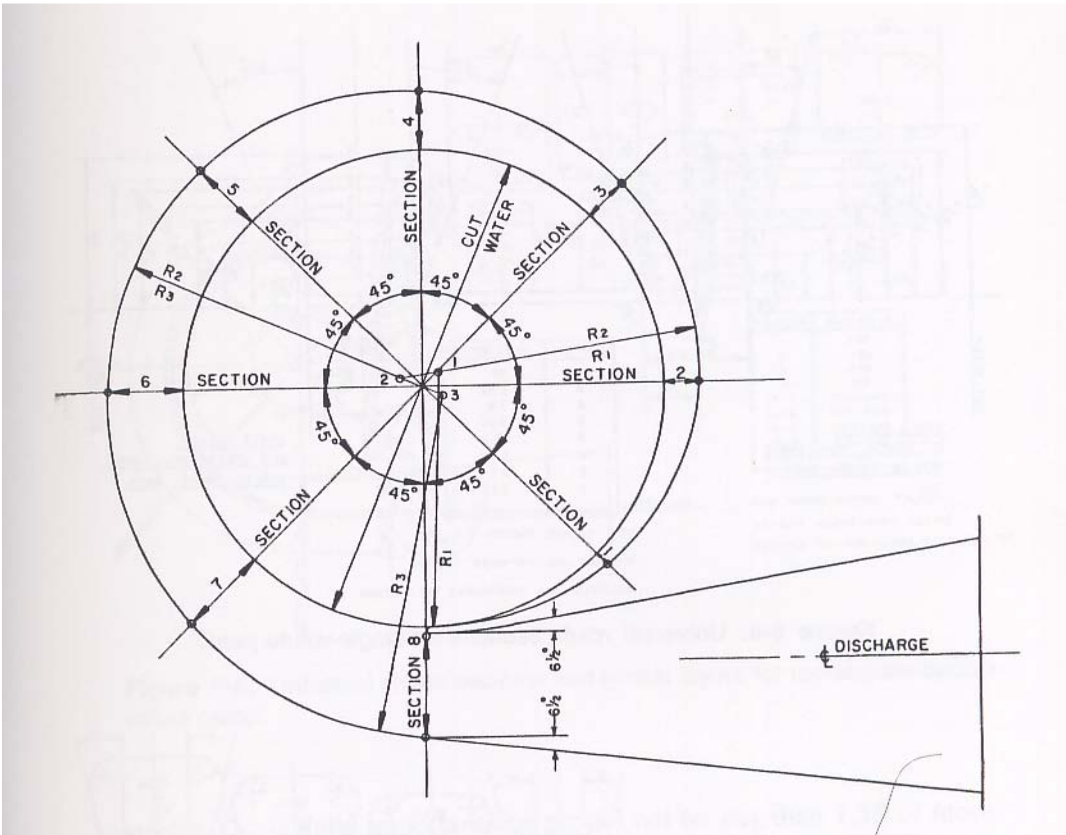


Figure 5: Basic Design of Volute

APPENDIX10 – Gray Cast Iron Properties

Table 5: Gray Cast Iron Properties

IRON	Shear			Modulus of Elasticity			
ASTM Number	Tensile strength KPSI	Compressive strength KPSI	modulus of rupture KPSI	MPSI		Endurance limit KPSI	Brinell Hardness Hb
				Tension	Torsion		
20	22	83	26	9.6 - 14	3.9 - 5.6	10	156
25	26	97	32	11.5 - 14.8	4.6 - 6.0	11.5	174
30	31	109	40	13.0 - 16.4	5.6 - 6.6	14	201
35	36.5	124	48.5	14.5 - 17.2	5.8 - 6.9	16	212
40	42.5	140	57	16.0 - 20	6.4 - 7.8	18.5	235
50	52.5	164	73	18.8 - 22.8	7.2 - 8.0	21.5	262
60	62.5	187.5	88.5	20.4 - 23.5	7.8 - 8.5	24.5	302
AISI-SAE STEEL	Tensile strength KPSI		Yeild	MPSI		Brinell Hardness Hb	Brinell Hardness Hb @ 425°F
	As rolled	Heat treated	KPSI	Tension	Torsion		
1020	65	~100	48 / 80	29.5		143	~300
1050	105	145	60 / 100	30		229	375
1095	140	216	83 / 139	30		293	388

APPENDIX11 – First Draft to Perform 2D Simulation Using Multiple Reference Frame technique

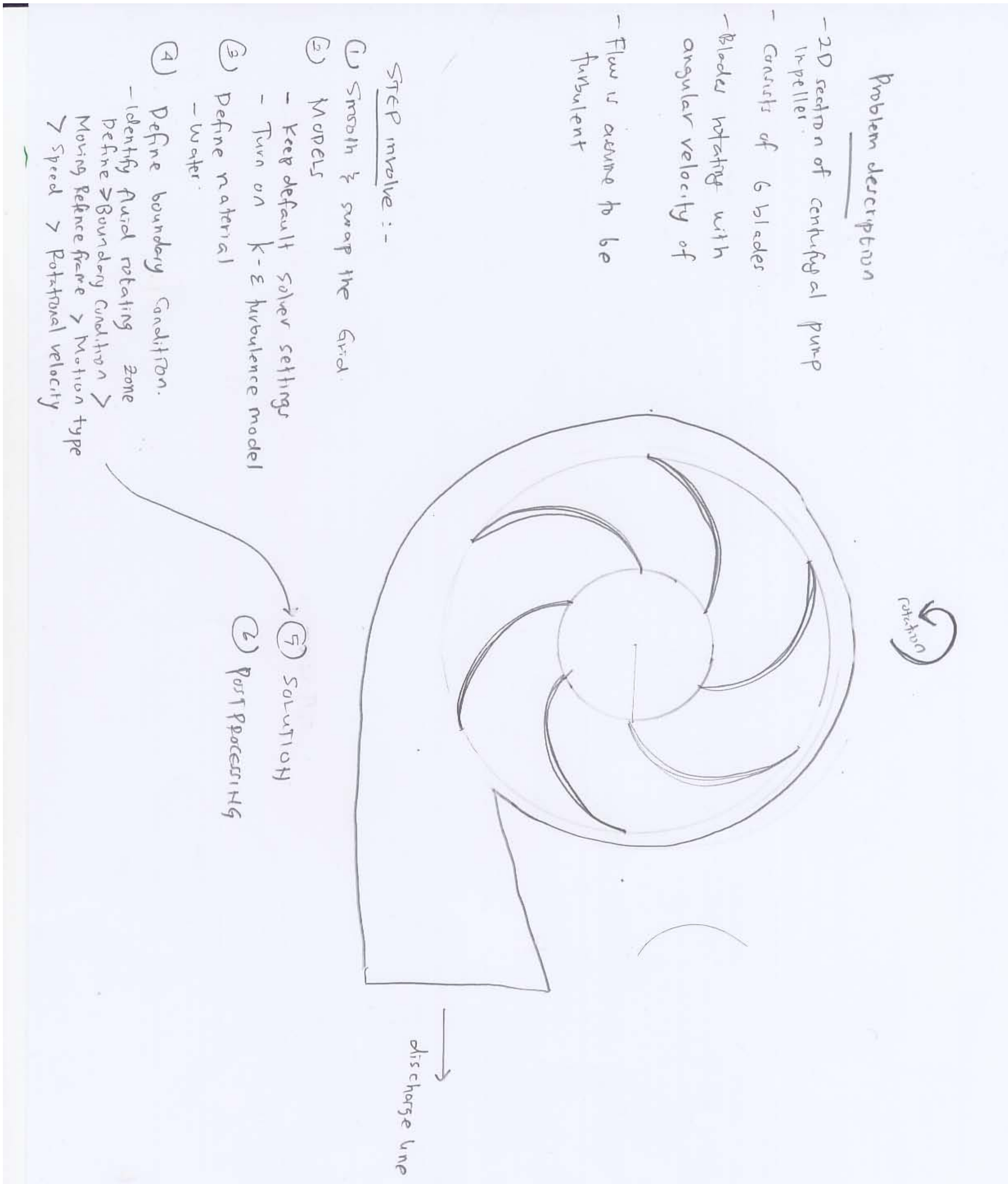


Figure 6: First Draft to Perform 2D Simulation Using Multiple Reference Frame technique