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Parametric Study and Design Optimization of Centrifugal Pump Impeller-A Review

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Abstract
Centrifugal pumps are widely used for irrigation, water supply plants, steam power plants, sewage, oil refineries, chemical plants, hydraulic power service, food processing factories and mines, because of their suitability in practically any service. Therefore it is necessary to find out the design parameters and working conditions that yield optimal output and maximum efficiency with lowest power consumption. Study indicates that Computational fluid dynamics (CFD) analysis is being increasingly applied in the design of centrifugal pumps. With the aid of the CFD approach, the complex internal flows in water pump impellers, can be well predicted, to speed up the pump design procedure. This paper exposes the various research work carried out in this direction especially in the content of parametric study and optimization of centrifugal pump impeller using CFD tool and DoE technique. Literature surveys indicate that very restricted work has been done in this area.
***Keywords* —** Centrifugal pump, CFD, DOE.

I. INTRODUCTION

1. Centrifugal pump

The centrifugal pump is a member of family known as rotary machine consists of two basic parts 1.The rotary element or impeller.2.The stationary element or casing (volute). A centrifugal pump delivers useful energy to the fluid on pumpage largely through velocity changes that occur as this fluid flows through the impeller and the associated fixed passage ways of the pump. It is converting of mechanical energy to hydraulic energy of the handling fluid to get it to a required place or height by the centrifugal force of the impeller blade. The input power of centrifugal pump is the mechanical energy and such as electrical motor of the drive shaft driven by the prime mover or small engine. The output energy is hydraulic energy of the fluid being raised or carried. In a centrifugal pump, the liquid is forced by atmospheric or other pressure into a set of rotating vanes. A centrifugal pump consists of a set of rotation vanes enclosed within a housing or casing that is used to impart energy to a fluid through centrifugal force. A pump transfer mechanical energy from some external source to the liquid flowing through it and losses occur in any energy conversion process. The energy transferred is predicted by *the Euler Equation*. The energy transfer quantities are losses between fluid power and mechanical power of the impeller or runner. Thus, centrifugal pump may be taken losses of energy.

2. CFD

Computational Fluid Dynamics usually abbreviated as CFD, is a branch of fluid mechanics uses numerical methods and algorithms to solve and analyze problems that involve fluid flow. Computers are used to perform the calculations required to simulate the interaction of liquids and gases with surfaces defined by boundary conditions. Computational techniques replaces the governing partial differential equations with algebraic equations that are much easier to solve using computer.

3. DOE

Design of experiments (DOE) or experimental design is the design of any information-gathering exercises where variation is present, whether under the full control of the experimenter or not. However, in statistics, these terms are usually used for controlled experiments. Formal planned experimentation is often used in evaluating physical objects, chemical formulations, structures, components, and materials. Other types of study, and their design, are discussed in the articles on computer experiments, opinion polls and statistical surveys (which are types of observational study), natural experiments and quasi-experiments (for example, quasi-experimental design). See Experiment for the distinction between these types of experiments or studies. In the design of experiments, the experimenter is often interested in the effect of some process or intervention (the "treatment") on some objects (the "experimental units"), which may be people, parts of people, groups of people, plants, animals, etc. DOE is thus a discipline that has very broad application across all the natural and social sciences and engineering.

II. LITERATURE SURVEY

Erik Dick et al[1][2001] have used CFD-code Fluent 5.4for the flow analysis of two test pumps of end-suction volute type, one of low specific speed and one of medium specific speed. For both, head as function of flow rate for constant rotational speed is known from experiments. First, the impeller is generated. One impeller channel is meshed and is then rotationally copied the necessary number of times. For the first pump, the impeller is completely two-dimensional. The impeller mesh is made with hexahedra and wedge cells. For the second pump, the impeller channel is much more complex. The mesh is made in a completely unstructured way, mainly using tetrahedron, but other cell forms like pyramids, hexahedra and wedges also occur. The inlet channel is meshed for both pumps with prisms. The volute in both pumps is too complex for a structured grid. The total number of cell for pump 1 is about 300000. For pump 2, it is about 550 000.they found that Steady calculation methods like the Frozen Rotor method and the Mixing Plane method cannot be used with confidence to analyze the performance of volute centrifugal pumps.

K.W. Cheah et al[2][2007] have investigated the complex internal flow in a centrifugal pump impeller with six twisted blades by simulation using a three-dimensional Navier-Stokes code with a standard *k*-e two-dimensional equation turbulence model. Different flow rates were specified at inlet boundary to predict the characteristics of the pump At design point, the internal flow or velocity vector is very smooth along the curvature along the blades. The single and double vortical flow structures are observed in the volute casing. When operating at off-design load, the flow pattern has changed significantly from the well-behaved flow pattern at design load condition. A strong flow recirculation at the center of the passage of the impeller can be observed. The stall region developed due to the recirculation is blocking the flow passing through the passage.

E. C. Bacharoudis *et al*[3]*[2008]* have studied various parameters which affect the pump performance and energy consumption like the impeller outlet diameter, the blade angle and the blade number and evaluated the performance of impellers with the same outlet diameter having different outlet blade angles. The one-dimensional approach along with empirical equations is adopted for the design of each impeller. The influence of the outlet blade angle on the performance is verified with the CFD simulation. As the outlet blade angle increases the performance curve becomes smoother and flatter for the whole range of the flow rates. The numerical simulations seem to predict reasonably the total performance and the global characteristics of the laboratory pump. The influence of the outlet blade angle on the performance is verified with the CFD simulation. As the outlet blade angle increases the performance curve becomes smoother and flatter for the whole range of the flow rates.

Andrzej Wilk [4][2010] discusses the results of measurements of parameters of a high speed impeller pump with open-flow impeller having radial blades. They found that at high rotational speed pump has obtained a large delivery head, because the blade angle at outlet from the impeller is wide, liquid flowing out the impeller has large absolute velocity and dynamic delivery head of the impeller is large. The kinetic energy of the liquid was converted to pressure in spiral case and in the diffuser

LIU Houlin et al[5][2010] their investigation focuses mostly on the performance characteristics of axis flow pumps, the influence of blade number on inner flow filed and characteristics of centrifugal pump. the methods of numerical simulation and experimental verification are used to investigate the effects of blade number on flow field and characteristics of a centrifugal 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 noncavitation and caviation conditions by using commercial code FLUENT. The comparison between prediction values and experimental results indicates that the prediction results are satisfied. The maximum discrepancy of prediction results for head, efficiency and required net positive suction head are 4.83%, 3.9% and 0.36 m, respectively.

S. Chakraborty et al[6][2011] evaluated the performance of impellers with the same outlet diameter having different blade numbers for centrifugal pumps. The model pump has a design rotation speed of 4000 rpm and an impeller with 4,5,6,7,8,9,10,12 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 Fluent software. The simulation is steady and moving reference frame is applied to take into account the impeller-volute interaction. 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, the head and static pressure of the model increases, but the variable regulation of efficiency are complicated, but there are optimum values of blade number for each one.

K.M. Pandey et al[7][2012] has studied the performance of impellers with the same outlet diameter having different blade numbers is thoroughly evaluated. The investigation focuses mostly on the performance characteristics of pump. the methods of numerical simulation and experimental verification are used to investigate the effects of blade number on flow field and performance of a centrifugal pump. They have performed two-dimensional steady numerical analysis for centrifugal pumps with impeller blades 7, 8 and 9 using Ansys Fluent 6.3 software for inlet diameter 80 mm and outlet diameter 168 mm at 2500 rpm rotational speed and also investigated the changes in head as well as efficiencies with the increase of blade number. They concluded that the head of centrifugal pump grows all the time with the increase of blade number but the change regulations of efficiency is little bit complex. The efficiency is maximum for 7 bladed impeller centrifugal pump. So the optimum blade number of the model pump in this paper for efficiency is 7.

SHI Weidong et al[8][2012] has evaluated the performances of the deepwell centrifugal pump with four different impeller outlet widths and studied the numerical, theoretical and experimental methods . Two stages deepwell centrifugal pump equipped with different impellers are simulated employing the commercial CFD software to solve the NavierStokes equations for three dimensional incompressible steady flow. The changing value of the impeller outlet width ($b2$) is 9 mm, 10 mm, 11 mm, and 12 mmThe commonly used deepwell centrifugal pump of 150QJ20 type was selected as the research object. Its main parameter at the design condition as follows: rated flow QN=20 m 3 /h, single stage head Hs=13 m, stage number N=5, speed n=2 850 r/min, specific speed ns=113. result they found Oversized impeller width leads tothe impeller area ratio increasing, and causes the poor pump performance. A point worth emphasizing is that a relative small impeller outlet width conducive to get a better performance and lower power.

R Ragoth Singh et al[9][2012] has discussed an application of the Taguchi method for optimizing the design parameters in blower operation. Optimization of design parameters using this technique is directly inclined towards economic solution for the turbo machinery industry. They have studied, the methodology to find near optimum combination of blower operating variables for performance enhancement were analyzed using computational fluid dynamics(CFD). Taguchi orthogonal array (OA) based design of experiments (DoE) technique determines the required experimental trials. The experimental results are justified by Analysis of Variance (ANOVA) and confirmed by conformation experiments. The parameters chosen for design optimization are Impeller outlet diameter, Impeller wheel width, Thickness of blade and Impeller inlet diameter. The levels for the parametric specification are chosen from the ranges where the blower will get the best efficiency. CFD results were validated by the fine conformity between the CFD results and the experimental results.

R. R Singh et al[10][2012] have evaluated the characteristics of low specific speed centrifugal water pump by studying the relationships among the impeller eye diameter, vane exit angle and width of the blade at exit. As these pumps are of Non-positive type, the discharge is greatly affected by any resistance to flow, outlet conditions and design parameters of impeller and casing. Different pump models are developed by varying critical design parameters to different levels. Response surface method is used for Optimization and Experimental Design (DoE). Computational Fluid Dynamics (CFD) analysis is carried out on the developed models to predict the performance virtually and to verify with the experimental result of the pump. Optimal pump design is formulated using Response surface method. The objective functions are defined as the total head and the total efficiency at the design flow-rate.

Ashok Thummar *et al*[11] [2012] A performance analysis of centrifugal pump is carried out and analyzed to get the best performance point. The various performance parameters of centrifugal pump such as overall efficiency, cavitations, slip factor, losses etc. have been calculated. For that four different types of open well centrifugal pump namely impeller 165mm, 210 mm, 170 mm, and123 mm were selected for the performance analysis. During the investigation period it is found that the overall efficiency of the pump is increases as the flow rate and head decreases where as the power input is increased.

Ling Zhou et al[12][2013]have used an orthogonal experiment to optimize the impeller design parameters. The prototype experimental test results of the original pump were acquired and compared with the data predicted from the numerical simulation, which presents a good agreement under all operating conditions. Five main impeller geometric parameters namely impeller outlet width $b2$, impeller inlet diameter$D1$, impeller blade wrapping angle φ, impeller blade outlet angle $\beta2$, and impeller blade inlet angle $\beta1$. were chosen as the research factors. 16 impellers were designed and modeled according to orthogonal array table. Then, the 16 impellers equipped with the same volute were simulated by the same numerical methods. Through the variance analysis method, the best parameter combination for higher efficiency was captured finally. Compared with the original pump, the pump efficiency and head of optimal pump have a significant improvement. optimal impeller design was adopted as , $b2$ =11 mm, $D1$ = 66 mm, φ = 130°, $\beta 2$ = 15°, and $\beta 1$ = 12° based on the results of the orthogonal experiment. Then, the final optimized impeller was designed and assembled with the same volute and simulated by the same numerical methods. At the design flow rate, the optimal pump has 67.55% efficiency and 30.93m head. Compared with the original pump with 64.11% efficiency and 29.21 m, the increase is 5.4% and 5.9% in percent separately

Shalin P Marathe et al[13][2013] has studied the performance of the centrifugal pump having the backward, radial and forward bladed type of impeller. The impeller is modeled using Creo Parametric 1.0 having 70 and 80 degree outlet blade angle for the backward type and outlet blade angle 90 for radial and 100 degree for forward type impeller respectively. Numerical simulation is carried out using ANSYS CFX and standard k- turbulence model is adopted for the analysis purpose. The results obtained from the analysis shows that the characteristic curve for different outlet blade angles are completely matched with the numerical results and it can be concluded from the results that for low head operating conditions, the impeller with backward bladed works efficiently and the problem of the cavitations, which reduces the performance of the pump is less.

Alok ku Nanda et al[14] [2013] Used to assess the performance of pelton wheel turbine with different range of rotational speeds and varying loads using surface response methodology (RSM). The result value reveals that the predicted value and the observed value for turbine shaft rotation in rpm are indicating a very good fit for the response function equation.

III. CRITICAL PARAMETERS OF CENTRIFUGAL PUMP IMPELLER

From the literature review critical parameter of the centrifugal pump impeller is found out which highly affect the performance characteristic of centrifugal pump are,

1. Impeller outlet width ($b2$) Pump head decreases with increased blade width. This is due to augmenting the liquid pressure drop with increasing blade width. Also, the required pump brake horsepower decreases when the blade width rises.
2. Impeller outlet diameter($D2$) pump head increases with increasing impeller diameter, which can be explained by the fact that the liquid static pressure drop in impeller decreases with increasing impeller diameter. In other words, for a given volume flow-rate, the pressure difference between the volute outlet and the impeller inlet is higher for an impeller with a greater diameter. In addition the brake horsepower increases relative to the increasing impeller diameter, due to the requested augmented impeller shaft torque relative to the size of the impeller diameter.
3. Impeller Outlet Blade Height pump head as a function of the volume flow rate with the outlet blade height pump head increases with increasing outlet blade height. This can be explained by the fact that, when the volume flow rate is kept constant, the increased outlet blade height leads to the decreasing meridional velocity, which increases the pump head since the outlet tangential velocity and the outlet blade angle remain constant. In other words, the liquid pressure drop in the impeller decreases as a function of the increase in outlet blade height as a parameter.
4. Impeller blade outlet angle ($\beta 2$) For any viscosity, the total hydraulic loss in the impeller and volute rises with increasing blade exit angle. Head increase with increasing discharge angle, efficiency has less effect but the efficiency was improved while handling viscous oils. The higher the oil viscosity, the larger the improvement in efficiency**.**
5. Number of blade on the impeller(Z) Experiments shows that pump head increases with a greater blade number. This is explained by the decrease in the liquid pressure drop in the flow passage with an augmented impeller blade number, keeping the same total volume flow rate the pump brake horsepower increases relatively with the augmented blade number. This is due to the increase in the request pump shaft torque, as the pump blade number also increases.

IV. SCOPE OF THE WORK

Flow through the pump have adverse pressure gradient hence pump efficiency will be lower than the turbine. so by studying the flow pattern inside the pump and varying the critical parameters efficiency of the pump can be improved.

V. CONCLUSION

Centrifugal pump is more widely used because of following advantages.

- Its initial cost is low Efficiency is high
- Discharge is uniform and continuous flow
- Installation and maintenance is easy.

As the centrifugal pump is used in very wide verity of applications So, it is quite necessary to measure the various pump performance parameters for the efficient operation of centrifugal pump, but Experimental studies to determine different performance parameters in different type of pumps are complex, time consuming and costly. So by using CFD and DOE prediction model it is easy to predict the performance of different pump and speed up the production.

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