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Design of a mixed flow pump impeller blade and its validation using stress analysis

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Abstract

The failure of blades of a mixed flow pump impeller is generally due to excessive stress development. In order to avoid such situation one should design the blades taking into consideration the Von Misses stress distribution in the impeller blades. In this present 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.

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Keywords: Mixed flow pump, blade, meridional annulus, ANSYS, Von Mises stress

1. Introduction

A pump is a devise, which converts mechanical energy to hydraulic energy. Pumps play a vital role in numerous household and industrial purposes. A wide variety of pump types are used for various applications. Among the various types of pumps, mixed flow pumps are widely used in flood supply, irrigation, urban water supply, cooling water system for various power plants, fire fighting systems and other numerous other fields. The mixed flow pump is a unification of radial and axial characteristics. The design of mixed flow impellers of high specific speed is a

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direct extension of the well-established empirical methods of the designing of radial flow impellers. The extension of similar methods serves for the design of mixed flow impellers, but the introduction of near diagonal flow layout at a still larger specific speed stimulated the incorporation of axial pump impeller design techniques in mixed flow pump technology.

Nomenclature

B	width, m	S	blade spacing, mm
C	blade chord length, m	T	Torque, N-m
H	fluid pressure head, m	w	surface density force, N/m^2
I	moment of inertia, m^4	y	distance, m
L	length, m	β	blade angls, degree
N	rotational speed, rev./min.	σ'	Von Mises stress, N/m^2
P	power input, kW	σ_B	bending stress, N/m^2
Q	volumetric discharge, m^3/sec	τ	shear stress, N/m^2

The usual industrial design practice of mixed flow pump impeller design starts with the estimation of approximate meridional streamlines by dividing the annulus by the equal area method (Hao et al. (2013)). Empirical co-efficients depending on the specific speed used to fix the inlet and outlet blade angles. Similar co-efficients are used to determine overall impeller layout before the meridional streamlines are estimated. The inlet and outlet angles being fixed in this manner, the blade sections are laid out on the developed stream surfaces. Adjusting the shape of the blade sections on the adjusted stream surfaces controls the shape of the composite blade.

The industrial design method, which is basically based on some empirical co-relations and design constants, often ignores the actual happening within the pump flow passage and is consequently a poor guide when the question of a new design & development of pumps comes to picture. In the above design process the designer has less control than desirable over events. The lack of clear-cut rational basis also inhibits the correction of manufacturing of shortfalls in expected performance. To overcome the above difficulties, one has to formulate a rational basis for the designing of impellers starting from basic principles, such that the use of empirical co-relations is minimized. Such a design from the basic principles has advantages that the designer will have more control over the outcome of his design, while keeping the physical principle constantly in view and enables him to rectify any faults in the performance of the pump.

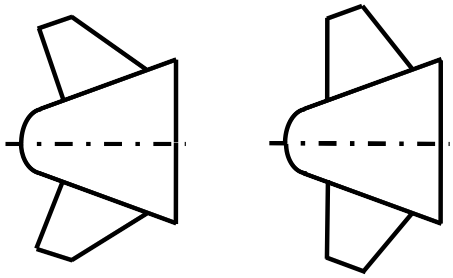
Over a period of time research on mixed flow pump has been carried out by various researchers. Wislicensus (1965) initiated the design of a mixed flow pump impeller. The modification of mixed flow pump impeller was carried out by Myles (1965). Busemann (1928) developed a formula for slip velocity for a mixed flow pump. Senoo and Nakase (1972), Inoue et al. (1980) developed a design method by calculating the meridional stream line. A.J. Stepanoff (1967) gave a design procedure for mixed flow pump impeller. Neumann's (1991), Gahlot and Nyiri (1993) have suggested the step-by-step design procedure for designing Mixed flow pumps. Yumiko Takayama and Hiroyoshi Watanabe (2009) presented a multi-objective optimization strategy of mixed-flow pump design by means of Three Dimensional Inverse Design Approach. Jim- Hyuk Kim & Kwang-Yong Kim (2011) developed an optimization procedure for high efficiency design of mixed-flow pumps. Hao et al. (2013), Mehta and Patel(2013) studied the effects of meridional flow passage shape on hydraulic performance of mixed-flow pump impellers.

K. Sham Sunder (1981) presented a three-dimensional method of stress analysis using finite element techniques for determining the stress distribution in centrifugal impellers. Ramamurti and Balasubramanian (1987), Jonker and Van Essen (1997), Jonker and Van Essen (1997), Samir Lemeš and Nermina Zaimović-Uzunović (2002), Bhope and Padole (2003), Arewar and Bhope(2013) contributed much on the stress analysis for highly complex blades of various turbomachines.

Here in this paper mixed flow pump impeller blades have been designed having different blade positioning in the meridional annulus using the basic principles of fluid mechanics and turbomachinery. The stress analysis of the pump blades has been carried out using ANSYS 11 software.

2. Research methodology

In this research work a mixed flow pump impeller has been developed for two different blade positioning in the meridional annulus for a non-dimensional specific speed of 1.998 rad. /sec., having the specification: discharge (Q) = 0.125 m3/sec., pressure head (H) = 5 m and speed of rotation (N) = 1000 rev. /min. The design method was based on free vortex theory. The fundamental relations were developed based on principles of fluid mechanics and turbo-machinery and the design and development was carried out for two different blade positioning, inlet inclined (case-I) and trapezoidal (case-II) which are shown in Fig. 1(a-b) respectively.



(a) Case-I: Forward (b) Case-II: Trapezoidal

Fig. 1: Two different positions of the mixed flow pump impeller blades in the meridional annulus

2.1. Design procedure

The design procedure involves:

1. Selection of inlet and outlet diameter of the pump impeller.
2. Meridional flow analysis resulting in surface of revolution.
3. Calculation of blade angles from hub to tip based on free vortex theory.
4. Selection of cascades to deliver required flow angles and blade loading.
5. Geometrical transformation of each surface of revolution into a plane with flow angles.
6. Reverse transformation of cascade geometry and flow data to the back to back intersections on the surfaces of revolution.
7. Recalculation of meridional axisymmetric flow for convergence check.

2.2. Modelling of pump impeller blades

Once the design parameters such as blade angle, blade stagger angle, blade chord length, blade solidity were calculated, the development of complex shaped blades were carried out by superimposing the various blade sections one over another to satisfy blade stagger angle on the conical surface of the pump impeller. Here, NACA 10C4 circular arc profile was used for the blades.

2.3 Stress analysis of the impeller blades

The calculation of stresses in a mixed 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 above a 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 Eqs. (1-6). It is assumed that each blade of the mixed flow pump impeller acts as a cantilever fixed to the hub and due to torque applied on the impeller; a surface force acts on the blade.

Torque applied on the plate:

$$T = w\,.\,L.b.\frac{L}{2}.N \tag{1}$$

Also, torque applied:

$$T = \frac{P.(60).(1000)}{2.\Pi.N} = 191 \text{ N-m} \tag{2}$$

Where,
P = 20 Kw, N = 1000 rev. /min., n = number of blades in the impeller = 8
L = span of each plate= 58 mm, b = mean width of each plate= 162 mm, t = thickness of each plate = 17 mm

So from the above equation,

$$w = \frac{2T}{L^2.b.n} = \frac{(2).(191000)}{(58^2).(162).(8)} = 0.088\text{N/mm}^2 = 88000\text{N/m}^2 \tag{3}$$

Bending stress is given by the relation:

$$\sigma_B = \frac{M}{I}.y \tag{4}$$

where ,
M=bending moment=w . b N-m, I=moment of inertia=(b . t^3)/12 m^4, y=varying distance from neural axis ,m.
and shear stress can be written as:

$$\tau = \frac{6.(w.b.I).}{b.t^3}.\frac{(t^2)}{(4-y^2)} \tag{5}$$

So, Von Mises stress is given by the relation:

$$\sigma' = \sqrt{(\sigma_B{}^2 + 3\tau^2)} \tag{6}$$

So, the calculated value of the Von Misses stress at the root of the plate is 3.07299 10^6 N/m^2.
While calculating the Von Misses stress the following material properties were taken into consideration.

Material	: Bronze
Young Modulus	: 1.1 x 10^5 MPa
Poisson Ratio	:0.341
Density	:8.86 x 10^{-9} kg/mm^3
Thermal Expansion	:1.78x 10 $^{-5}$/°K
Yield Strength	:5.2 x 10^8 N/m^2

Once the value of the Von Misses stress was calculated for the plate, FEM convergence test was carried in the plate with different size of the element find out the optimum size of the element using ANSYS. Using the optimum element sizes, numerical stress analysis for the pump impeller blades were carried out.

As the mixed flow pump impeller blades have complex surfaces, before applying any force to the impeller blades, calculations were carried out for the surface force density to be applied in the blades for stress analysis.

For the case of Inlet inclined blades (case-I) the surface area of each side of the blade was found to be 0.014 m2 therefore, a surface force density of 58805 N/m2 was applied to the impeller blades for case-I. For the case of trapezoidal positioning blades (case-II) the surface area of each side of the blade was found to be 0.013 m2 so a surface force density of 63328 N/m2 was applied to blades for case-II.

3. Results and discussion

In this work, two different blade positioning in the meridional plane have been selected for the detailed design and optimization of the impeller blades. From the design, first of all the annulus geometrical dimensions have been calculated. To calculate the span-wise variation of the blade angles, the blade span was divided into ten equal sections parallel to hub and casing. The span-wise variation of mean blade angle (βm) for inlet inclined and trapezoidal blade positioning in the meridional annulus is shown in Fig.2. Fig.3 shows the span-wise variation of blade aspect ratio (S/C) for inlet inclined and trapezoidal blade positioning in the meridional annulus.

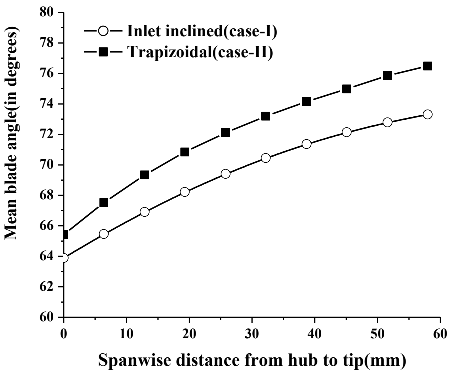


Fig. 2: Span-wise variation of mean blade angles

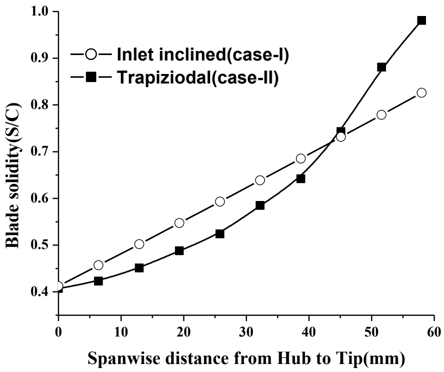


Fig. 3: Span-wise variation of blade solidity

During the calculation of the blade angles, ten sections along blade height were considered and diffusion factor (D_L) for Leiblein blade loading criteria, using Eq. 7, has been checked to ascertain no separation of boundary layer on the suction side of the blade.

$$D_L = [(1-\frac{\cos\beta_1}{\cos\beta_2}) + \frac{S}{C}.\frac{\cos\beta_1}{2}(\tan\beta_1 - \tan\beta_2)] < 0.6 \quad (7)$$

The blade aspect ratio, the ratio of blade spacing to blade chord length (S/C), plays a very important role on the overall performance of a turbomachine. So to vary this parameter one needs to vary blade spacing, pitch and chord length for optimal design. Here optimal number of blade is found to be eight in this present design. The blade aspect ratio is related to coefficient of lift for an aerofoil/hydrofoil blade as given in Eq. 8.

$$C_L = 2(\frac{S}{C})(\tan\beta_1 - \tan\beta_2)\cos\beta_m \quad (8)$$

Where β_m is the mean blade angle, which can be written as:

$$\tan\beta_m = \frac{1}{2}(\tan\beta_1 + \tan\beta_2) \quad (9)$$

By knowing the span-wise variation of blade angles, the 10C4 straight cascade was given suitable curvature using conformal transformation for ten different sections from hub to tip of the blade. The top view of the different blade sections for inlet inclined and trapezoidal blade positioning in the meridional annulus are shown in Fig. 4 and Fig. 5 respectively. The 3D models of the inlet inclined blade positioning (case-I) and trapezoidal blade positioning (case-II) in the meridional annulus are also shown in Fig. 6 and Fig.7 respectively.

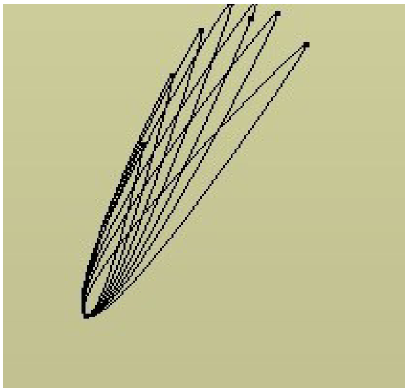


Fig. 4: Top view of different blade sections (case-I)

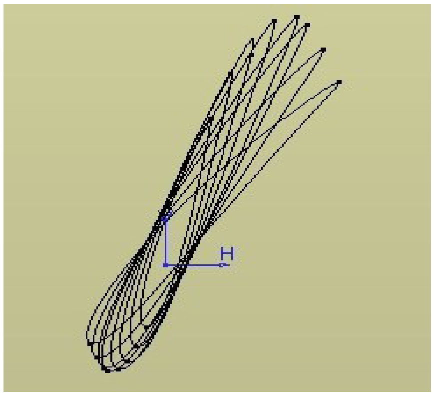


Fig. 5: Top view of different blade sections (case-II)

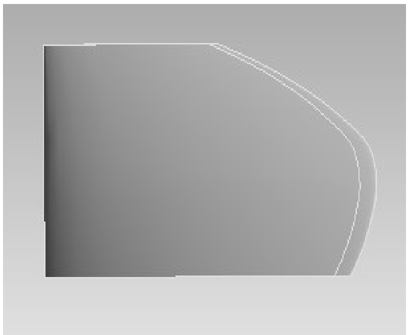


Fig. 6: 3D model of the impeller blade (case-I)

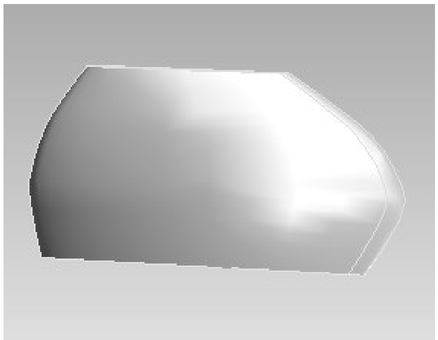


Fig. 7: 3D model of the impeller blade (case-II)

Once the 3D model of the blades was prepared, stress analysis on equivalent plate and blades of the pump impeller were undertaken. First of all the optimum size of the element was found out using ANSYS for the plate. Fig. 8 shows the analysis to find out the optimal element size for FEM analysis. From Fig. 8 it is observed that the optimal size of the element is 4.25 mm. Here, tetrahedral element was used for the present analysis. Span wise variation of Von Misses stress for the plate for an element size of 4.25 mm is shown in Fig. 9. While applying the surface density force on the blade profiles, it is assumed that the pressure force is acting uniformly on the plate/blade surfaces. Span wise variation of Von Misses stress for the inlet inclined blade (case-I) and trapezoidal blade positioning in the meridional annulus are shown in Figs.10 and Fig.11 respectively. Variation of principal stresses in the pump impeller blades for (case-I) and (case-II) is shown in Fig. 12 and Fig.13 respectively.

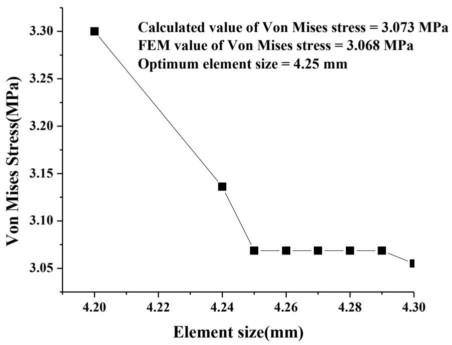


Fig. 8: Analysis for optimum element size

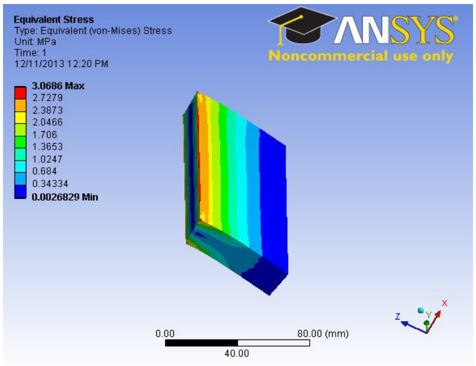


Fig. 9: Span-wise variation of Von Misses stress for plate

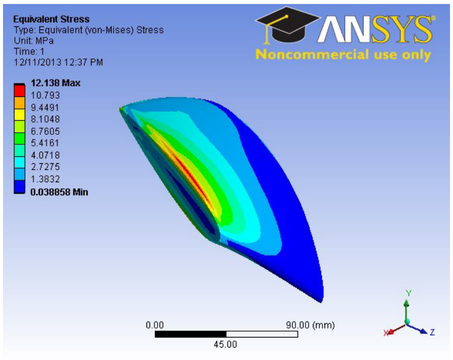


Fig. 10: Span-wise variation of Von Misses stress (case-I)

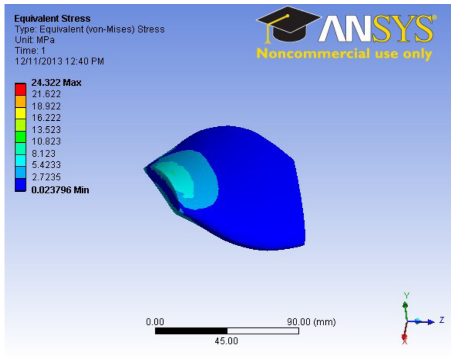


Fig. 11: Span-wise variation of Von Misses stress (case-I)

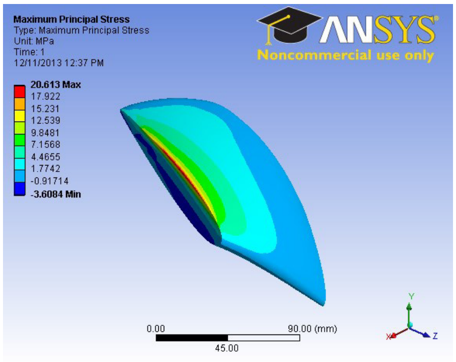


Fig.12: Span-wise variation of principal stress (case-I)

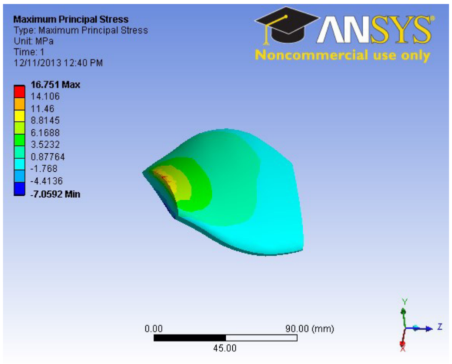


Fig.13: Span-wise variation of principal stress (case-II)

From the Fig. 10 and Fig.11 is was observed that the Von Misses stress at the root of the pump blade for inlet inclined blade position was 12.131 MPa, where as for trapezoidal blade positioning in the meridional annulus it was 24.322 Mpa. While comparing the maximum principal stresses, from Fig. 12 and Fig.13 it was observed that the maximum value of principal stress for inlet inclined blade positioning was 20.751 MPa and for trapezoidal blade positioning it was observed to be 16.751 MPa at the root of the blade. It is also observed that the inlet inclined blade position shows better characteristics than that of trapezoidal blade positioning in the meridional annulus as shown in Fig.3.

4. Conclusion

It can be observed from the above figures that the Von Misses stress at the root of the pump blade for inlet inclined blade position was much lower than that for trapezoidal blade positioning in the meridional annulus which clearly indicates that the inlet inclined blade position is a better option than the other one. Moreover this observation was supported by the maximum principal stresses obtained.

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