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Design of Impeller of Centrifugal Pump by Using Analytical and Numerical Method

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ABSTRACT:

Pumps are used in the process of transferring fluids from one place to other and these pumps have a vital role in the domestic and industrial areas. This project deals with the application and need of Structural analysis in the pump industries. For this purpose, we have made a design and analysis of impeller used in Domestic Open well Radial flow water pumps. The impeller selected is of enclosed type, which is commonly used in domestic water pumps. In this project we have designed an impeller for a domestic need using formulas formulated by Dr. K.M Srinivasan, in the book Rotodynamic Pumps. The impeller is modeled using CAD software and analyzed using Ansys package. The Ansys output is cross checked with desired requirements, so as to state the accuracy and need of Ansys analysis.

In this study, the performance of impellers with the same outlet diameter having different blade numbers for centrifugal pumps is thoroughly evaluated The impeller outlet diameter, the blade angle and the blade numbers are the most critical parameters which affect the performance of centrifugal pumps. The model pump has a design rotation speed of 4000rpm and an impeller with 4, 8 & 12 numbers of blades has been considered. The inner flow fields and characteristics of centrifugal pump with different blade number are simulated and predicted by using Ansys software. The simulation is steady design pressure to take into account the impeller. For each impeller, static pressure distribution, total pressure distribution and the changes in head as well as efficiencies of centrifugal pump are discussed.

With the increase of blade number and Type of blade like forward, backward and radial blades types also design. By checking material variation and find out best material for best design type will be finalized.

Introduction:

A pump is a device that moves fluids (liquids or gases), or sometimes slurries, by mechanical action. Pumps can be classified into three major groups according to the method they use to move the fluid: direct lift, displacement, and gravity pumps. Pumps operate by some mechanism (typically reciprocating or rotary), and consume energy to perform mechanical work by moving the fluid. Pumps operate via many energy sources, including manual operation, electricity, engines, or wind power, come in many sizes, from microscopic for use in medical applications to large industrial pumps [1]. Mechanical pumps serve in a wide range of applications such as pumping water from wells, aquarium filtering, pond filtering and aeration, in the car industry for water-cooling and fuel injection, in the energy industry for pumping oil and natural gas or for operating cooling towers. In the medical industry, pumps are used for biochemical processes in developing and manufacturing medicine, and as artificial replacements for body parts, in particular the artificial heart and penile prosthesis.
There are two main categories of pump:

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Appositive-displacement Pumps:

A variety of positive-displacement pumps are also available, generally consisting of a rotating member with a number of lobes that move in a close-fitting casing. The liquid is trapped in the spaces between the lobes and then discharged into a region of higher pressure. A common device of this type is the gear pump, which consists of a pair of meshing gears. The lobes in this case are the gear teeth [2.]

B. Rotodynamic pump (Kinetic Pumps):

A rotodynamic pump is a kinetic machine in which energy is continuously imparted to the pumped fluid by means of a rotating impeller, propeller or rotor[3].

1.2 Centrifugal pumps:

Centrifugal pumps have a rotating impeller, having a series of blades that is immersed in the liquid. Liquid enters the pump near the axis of the impeller, and the rotating impeller sweeps the liquid out toward the ends of the impeller blades at high pressure. For low flows and high pressures, the action of the impeller is largely radial [4].

1.2.1 Components of Centrifugal Pumps:

Fig: 1.2 cut section of impeller and parts of pump

A. Casing:

The volute pump is so called because of the shape of the casing. The object of the volute is gradually to reduce the velocity of the water after it leaves the impeller, and so convert part of its kinetic energy to pressure energy. For general purposes the volute pump is commonly used [5].

Fig: 1.3 volute casing

B. Impeller:

An impeller is a rotating component, which transfers energy from the motor that drives the pump to

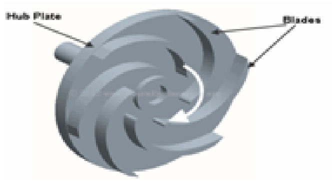

Fig: 1.4impeller with blades

The fluid being pumped by accelerating the fluid outwards from the centre of rotation. The blades are mounted to this base of impeller.

2. Literature Review:

Haridass Ramasamy and Prabhu Prakash did a journal on CFD Approach in the Design of Radial Flow Centrifugal Pump Impeller [6]. This project deals with the application and need of CFD analysis in the pump industries by designing and analyzing the impeller used in Domestic Open well Radial flow water pumps. The modeling and analyzing of the impeller is done by CAD and CFD packages respectively. The CFD output is cross checked with desired requirements, so as to state the accuracy and need of CFD analysis.

Sambhrant Srivastava, Apurba Kumar Roy and Kaushik Kumar did a work on Design of a mixed flow pump impeller blade and its validation using stress analysis [7]. The main objective of the paper is to avoid the failure of blades of a mixed flow pump impeller is generally due to excessive stress development. They used the Von Misses stress distribution in the impeller blades.

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The work design and stress analysis has been carried out on mixed flow pump impeller blades having different positions in the meridional annulus. The maximum Von Misses stress distribution was compared among the different blade positions. The inlet inclined blade position in the meridional annulus was found to be more suitable than the trapezoidal one as the Von Misses Stress distribution was lesser for inlet inclined blade.

Sverre Stefanussen Foslie studied the design and centrifugal pump for produced water [8]. The main objective of this study is to find the velocity distribution at the pump outlet, which is the entrance of the diffuser.

3. Problem statement

3.1Research need:

Centrifugal pumps are widely used in many applications, so the pump system may be required to operate over a wide flow range in some special applications. Thus, knowledge about off-design pump performance is a necessary [9]. On the other hand, it was found that few researchers had compared flow and pressure fields among different types of pumps. Therefore, there is still a lot of work to be done in these fields. The centrifugal pump performance and its efficiency greatly rely on the components like impeller and casing.

To achieve the better performance for a centrifugal pump, design parameters of impeller such as number of blades, the blade angle, blade width etc have to be considered for the impeller. The rise in head is done only by the impellers action with the help of the blades. The design and count of the blades will rise the pressure inside the casing, which in turn increases the head. This rise in head is used to discharge fluid for required high heads. However, the large force of fluid can cause the failure of the blade when the fatigue stress exceeds the allowable stress [10]. The impeller fraction is a very serious accident which is strictly prohibited in industries.

The static stress in different medium is proportional to the pressure distribution because a large percentage of the total stress is caused by hydraulic pressure.so the study of stresses on impeller by varying its blades count and shape is very prominent to reduce and decide the best blade with best count for specific purposes.

3.2 Aspects of proposed work:

The proposed research work is intended to exploit the best impeller for centrifugal pump by varying the number of blades and its shape .This study is done in both theoretically and numerically .This provides the knowledge about the following aspects:

- Variations in the head developed by changing number of blades in series of 4,8,12 is studied on different types of blades like forward, backward and radial shapes.
- the deformations over impeller for all its considered blade number and shape
- Von-misses stress on each shape of blade with changes in blade number.
- von misses strain on each shape of blade with changes in blade number

4. IMPELLER DESIGN:

Design is the application of scientific and mathematical principles to practical ends to form efficient and economical structures, machines, processes, and systems. Design of centrifugal impeller is done using K. M.Srinivasan method. Impeller design parameters are calculated using his procedure by giving head, volume flow rate and pump speed as input as mentioned in specifications of pump.

4.1 Design approach:

The design of centrifugal pump impeller is done based on the method proposed by K.M.Srinivasan in his book ROTODYNAMIC PUMPS (Centrifugal and axial).

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4.1.1 Specific speed:

- The **Specific speed** for the pump is calculated from the following formula for the given values

$$n_s = 3.65\frac{n\sqrt{Q}}{H^{3/4}}$$

4.1.2 Power input to pump:

- The Power is given as:

$$P = \frac{\rho QgH}{\eta_o}$$

4.1.3 Shaft diameter:

- Shaft diameter can be found using the following formula

$$d_s = \sqrt[3]{\frac{16}{\pi}\frac{T}{\tau_t}}$$

4.1.4 Outer diameter of impeller:

- The outer diameter D_2can be calculated using:
  The head coefficient (ψ)

$$\psi = \frac{gH}{U_2^2/2}$$

$$U_2 = \frac{\pi D_2 n}{60} = \sqrt{\frac{2gH}{\psi}}$$

$$D_2 = \frac{60}{\pi n}\sqrt{\frac{2gH}{\psi}}$$

4.1.5 Velocity of fluid at the impeller inlet:

Velocity of fluid at the impeller inlet is calculated by

$C_{m1}=(\frac{\pi D1}{\pi D1-ZS})C_{m0}$

4.1.6 Inner Diameter of impeller:

- The eye diameter (D1) can be calculated by assuming inlet number. The radial velocity at the inlet is given by:

$$C_{m0} = \varepsilon\sqrt{2Y}$$

- The volume flow rate at the suction end is given by:

$$\varrho' = C_{m0}\frac{\pi}{4}(D_1^2 - d_h^2),$$

$$\text{where}\varrho' = \frac{\varrho}{\eta_V}$$

- Calculating for the eye diameter,

$$D_1 = \sqrt{\frac{4\varrho}{\pi \times C_{m0} \times \eta_V} + d_h^2}$$

- The volumetric efficiency is given by:

$$\frac{1}{\eta_V} = 1 + \frac{0.287}{n_s^{2/3}}$$

- The inlet number can be found from the following figure.

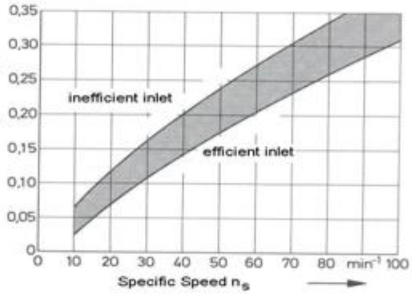

Figure 4.1 the inlet number values

4.1.7 Inlet blade angle:

- Blade angle β_0

$$\beta_0 = \tan^{-1}\left[\frac{C_{m0}}{U_1}\right] = \tan^{-1}\left[\frac{C_{m0}}{\pi D_1 n}\right]$$

4.1.8 Impeller width at inlet:

$Q_{th}= \pi D1\ B1\ Cm0$

Or $B_1=T_{hough}/\ \pi D1\ \ Cm0$

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4.1.9 Blade angle at outlet:

- Blade angle $\beta_2$can be estimated from the figure.

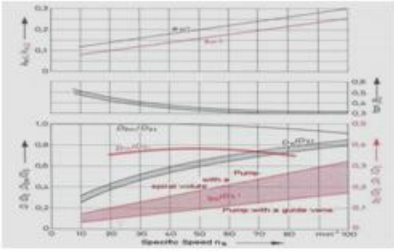

Figure: 4.2 Blade angle $\beta_2$values

4.1.10 Design for stresses on impeller:

Stress analysis of the impeller blades:

The calculation of stresses in a radial flow pump impeller blade is extremely complicated owing to number of reasons, the complex loading characteristics and the geometry of the blade is rather complicated. To get an accurate estimation of the stresses in the blades, validation of stress values are required to be compared with the calculated values. To accomplish the simplified method of stress validation among the calculated and numerically predicted values was carried out by replacing the twisted blades with an equivalent plate having rectangular cross-section, which acts like a cantilever. The material properties and the volume of both plate and blade were kept identical. The theoretical calculation of Von Misses stress was carried out using the following equations

4.1.10.1 Torque applied on the plate (T): N-m

$$\frac{T = P * 60}{2\pi N}$$

Or

$$\frac{T = WL^2 bn}{2}$$

Impeller N/m^2

L-span of each plate m

B-mean width of plate m

N-number of blades

4.1.10.2 Bending stress (σ_B): N/m^2

$$\sigma_B = \frac{M}{I} y$$

Where M-Bending moment =W*b (N-m)

I-moment of inertia =b $t^3/12$ m^4

Y-varying distance from neutral

Axis =t/2 mts

T-thickness of plate m

4.1.10.3 Shear stress (τ): N/m^2

$$\tau = \frac{6WbI}{bt^3} \frac{t^2}{(4 - y^2}$$

4.1.10.4 Von Misses stress (σ): N/m

$$\sigma = \sqrt{\sigma_B^2 + 3\tau^2}$$

4.1.10.5 Von Misses strain (ϵ):

$\epsilon = \frac{\sigma}{E}$ Where E-Young's Modulus of Elasticity N/m^2

4.2 Specifications of pump:

The specifications of pump are directly taken from the reference(2).

S.no	Parameters	Values
1	Head H	24 m
2	Discharge Q	95 lpm=1.583 lps
3	Power Output P	1 hp=746W
4	Speed N	2880 rpm
5	Pipe size	25X25
6	Total pressure developed in the fluid (P)	141744.4773 Pa = 0.141744 MPA

Table 4.1 specifications of centrifugal pump

4.3 Material Properties:

For impeller and blades, structural steels is the material selected. The below table shows the mechanical properties of structural steel.

Type of steel	Ultimate strength (MPa)	Yield strength (MPa)	Density (g/cm^3)	Young's Modulus (GPa)
Structural steel ASTM A36 Steel	400	250	7.8	200

Table 4.2 material properties of centrifugal pump

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4.4. Modeling using catia v5 software

The above profile is then developed into a model using CATIA V5. Some considerations are made while developing the model. Considerations like, the impeller is without hub portion, the shrouds are flat, etc., this made because, in this work, we have concentrated in the analysis of impeller's vane profile. Hence the parameters associated with Casing are neglected. The following image is the model developed using CATIA V5.

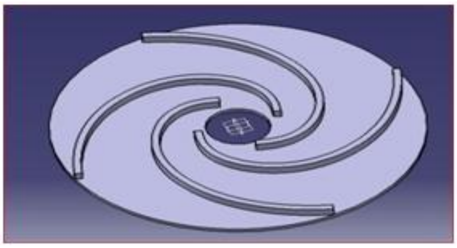
Vane profile development:

K.M.Srinivasan method: Single curvature blade or plane vane development is adopted for pure radial blades, where the inlet and outlet edges lie parallel to axis. The specific speed 'ns ' of such pump will be less than 100 i.e., ns < 100 and normally the diameter D2 < 70 to 100 mm.)Vane development is done either by single or by double arc method or by step by step method called as point by point method, must provide uniform variation in relative velocity 'w', meridional velocity Cm and angle of divergence from inlet to outlet along the flow passage .For smaller pumps the blade thickness will be 3 mm at inlet, 5 mm to 6 mm at the middle and 1 mm to 2 mm at the outlet. For larger pumps blade thickness is increased up to 10 to12 mm. Selection of minimum thickness provides a larger flow passage between blades. Nowthe profile is traced. The more number of points we employ, the tracing of the profile is made easy. In this case we have selected 7 trace points

CATIA MODEL:

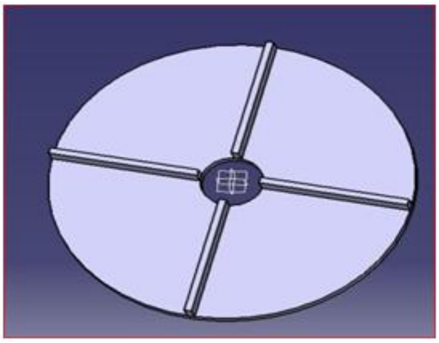
Model of impeller

Backward blades:



4 BLADE MODEL

RADIAL BLADES:



4 BLADE MODEL

5. FINITE ELEMENT ANALYSIS:

In mathematics, the finite element method (FEM) is a numerical technique for finding approximate solutions to boundary value problems for partial differential equations. It uses subdivision of a whole problem domain into simpler parts, called finite elements, and vibrational methods from the calculus of variations to solve the problem by minimizing an associated error function. Analogous to the idea that connecting many tiny straight lines can approximate a larger circle, FEM encompasses methods for connecting many simple element equations over many small sub domains, named finite elements, to approximate a more complex equation over a larger domain.

5.1Principles of FEA:

The finite element method (FEM), or finite element analysis (FEA), is a computational technique used to obtain approximate solutions of boundary value problems in engineering. Boundary value problems are also called field problems.

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The field is the domain of interest and most often represents a physical structure. The field variables are the dependent variables of interest governed by the differential equation. The boundary conditions are the specified values of the field variables (or related variables such as derivatives) on the boundaries of the field. For simplicity, at this point, we assume a two-dimensional case with a single field variable φ(x, y) to be determined at every point P(x, y) such that a known governing equation (or equations) is satisfied exactly at every such point. -A finite element is not a differential element of size dx × dy. - A node is a specific point in the finite element at which the value of the field variable is to be explicitly calculated.

5.2 Introduction to ANSYS:

ANSYS is a finite element analysis (FEA) software package. It uses a pre-processor software engine to create geometry. Then it uses a solution routine to apply loads to the meshed geometry. Finally it outputs desired results in post-processing. ANSYS is used throughout industry in many engineering disciplines. This software package was even used by the engineers that investigated the World Trade Centre collapse in 2001.

Models are imported into ANSYS 15.0 and Mesh model of Forward model

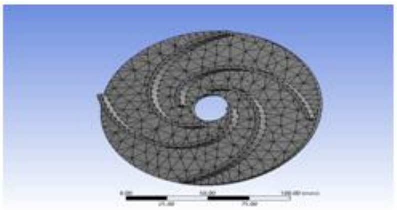

Fig.5.2 mesh model of impeller with blades

6. THEORETICAL CALCULATIONS

6.1 Theoretical calculations for impeller:

6.1.1 Specific speedN_s:

- The **Specific speed** for the pump is calculated from the following formula for the given values

$$N_s = 3.65\frac{N\sqrt{Q}}{H^{3/4}} = 3.65\frac{2880\sqrt{1.583}}{24^{3/4}} = 38.57$$

6.1.2 Power input to pump P: hp

- The Power is given as:

$$P = \frac{\rho QgH}{\eta_o} = \frac{1000}{0.63}X1.583X9.81X24 = 1.84\ hp$$

6.1.3 Shaft diameter d_s: mm

- Shaft diameter can be found using the following formula

$$d_s = \sqrt[3]{\frac{16}{\pi}\frac{T}{\tau_t}} = \sqrt[3]{\frac{16}{\pi}\frac{4.6}{1.31X10^{-7}}} = 25mm$$

6.1.4 Outer diameter of impellerD_2: mm

- The outer diameter D_2can be calculated using:

The head coefficient (ψ)

$$\psi = \frac{gH}{U_2^2/2} = \frac{9.81X24}{(21.71)^2\ /2} = 2$$

$$U_2 = \frac{\pi D_2 N}{60} = \sqrt{\frac{2gH}{\psi}} = \sqrt{\frac{2X9.81X24}{2}} = 21.71m/s$$

$$D_2 = \frac{60}{\pi N}\sqrt{\frac{2gH}{\psi}} = \frac{60\ U_2}{\pi N} = \frac{60X21.71}{\pi X2880} = 144mm$$

7 RESULTS & DISCUSSIONS

7.1 Results from Theoretical calculations:

S.NO.	Number of blades	VON MISES STRESS (N/mm2)	VON MISES-STRAIN
1	4	$2.6X10^6$	$1.3X10^{-5}$

7.2 Results from ANSYS:

7.2.1Load and Boundary Conditions for Forward blade:

Load and Boundary Conditions for design is given below:

I. As shaft position all DOF is fixed
II. Angular Velocity = 2*phi*2880/60 = 300.00 Rad/sec

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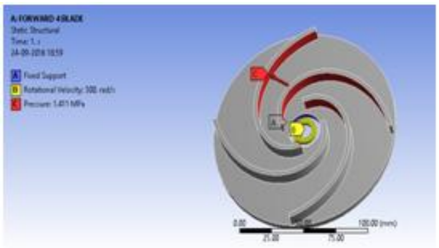
III. Pressures load P = 1.411 MPA

Load and Boundary Condition for Impeller blade for forward blade for all shapes are shown below:



7.2.2 STRUCTURAL ANALYSIS FOR FORWARD BLADE ARE GIVEN BELOW RESULTS:

7.2.2.1Total Deformation for all models forForward blades:

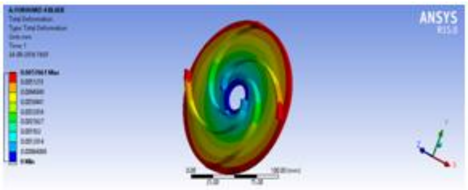


Fig 4 nos of blade deformartion andvalue of 0.005 mm(Max)

7.2.2.2 Von Misses Stress for For Forward Blades:

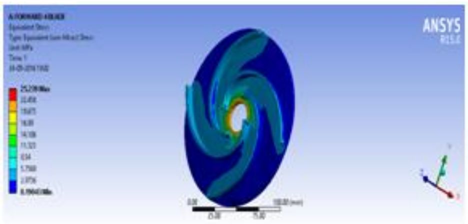


Fig 4 nos of blade Stress andvalue of 25.23 MPA (Max)

7.2.2.3 Von Misses Strain for For Forward Blades:

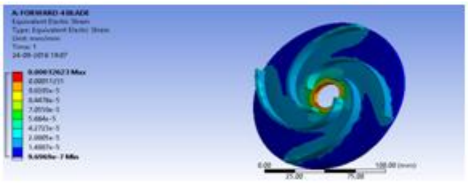


Fig 4 nos of blade Strain andvalue of 0.0001262 (Max)

7.3Resulttable from ANSYS:

From the above results from ANSYS ,it is concluded that the maximum values of von misses stresses is observed for 12 blades. Also the backward blade is experiencing less stress compared to the forward and radial blades. The following tables illustrate the results comparison from ANSYS.

Case1: 4 Blade Impeller Design Values:

7.4. GRAPHS FOR 4 BLADES FROM ANSYS RESULTS:

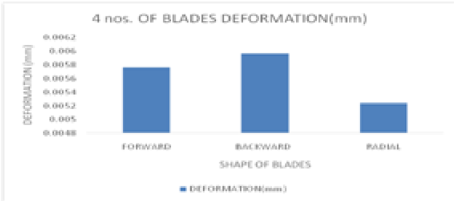


Fig 7.4.1 shape of blades vs deformation

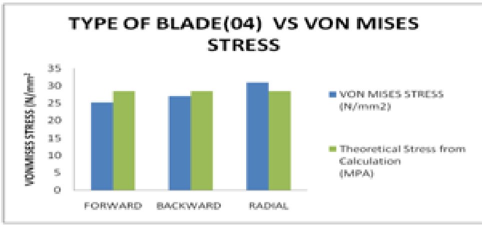


Fig 7.4.2 shape of blade vs von misses stress

8. Conclusion and Future Scope

Conclusion:

An impeller was designed for the input details using standard formulas and the vane profile was traced accordingly. Since the simulation is done only for the impeller's blade , the front and rear shrouds and hub portions are neglected in the modeling. The output of the simulation is close enough to the theoretical calculations. Hence it can be stated that, the usage of ANSYS structural analysis is worthy when compared to Forward, Backward and radial are analyzed with changing no. of blades as 4, 8 and 12 steps of blades. From the Results and plot table it is concluded that Backward blade has reduction in deformation, Stress and Strain when compared with other types of blades by increases in blade numbers. Thus by results we are reducing the time for various prototypes, and reducing the financial investments for each trials.

Percentage of reduction of stress comparing Backward blade with Forward & Radial is varies from 6 to 14 % for 4no. Blade, 8 to 32 % for 8 no. blade, 31 to 69 % for 12 no. blade. By results we come to conclusion by increasing number of blades in backward flow gives the best design for high head and low stresses and Concluded with best results.

Future scope:

- This study can also be done with other design parameters of pump for achieving the better performance.
- Can also be analysed with the CFD, MAT LAB etc.
- Can also be analysed by changing the material suitable for the impeller defects like cavitation, etc.
- Can also be done on different types of centrifugal pump like mixed flow and axial flow.
- Vibrational analysis can be done for the same impeller specifications.
- By changing the curved shape of blade into trapezoidal shape, the performance can be analysed.

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