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Department of Mining Engineering

3D Design and Numerical Simulation of a Refinery Centrifugal Pump

A Project Submitted As Partial Fulfillment for the Requirements of the

Degree of Bachelor of Science in Mining Engineering

SUBMITTED BY

Mohammed Muthana Mohammed **Zakaria Douraid Najeeb**

Mustafa Khaled Abdulkarim **Hassan Safwan Hazem**

SUPERVISIED BY

Dr. Ahmed M. Daabo **Mrs. Shahd S.Ibrahim**

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Abstract

This study focused on designing and, aerodynamically, improving a petroleum pump, numerically, using ANSYS software i.e. CFX application. After designing the main two parts of the pump, volute part and rotor part, the main work aimed for enhancing the pump’s performance by focusing on improving the rotating part as it has a direct influence on the pump’s overall efficiency. The study was 3D analysis and the effect of fluid properties was taken into account by defining the fluid properties. The rotor blade shape was modified based on changing some of its parameters and the relationships between head, efficiency and power with the values of the blade angle were figured out, where the objective was to achieve maximum pump’s efficiency and reducing the consumed power. The results showed that the twist angle of 24.5^o from shroud side and 35.5^o from hup side were the ideal value for highest efficiency of (95.75%).

Acknowledgment

For God...

For home...

For the humanity of man in a comfortable time..!!

For my Colleagues, they are falcons who love to travel.

They desire freedom for their insides

Filled with passion, longing, and memories.

For those

They were a beacon and a sun that lit up the darkness of our path and the darkness inside us by knowledge and light.

For everyone who taught me letter in this mortal world.

Contents

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Nomenclature

Symbols

P	Pressure (pa)
ρ	Density (kg/ m^3)
V	Velocity (m/s)
g	Gravitational acceleration (m/s^2)
h	Height (m)
L	Pipe length (m)
D	Pipe diameter (m)
Q	Volume flow rate (m^3/s)
A	Area of the flow section (m^2)
N	Pump rotation speed (rpm)
H	Potential Energy Head (m)
η	Efficiency of the pump (%)
K	friction constant in joint

CHAPTER ONE

1. Introduction

1.1 Backgrounds

The transfer of liquids against gravity existed from time immemorial. A pump is one such device that expends energy to raise, transport, or compress liquids. The earliest known pump devices go back a few thousand years. [1]

The ancient Egyptians invented water wheels with buckets mounted on them to transfer water for irrigation. More than 2000 years ago, a Greek inventor, Ctesibius, made a similar type of pump for pumping water. During the same period, Archimedes, a Greek mathematician, invented what is now known as the 'Archimedes' screw' - a pump designed like a screw rotating within a cylinder. [1]

1.2 What is a centrifugal pump?

A centrifugal pump is a mechanical device designed to move a fluid by means of the transfer of rotational energy from one or more driven rotors, called impellers. Fluid enters the rapidly rotating impeller along its axis and is cast out by centrifugal force along its circumference through the impeller’s vane tips. The action of the impeller increases the fluid’s velocity and pressure and also directs it towards the pump outlet. The pump casing is specially designed to constrict the fluid from the pump inlet, direct it into the impeller and then slow and control the fluid before discharge [2].

1.2.1.For example (characterization of centrifugal pumps)

There are dozens of pumps that are designed in various sizes and capacities to suit all requirements, and are manufactured from different materials such as cast iron, carbon steel and others. In this project we will focus on centrifugal pumps because they are characterized by [3].

1. Suitable for a wide range of operating speeds.
2. The amount of disbursement and the compressor depends on the fan's rotational speed, diameter and width.
3. The horsepower to run it depends on the disposition, compressor and pump efficiency.
4. The total hydraulic pressure increases and the horsepower decreases as the action decreases when the speed is constant vice versa.
5. The performance of the pumps can be affected by the change of the pump or the motor or both.

1.3 Main components of the centrifugal pump

1. Shaft
2. Impeller
3. Casing
4. Stuffing Boxes
5. Wearing Rings

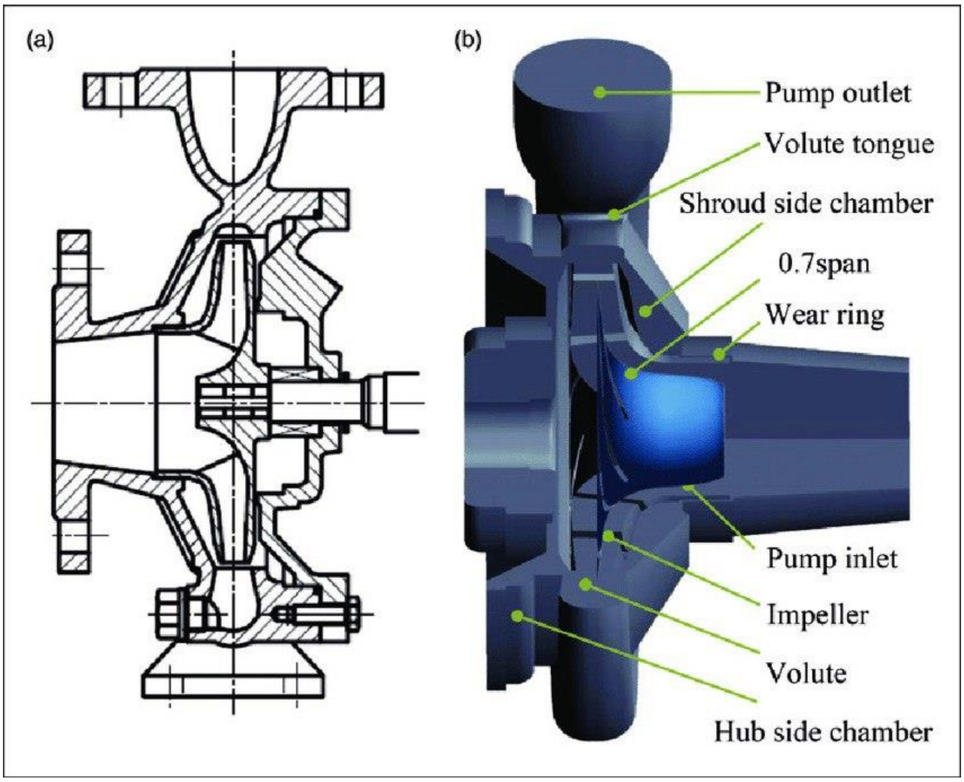


Figure 1: Components of the centrifugal pump [1].

1.3.1 Shaft and shaft sleeve

The shaft is a central part of the pump, which rotates with the connected impeller. It is coupled with the prime mover to get the power. The shaft fits with the ball bearing. Shaft sleeve is also employed, which prevents the shaft of the pump from leakage and corrosion. One end of the sleeve should be sealed [2].

1.3.2 Impeller

The impeller consists of a series of backward-curved vanes. It is mounted to the shaft of an electric motor. An impeller is a rotating part of the centrifugal pump. It is enclosed in a watertight casing. The centrifugal pump impeller is divided into three types [2]:Figure2 shows the impeller types.

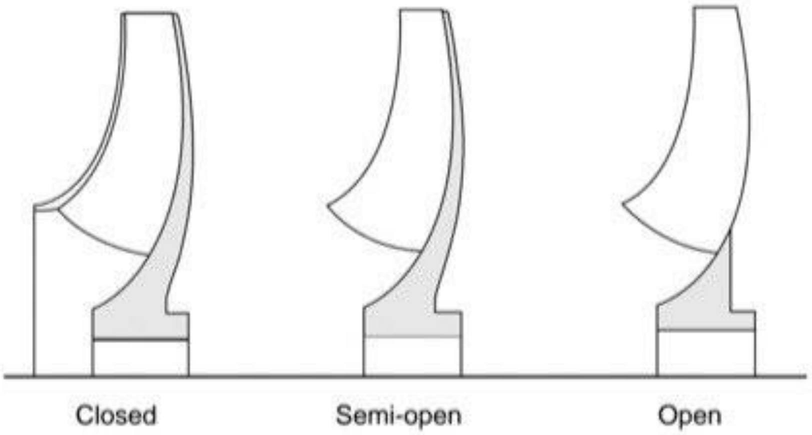


Figure 2 type of impeller [1].

a) Open Impeller

An open impeller consists of vanes attached to a central hub and mounted directly on the shaft. The vanes have no walls or cover around them, making open impellers weaker than closed valves. Still, these are generally quick and easy to clean and repair.

b) Closed Impeller

The closed impeller has both front and back cover plates. In this, the impeller vanes are sandwiched between two cover plates. These are installed in radial flow centrifugal pumps and can be either single or double inlets.

c) Semi-open impeller

Semi-open impellers have a back-wall cover plate that gives mechanical power to the van, while the other side remains open. Semi-open impellers are used in medium-sized pumps. This impeller is designed for debris-loading fluid [2].

1.3.3 Casing

The casing is an airtight passage surrounding the impeller. It is designed in such a way that the kinetic energy of the water discharged at the outlet is converted into pressure energy before the water leaves the casing and enters the delivery pipe [2].

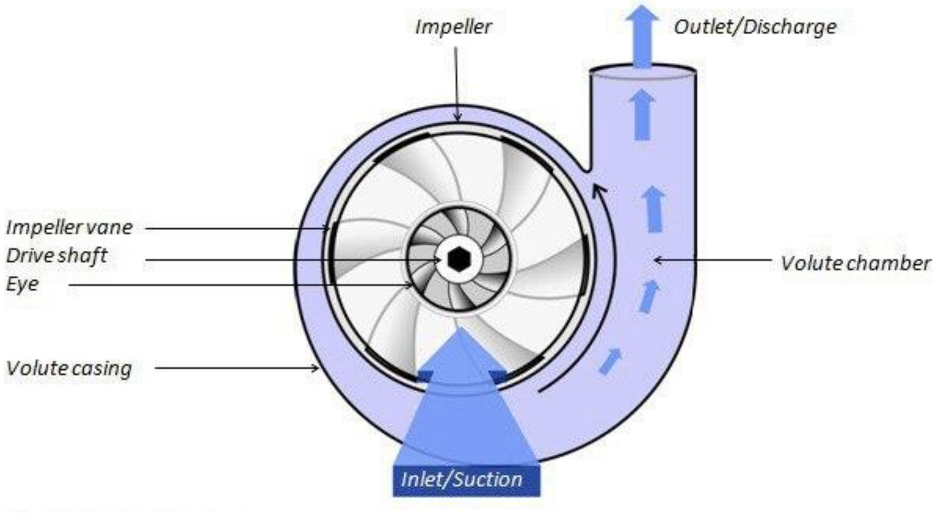


Figure 3: Volute casing design [2].

The casing works as a cover to protect the system.Figure 3 presents the volute casing. The casing of the centrifugal pump is further classified into three types.

a) Volute casing (Spiral casing)

It is surrounded by the impeller. Such a casing provides a gradual increase in the area of a flow, thus decreasing the velocity of water and correspondingly increasing the pressure.

b) Vortex casing

A vortex casing is a circular chamber introduced between the impeller and casing. Here the fluid from the impeller has to first pass through the vortex chamber and then through the volute casing. In such a case, there is a better conversion done that is velocity energy into pressure, and it has good efficiency than the volute casing.

c) Casing with Guide Blades

In casing with guide blades, the blades surround the impeller. These blades are designed and arranged in such a way that the water from the impeller enters the guide vane without shock and creates a passage of increasing area, through which the water passes and reaches the delivery to leave with pressure [2].

1.3.4 Stuffing box

It is obvious during the operation of the pump that the impeller is completely immersed in the fluid in addition to that it takes its movement from a shaft whose end passes through the pump casing Therefore a means must be found to prevent the fluid from leaking around this column so the stuffing box is used which is a body with a cylindrical cavity with a diameter greater than the diameter of the column that surrounds it The filling material fills the space between them and is then pressed by means of a threaded cylindrical sleeve that is installed from one end [2].

1.3.5 Wearing rings

It is used in the pump to ensure easy rotation of the impeller inside the casing with the least clearance to reduce water leakage. One of these rings is installed with the casing, while the other is installed with the impeller and is replaced when it wears out and the clearance increases in a way that affects the performance of the pump [2].

1.4 What are the main applications for centrifugal pumps?

Centrifugal pumps are commonly used for pumping water, solvents, organics, oils, acids, bases and any ‘thin’ liquids in both industrial, agricultural and domestic applications [2].

1.5 How does a centrifugal pump work?

The impeller is the key component of a centrifugal pump. It consists of a series of curved vanes. These are normally sandwiched between two discs (an enclosed impeller). For fluids with entrained solids, an open or semi-open impeller (backed by a single disc) is preferred .Fluid enters the impeller at its axis (the ‘eye’) and exits along the circumference between the vanes. The impeller, on the opposite side to the eye, is connected through a drive shaft to a motor and rotated at high speed (typically 500-5000rpm). The rotational motion of the impeller accelerates the fluid out through the impeller vanes into the pump casing.

There are two basic designs of pump casing: volute and diffuser. The purpose in both designs is to translate the fluid flow into a controlled discharge at pressure.

In a volute casing, the impeller is offset, effectively creating a curved funnel with an increasing cross-sectional area towards the pump outlet. This design causes the fluid pressure to increase towards the outlet. The same basic principle applies to diffuser designs. In this case, the fluid pressure increases as fluid is expelled between a set of stationary vanes surrounding the impeller. Diffuser designs can be tailored for specific applications and can therefore be more efficient. Volute cases are better suited to applications involving entrained solids or high viscosity fluids when it is advantageous to avoid the added constrictions of diffuser vanes. The asymmetry of the volute design can result in greater wear on the impeller and drive shaft [2].

CHAPTER TWO

2. Literature review

E.C. Bacharoudis et al. (2008) in this study, the performance of impellers with the same outlet diameter having different outlet blade angles is thoroughly evaluated. The One-dimensional approach along with empirical equations is adopted for the design of each impeller. The predicted performance curves result through the calculation of the internal flow field. Head-discharge curve play important role into different outlet angles. The influence of the outlet blade angle on the performance is verified with the CFD. The performance curve becomes smoother and flatter with the increase with the increase outlet blade angle. At nominal capacity, when the outlet blade angle was increased from 20° to 50°, the head was increased by more than 6% but the hydraulic efficiency was reduced by 4.5%. However, at high flow rates, the increase of the outlet blade angle caused a significant improvement of the hydraulic efficiency [5].

LIU Houlin, et al. (2010) add verb they found that the blade number play the important role during designing the pump which affects the characteristics of the pump. The model pump has a design specific speed of 92.7 and an impeller with 5 blades. The blade number is varied to 4, 6, 7 with the casing and other geometric parameters keep constant. The inner flow fields and characteristics of the centrifugal pumps with different blade number are simulated and predicted in non- cavitation and caviation conditions by using commercial code FLUENT. Using rapid prototyping the impeller with different blade numbers is made. With the increase of blade number, the area of low pressure region at the suction of blade inlet grows continuously, and the uniformity of static pressure distribution at screw section become worse and worse while at diffusion section become better and better. The head of model pump is increase with the increase with pump but there is variation with efficiency and cavitation is complicated. These results are important to design of the centrifugal pump [6].

Sambhrant Srivastaava et al. (2014) discussed natural frequency and deformation of mixed flow pump impeller were evaluated considering two different blade positions in the meridional annulus. ANSYS was used for the investigation of natural frequency and deformation. It was observed that the mixed flow pump impeller with inlet inclined blade position in the meridional annulus was more suitable than the trapezoidal one [7].

Neelambika,et al. a (2014) a detailed CFD analysis was done to predict the flow pattern inside the impeller which is an active pump component. The optimum inlet and outlet vane angles are calculated for the existing impeller by using the empirical relations.This study was divided in to three cases. In the first case, outlet angle is increased by 5°. From the outlet flow conditions, obtained from the CFD analysis, it is evident that the reduced outlet recirculation and flow separation cause the improved efficiency. By changing the outlet angle the efficiency of the impeller is improved to 59%. In the second case,the inlet angle is decreased by 10%. The efficiency of the impeller in this case is 61%. From this analysis it is understood that the changes in the inlet vane angle did not change the efficiency of the impeller as much as the changes in outlet angle. For existing impeller, the head and efficiency are found out to be 19.24 m and 55% respectively. The impeller 1, the percentage increase in the head and efficiency are 3.22% and 7.27% respectively. The impeller 2, the percentage increase in the head and efficiency are 10.29% and 10.91% respectively.For the impeller 3, the percentage increase in the head and efficiency are 13.66% and 18.18% respectively. Based on the above, it is concluded that impeller 3 gives better performance [8].

CHAPTER THREE

3. Methodology

A centrifugal pump is a machine used to transfer fluid from one place to another. The basic principle behind the working of a centrifugal pump is the transfer of kinetic energy from the impeller to the fluid. This energy transfer results in an increase in the fluid's pressure and its flow rate.

The design of a centrifugal pump is an iterative process that involves several steps. The first step is to determine the design flow rate and the required head. This can be done by analyzing the system in which the pump will operate and the required operating conditions. The next step is to select the type of impeller that will be used in the pump. Impellers are designed to convert the kinetic energy of the fluid into pressure energy. The type of impeller chosen depends on the required head, the fluid properties, and the flow rate.

Once the impeller type is selected, the next step is to determine the impeller geometry. This includes the diameter, the number of blades, the blade angle, and the blade thickness. The geometry of the impeller is critical in determining the pump's performance, including its efficiency, head, and flow rate [3].

3.1 Pump Equations

3.1.1 Conservation of Energy

The law of conservation of energy states that energy cannot be created or destroyed only transferred from one form to another. In a centrifugal pump, the kinetic energy of the impeller is transferred to the fluid, resulting in an increase in the fluid's pressure and flow rate [9].

3.1.2 Mass flow rate

The law of conservation of mass states that mass cannot be created or destroyed only transferred from one location to another. In a centrifugal pump, the mass flow rate of the fluid must remain constant throughout the pump [9].

3.1.3 Bernoulli's Principle

This principle states that an increase in the fluid's velocity results in a decrease in the fluid's pressure. In a centrifugal pump, the fluid is accelerated by the impeller, which increases its velocity, and subsequently lowers the pressure within the pump [9].

$$\frac{P}{\rho g} + \frac{V^2}{2g} + h = \text{constant} \qquad (1)$$

Where P is the pressure (in pascals), ρ is the density (in kilograms per cubic meter), V is the velocity (in meters per second), g is the gravitational acceleration (in meters per second squared), and h is the height (in meters)

3.1.3.1 Head:

It is the height of the column of fluid at a certain level and it is measured in meters. It is also called the column of water corresponding to the fluid energy (Pressure energy + Kinetic energy + Potential energy) at a certain point.

Component of Head:

1- Static Section Head (h_s)
The vertical distance between the free surface of the fluid to be pumped and the center of the pump

2- Static Delivery Head (h_v)
The vertical distance between the free surface of the fluid reservoir and the center of the pump

$$h_v = \frac{v^2}{2g} \qquad (2)$$

3- Total Static Head (h_t)
The sum of Static Section Head and Static Delivery Head

$$h_t = h_s + h_v \qquad (3)$$

4- Total Manometric Head
It is total static head additional head overcome friction loss
Friction Head:
It is the loss of pressure by friction during the fluid flow in a specific path, whether in the suction line or the discharge line, and it is expressed in meters (m), this loss is classified into two main types:

a) Pressure loss in pipes:

$$h_f = f\frac{L\,v^2}{D\,2g} \qquad (4)$$

Where: the coefficient of friction depends on the type of flow and surface roughness.

L= Pipe length (m), D = pipe diameter (m), v = the velocity of the fluid inside the tube (m/s)..

b) Pressure loss in connections such as elbow joints, valves, and others. (shock)

$$h_{sh} = K\frac{v^2}{2g} \qquad (5)$$

where K friction constant in joint

5- Pump head: the total head which a pump operates is based on.[9]

$$H = h_s + h_v + h_f + h_{sh} \qquad (6)$$

3.1.4 Law of Conservation of Mass equation:

$$Q = AV \qquad (7)$$

Where Q is the flow rate (in cubic meters per second), A is the cross-sectional area of the pump (in square meters), and V is the flow velocity (in meters per second).

3.1.5 Affinity Laws:

The affinity laws relate the performance of a centrifugal pump to changes in its rotational speed, impeller diameter, and flow rate. They are given by:

a) Capacity Q change in direct proportion to the change pump speed N ratio:

$$Q_2 = Q_1 \times \frac{N_2}{N_1} \qquad (8)$$

b) Head change in direct proportion to the square of the speed N ratio:

$$H_2 = H_1 \times \left(\frac{N_2}{N_1}\right)^2 \qquad (9)$$

c) Power change in direct proportion to the cube of the speed N ratio:

$$P_2 = P_1 \times \left(\frac{N_2}{N_1}\right)^3 \qquad (10)$$

3.1.6 Specific Speed:

Specific Speed: The specific speed is a dimensionless parameter used to classify pumps based on their flow rate, head, and rotational speed. It is given by:

$$N_s = \frac{N\sqrt{Q}}{(H)^{3/4}} \qquad (11)$$

Where N_s is the specific speed, N is the rotational speed (rpm), Q is the flow rate (m^3/s), and H is the head (m).

3.1.8 Hydraulic Power: in KW

$$P_{KW} = \frac{\mathbf{Q\times\rho\times g\times H}}{\mathbf{3.9\times10^6}} \qquad \mathbf{(12)}$$

3.1.8 Pump Efficiency equation:

$$\eta = (P_{out} / P_{in}) \times 100\% \qquad (13)$$

Where η is the efficiency of the pump, Pout is the output power of the pump (in watts), and Pin is the input power to the pump (in watts).

3.2 Software Numerical

3.2.1 Software Used

ANSYS 2021R2 is a simulation software program used in engineering analysis to simulate how products and systems will behave in real-world conditions. It is a finite element analysis tool that allows engineers to model and analyze the behavior of a wide range of physical phenomena, including structural mechanics, fluid dynamics, heat transfer, electromagnetic fields, and more. With ANSYS, engineers can optimize the performance of their designs, reduce costs, and improve safety by accurately predicting how their products will perform before they are built. The program offers a range of features and tools, including pre-processing, solution, and post-processing capabilities, making it a versatile and powerful tool for engineers and researchers in various fields. Overall, ANSYS is an essential tool for any engineer or researcher seeking to design, analyze, and optimize products and systems.

3.2.2 Pump design

We have based our design on the specifications of an oil pump from Midland Refineries Company (M.R.C) in Iraq as shown in Table (1)

Considering that the impeller is open type and the casing is spiral type
They are the most suitable for oil pump design, as they are suitable for complex oil properties

	Operation Condition	
1	Liquid	Hydrocarbon
2	Capacity	252 m^3/hr.
3	Head	38.5 m
4	Density	654.78 Kg/m^3
5	Speed	1500 [rpm]
6	Temp.	45 C
7	Pressure outlet	3 bar

Table-1- Operation condition for centrifugal pump

3.2.3 Parameter changed

Two parameters have been changed

- The first is the blade angle from the shroud side
- The second is the blade angle from the hup side

Figure 5 and Figure 6 show the torsion of the blade when the angle is changed

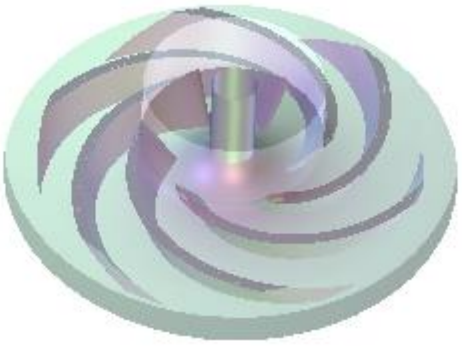


Figure 5: Blade angle = 15^{o}

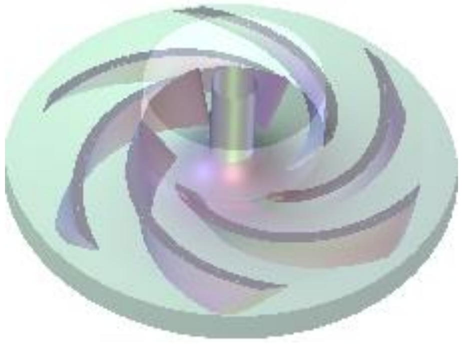
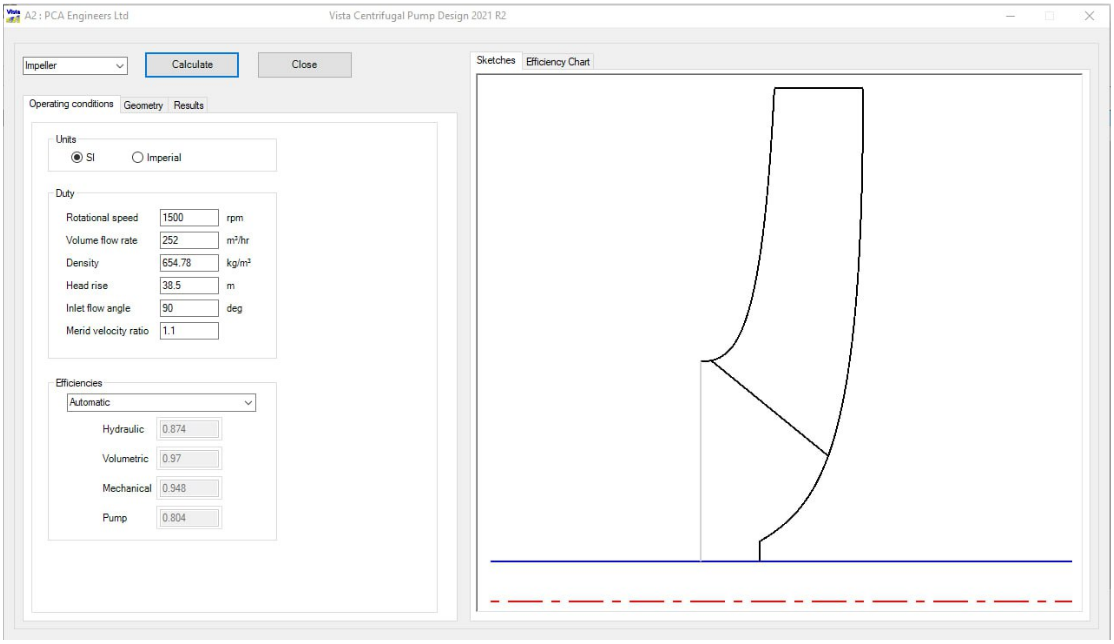


Figure 6: Blade angle = 30

3.2.3 Procedure

1. Start Workbench
2. Create "Vista CPD" from toolbox



Units
● SI ○ Imperial

Duty
Rotational speed 1500 rpm
Volume flow rate 252 m³/hr
Density 654.78 kg/m³
Head rise 38.5 m
Inlet flow angle 90 deg
Merid velocity ratio 1.1

Efficiencies
Automatic
Hydraulic 0.874
Volumetric 0.97
Mechanical 0.948
Pump 0.804

Figure 7: Screenshot of a vista CPD window.

3. Create Volute

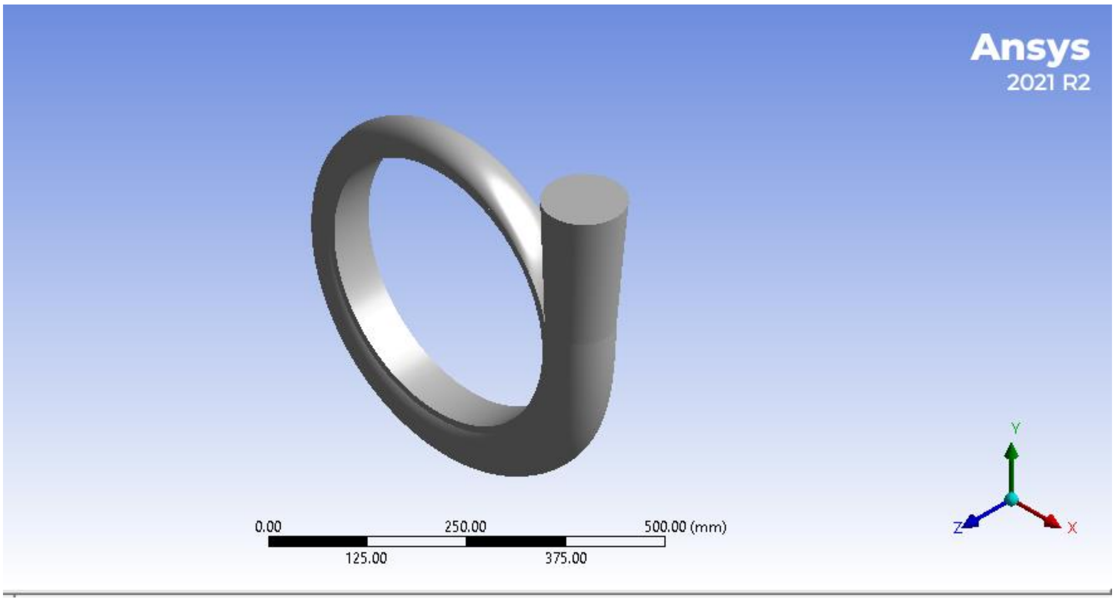


Figure 8: The volute of the designed pump.

4. Bladegen

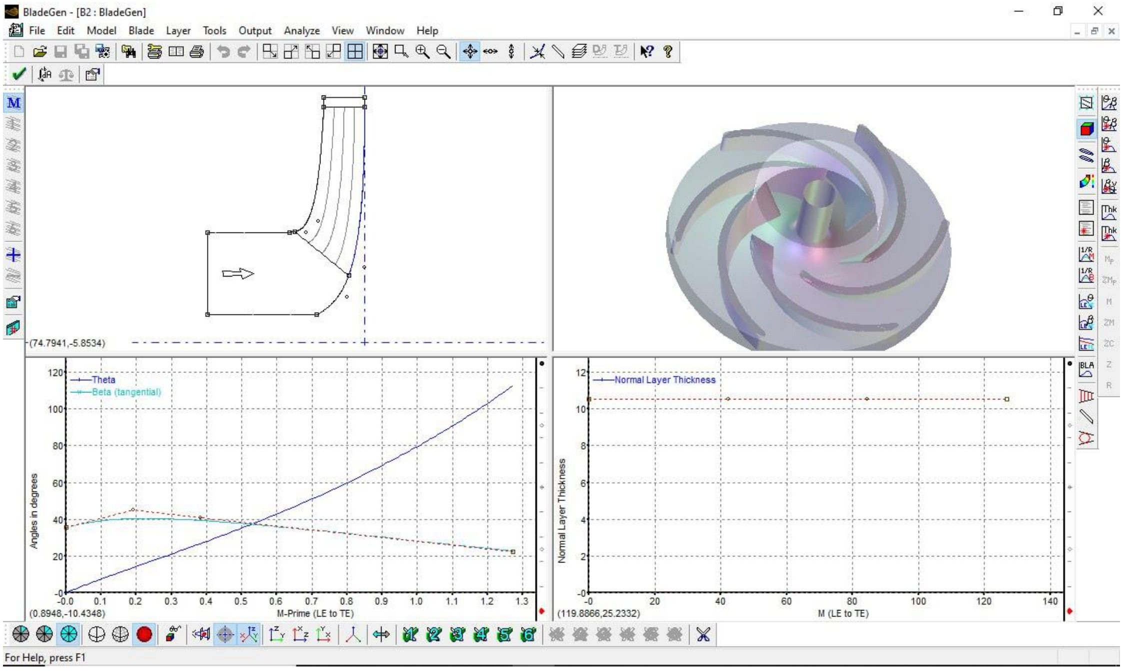


Figure 9: Screenshot of a Bladegen window.

5. Transfer data to Turbo Grid, then transfer the data to ICEM CFD:

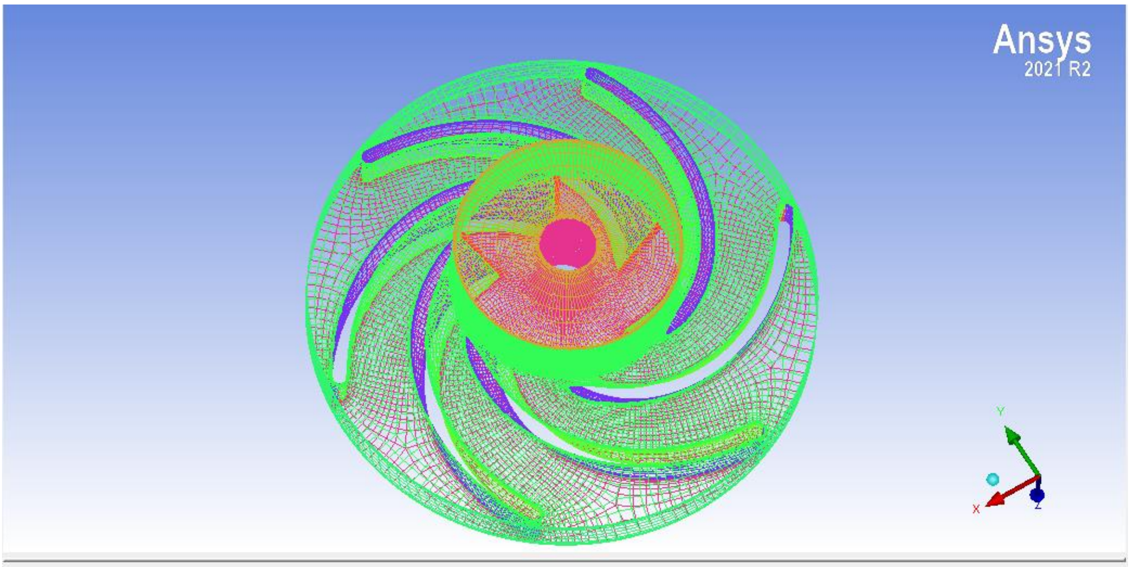
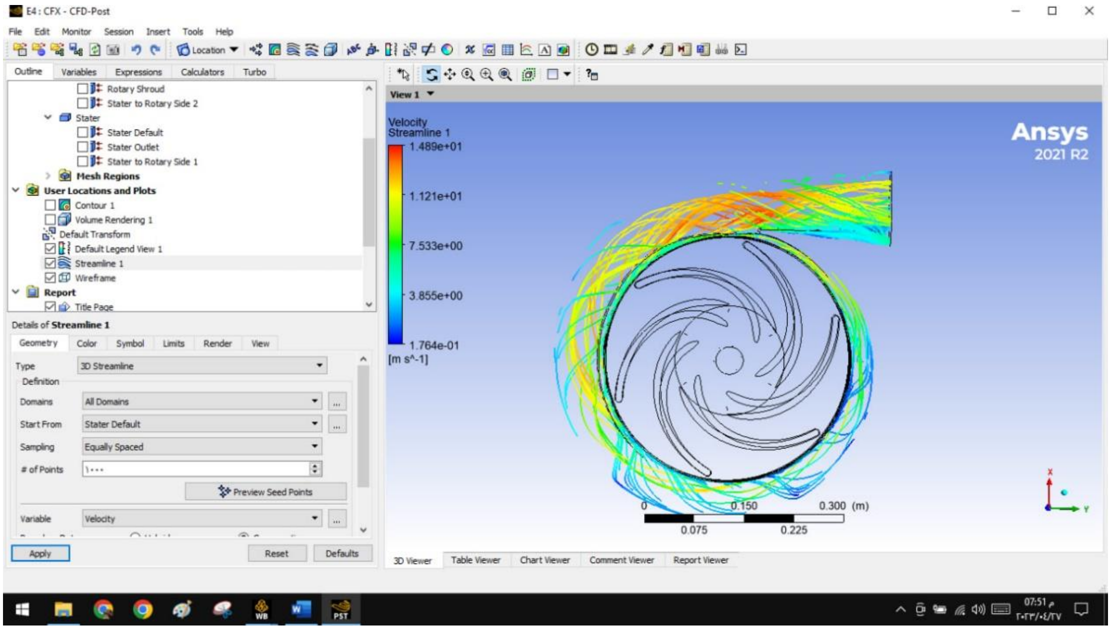


Figure 10: Meshed impeller.

6. Transfer data to CFX
7. Connection Volute with CFX
8. Solution CFX

9. Result



Details of **Streamline 1**

Geometry | Color | Symbol | Limits | Render | View

Type: 3D Streamline

Definition

Domains: All Domains

Start From: Stater Default

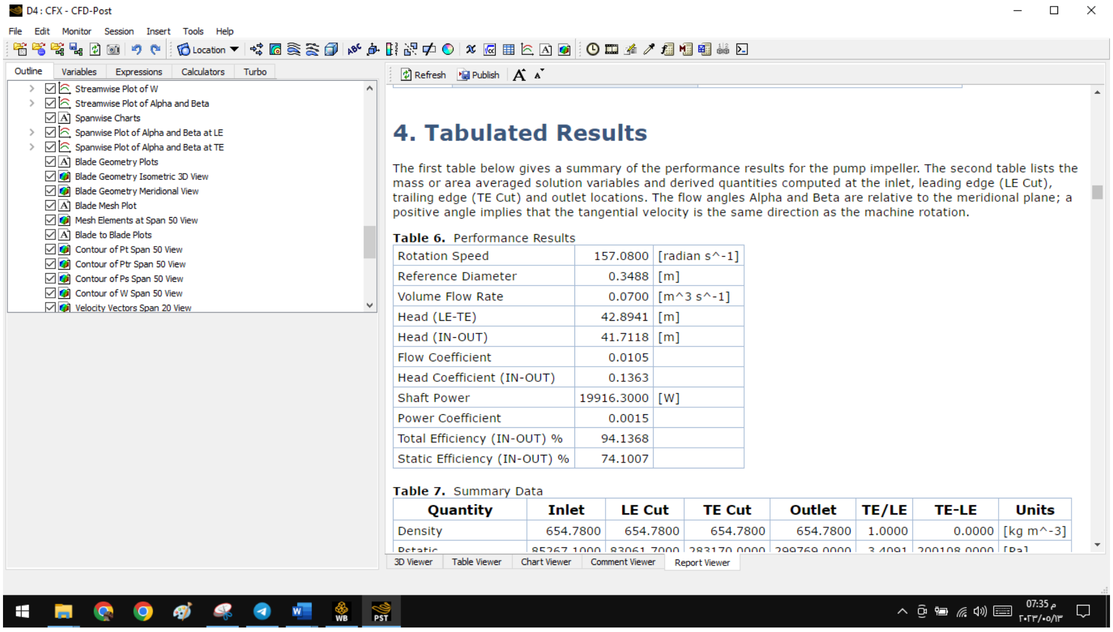
Sampling: Equally Spaced

# of Points: ١٠٠٠

Variable: Velocity

Figure11: Screenshot of the result window.

10. Impeller pump report



4. Tabulated Results

The first table below gives a summary of the performance results for the pump impeller. The second table lists the mass or area averaged solution variables and derived quantities computed at the inlet, leading edge (LE Cut), trailing edge (TE Cut) and outlet locations. The flow angles Alpha and Beta are relative to the meridional plane; a positive angle implies that the tangential velocity is the same direction as the machine rotation.

Table 6. Performance Results

Rotation Speed	157.0800	[radian s^-1]
Reference Diameter	0.3488	[m]
Volume Flow Rate	0.0700	[m^3 s^-1]
Head (LE-TE)	42.8941	[m]
Head (IN-OUT)	41.7118	[m]
Flow Coefficient	0.0105	
Head Coefficient (IN-OUT)	0.1363	
Shaft Power	19916.3000	[W]
Power Coefficient	0.0015	
Total Efficiency (IN-OUT) %	94.1368	
Static Efficiency (IN-OUT) %	74.1007	

Table 7. Summary Data

Quantity	Inlet	LE Cut	TE Cut	Outlet	TE/LE	TE-LE	Units
Density	654.7800	654.7800	654.7800	654.7800	1.0000	0.0000	[kg m^-3]

Figure12: Screenshot of the report window

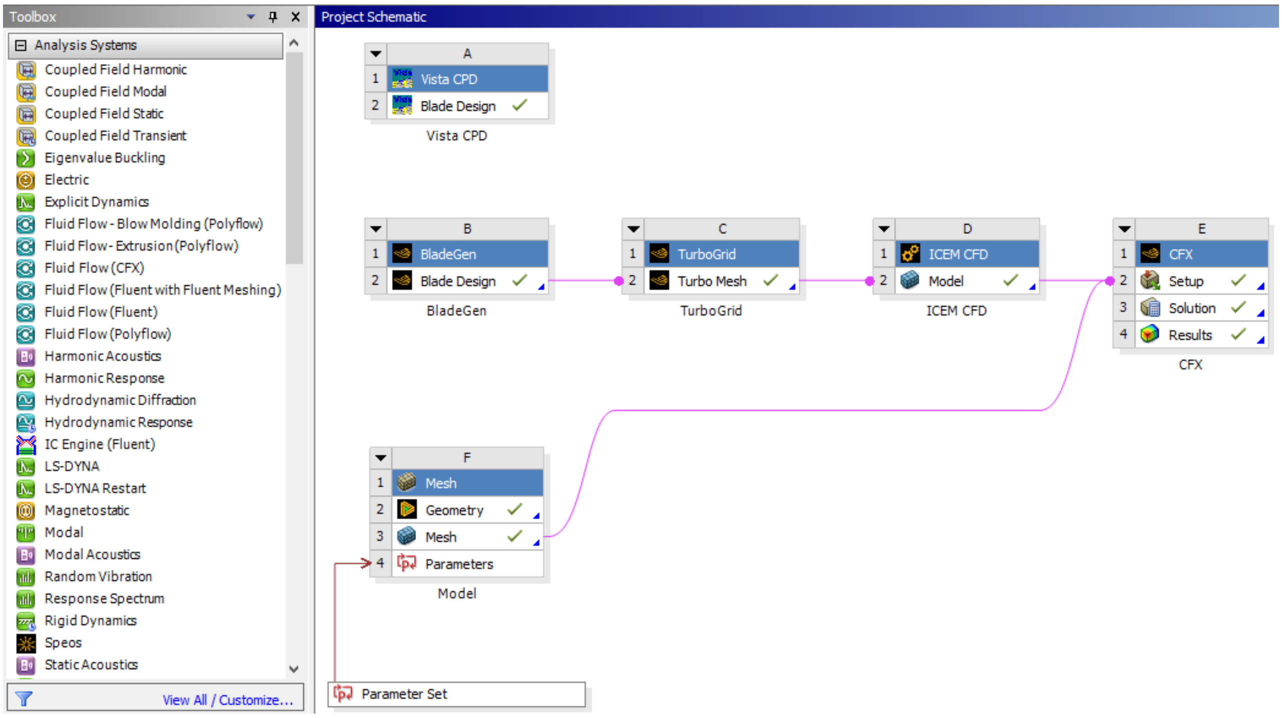


Figure 13: Toolbox of the workbench showing the complete steps of the designed pump.

CHAPTER FOUR

4. Result and Discussion

From the figure (14) it can be noticed that there is a relationship which is taken in consideration between the impeller’s blade angle and the pump head. The chart shows that whenever we decrease the blade angle then we get a shorter head and vice versa. The evidence of our context is as we see in the figure. We made many empirical runs and we figured out that the best angle is 24.5 where we get the maximum head. From this point we can give an advice of taking this angle in your designs

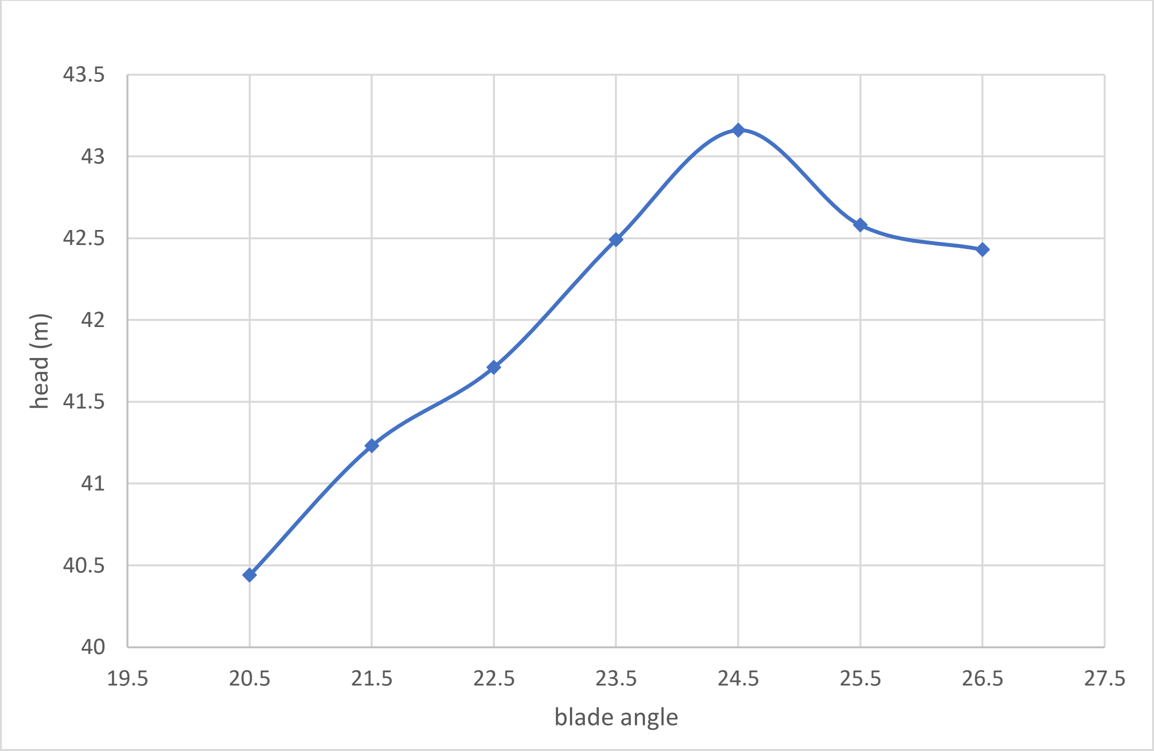


Figure 14: Variation of head with the change in blade angle (shroud) and head.

From the figure (15) it can be seen that there is a relationship which is taken in consideration between the impeller’s blade angle and its own efficiency. The chart shows that whenever we decrease the blade angle then we get worse efficiency for the impeller and vice versa. The evidence of our context is as we see in the figure. Moreover, we made many empirical runs and we figured out that the best angle is 24.5 where we get an ideal efficiency. From this point we can give an advice of taking this angle in your designs

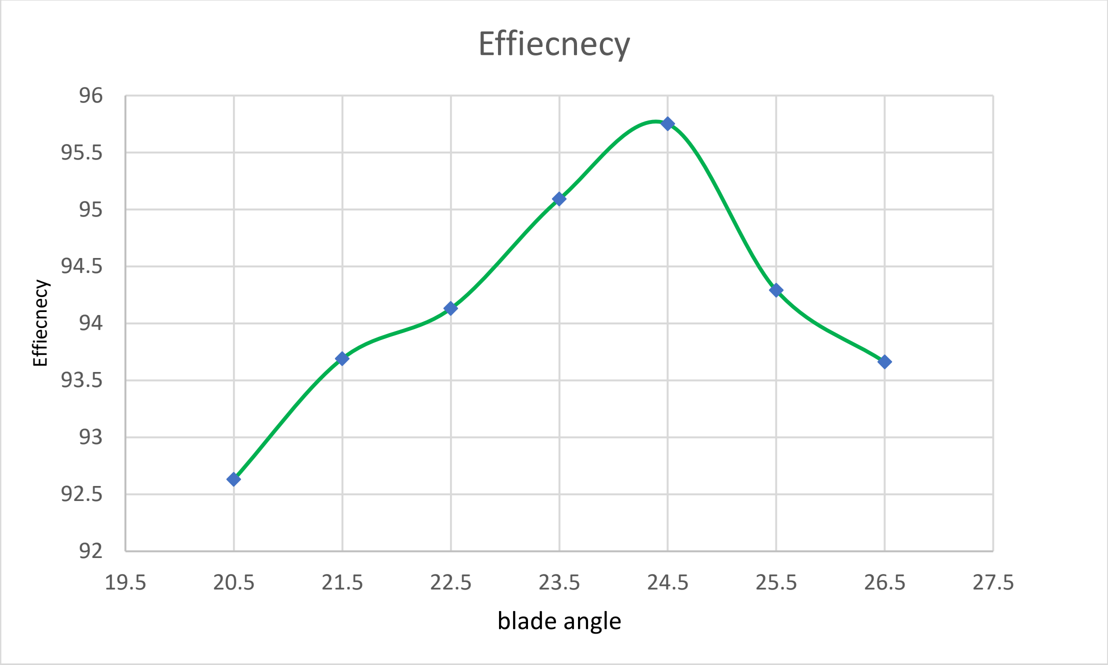


Figure 15: Variation of head with the change in blade angle (shroud) and efficiency.

Now we’ll speak about the most important section per any project (the cost) which is here represented in the pump’s power after a long time of empirical runs we figured out the chart (16) and it gives a perceive that it’s whenever we decrease the impeller’s angle then we’ll need less amount of the provided power

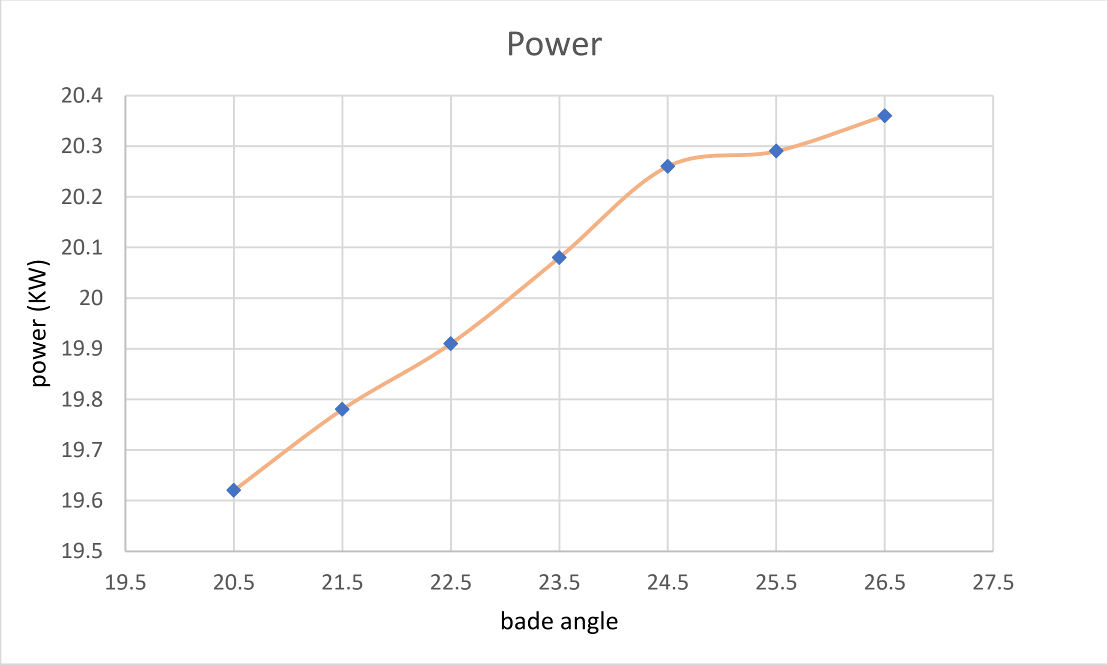


Figure 16: Varation of head with the change in blade angle (shroud) and power.

Blade Angle degree	**Head (m)**	**Efficiency %**	**Power (KW)**
20.5	**40.44**	**92.63**	**19.62**
21.5	**41.23**	**93.69**	**19.78**
22.5	**41.71**	**94.13**	**19.91**
23.5	**42.49**	**95.09**	**20.08**
24.5	**43.16**	**95.75**	**20.26**
25.5	**42.58**	**94.29**	**20.29**
26.5	**42.43**	**93.66**	**20.36**

Table-2-:Charging of Head, Efficiency and Power values with blade angle from shroud side

It is very clear from the chart (17) that there is a changeable head curve where we got the maximum head at the angle 35.5 and the minimum one was at 38.5.

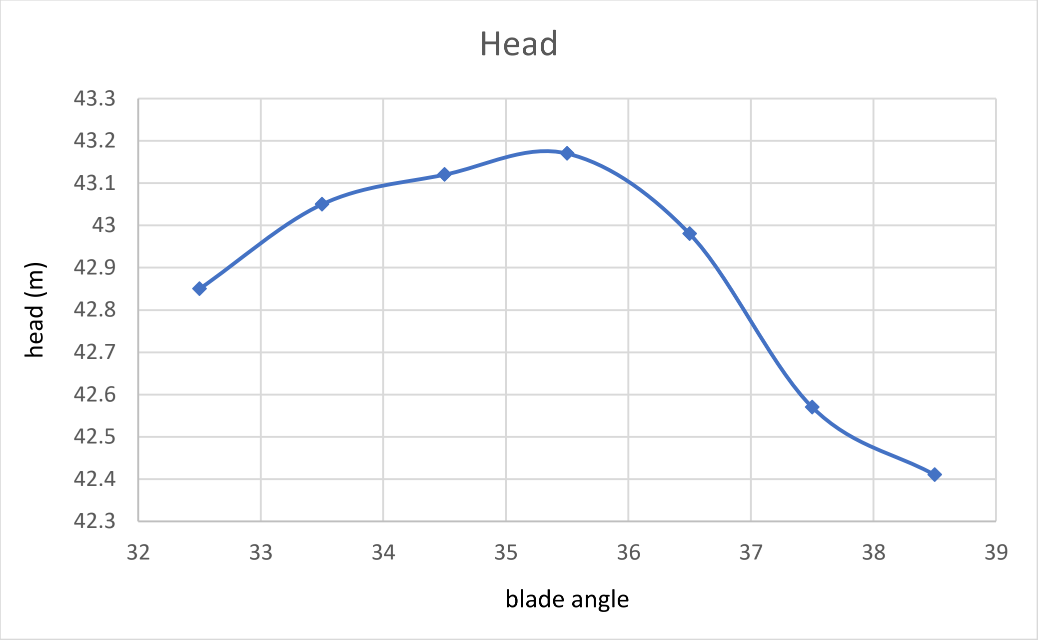


Figure 17: Variation of head with the change in blade angle (hup) and head.

It's evident from the figure (18) that there is a random change with the efficiency curve where we got the maximum efficiency at the angle 35.3 and the minimum one was at 38.5 ..

Figure 18: Variation of head with the change in blade angle (hup) and efficiency.

When we made run it was seen that there is a random change with the power curve where we got the maximum power at the angle 35.5 and the minimum one was at 37.5 Figure (19)

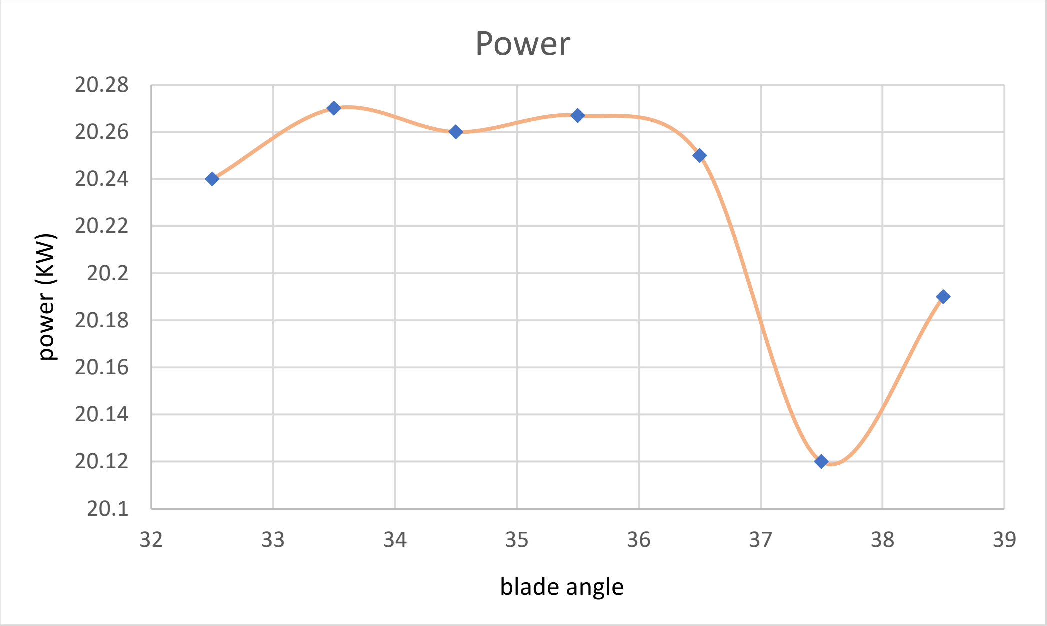


Figure 19: Variation of head with the change in blade angle (hup) and power.

Blade Angle degree	**Head (m)**	**Efficiency %**	**Power (KW)**
32.5	42.85	95.17	20.24
33.5	43.05	95.44	20.27
34.5	43.12	95.64	20.26
35.5	43.17	95.75	20.267
36.5	42.98	95.4	20.25
37.5	42.57	94.66	20.12
38.5	42.41	94.4	20.19

Table-3- Charging of Head, Efficiency and Power values with blade angle from hup side.

CHAPTER FIVE

5. Conclusions and Recommendations

5.1 **Conclusions:**

The main outcomes of this project can be summarised as follow:

1. The 3D pump was successfully designed and modelled using the CFX application in Ansys by starting with the mean line design in VISTA CPD.

2. Various values of head and efficiency were achieved by modifying the blade shape where their maximum values were achieved at a rotor shroud blade angle of 24.5°

3. We figured out that the blade angle from the shroud side has a serious effect on the rotor efficiency value .Where the hub has less impacting on the rotor efficiency value.

5.2 Recommendations:

1. Including the effect of the volute and/ or the stator within the analysis of the pump’s model to have more accurate results.

2. The structural analysis is another important field that need to be included within the analysis of the pump’s model to accurately evaluate any modifying occurs in the aerodynamic blade’s shape.

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