Review on Performance Improvement of Centrifugal Pump

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Abstract: Centrifugal pump is a device which is used to transport fluid by the conversion of rotational kinetic energy to hydrodynamic energy of the fluid flow. Centrifugal pumps are used for many applications in different fields. These are one of the major auxiliaries which consumes power and it is important to improve the performance of centrifugal pumps to save power and to make system more efficient. There are various methods by which we can improve the performance of centrifugal pumps viz. proper selection of pump for the operation, impeller trimming, de-staging, installation of variable frequency drive. Nowadays CFD analysis is being used to predict the performance of pump working under various conditions. The study of performance of centrifugal pump has been the area of interest for many researchers recently.

Keywords- centrifugal pump, computational fluid dynamics, de-staging, impeller trimming, pump as turbine, turbulent flow variable speed drive.

I. Introduction

Centrifugal pump converts rotational energy into pressure energy using external power source, mostly electric energy by motor. Fluid enters axially through eye of casing, is then caught in impeller blades where its kinetic energy as well as pressure energy increases. From impeller fluid gets thrown into the diffuser casing where its kinetic energy decreases and pressure energy increases.

Centrifugal pumps are used for many applications in different fields such as power plant, sewage, desalination plants and petroleum industries, etc. Pumps are the major auxiliaries which consumes power and it is desirable to improve the performance of pump to make the system efficient. Also, it is important to predict the performance of pump in advance before manufacturing them to make them more efficient for given application. The characteristics curve provided by the manufacturers are not always useful as pump may have to work at off-design condition. Variation in the load of system also affect the operation of centrifugal pump. Due to all these reasons it is required to analyze the system and select proper method to improve the performance of pump. Another interesting field of application of pump is their turbine mode. Pumps as turbine (PAT) are being extensively used for power generation in small hydropower plants.

II. Literature review

Tejas N. Raval, Dr. R.N. Patel [1] studied the auxiliary devices used in thermal power plant such as boiler feed pump, condense extraction pump and compressor, etc. for the consumption of energy mainly focusing on Boiler Feed Pump (BFP) and Condensate Extraction Pump (CEP). For this, actual data like discharge pressure, flow, temperature of fluid and current taken by motor for driving pump was used. the observation made are given in table no. 1. After the observation calculation had been carried out for power and efficiency, reasons for poor performance were also listed down which are given in table no. 2. Various suggestions were given to improve the efficiency of pumps such as proper selection of pump as per requirement, impeller trimming, de-staging, installation of variable frequency drive (VFD), etc. These improvements are given in table no. 3. Its concluded that part load efficiency of pump is poor, and performance of pump decreases as the load on the system varies. It observed that all recommendations viz. impeller trimming, de-staging, installation of VFD results in improvement in efficiency of system and is economically viable.

Table 1. Observation of running parameters

		Discharge Pressure (kg/cm^2)	Discharge flow (m^3/hr)	Temp. Of fluid (˚c)	Current (amp.)
BFP- 1	Design	121.8	100	160	65
	Actual	100	90	160.4	41.6
BFP- 2	Design	121.8	130	160	65
	Actual	100	90	160.4	44.4
BFP- 5	Design	172.7	185	200	155
	Actual	88.04	168.48	157	92.07

BFP- 6	Design	172.7	185	200	155
	Actual	95	182.57	164.4	104
BFP- 7	Design	100.47	120.4	160	53
	Actual	101.8	103	157.5	39.5
BFP- 8	Design	105.5	120.4	160	53
	Actual	101.9	103	157.5	39.7
BFP- 9	Design	100.47	120.4	160	53
	Actual	107.92	99.84	163	37.96
CEP- 1	Design	26	285	50	33
	Actual	26.03	230	43	28.93
CEP- 3	Design	26	300	50	34.5
	Actual	24.75	207.28	47.7	25.9
CEP- 4	Design	26	300	50	34.5
	Actual	24.4	230	41.8	28.2

Table 2. Power and efficiency calculation

		Power (kw)	Efficiency (%)	Remarks possible reasons
BFP- 1	Design	385	75.5	Part load eff. is poor. Pump over sizing operation of combination of pump Throttling Impeller diameter Discharge pressure is higher than what require.
	Actual	204.98	51.01	
BFP- 2	Design	541	75.5	
	Actual	204.98	47.79	
BFP- 5	Design	1024	73	
	Actual	292.19	32.19	
BFP- 6	Design	1024	73	
	Actual	345.68	33.58	
BFP- 7	Design	500	73	
	Actual	241.46	62.95	
BFP- 8	Design	500	73	
	Actual	241.46	62.97	
BFP- 9	Design	500	73	
	Actual	245.98	67.01	
CEP- 1	Design	260	73	
	Actual	161.52	57.79	
CEP- 3	Design	260	73	
	Actual	151.4	55.58	
CEP- 4	Design	260	73	
	Actual	133.09	53.19	

Fig 3. Suggestions and Improvements

Sr No.	Suggested Method	Annual Savings -suggested (Rs/ year)	Annual Savings-implemented (Rs/ year)	Simple Payback Period-suggested	Simple Payback Period-implemented
1	De-staging	70,58,808	46,90,980	0.1481	0.2229
2	Impeller Trimming	24,12,504	18,98,730	0.3108	0.3950
3	Installation of VFD	36,58,176	16,39,872	3.075	6.86

Daniele Fiaschi, et al. [2] studied a solar pumping system with a modular centrifugal pump & variable frequency drive to improve the effectiveness of the pump. In the experiment a centrifugal pump with variable rotational speed and modular number of working stages was compared with a centrifugal pump having fixed number of stages. These pumps were used in a solar pumping system to provide water in remote areas. A commercially available CP with given head and mass flow characteristics is taken. Then a simulation tool to study the modified pump performance and cost was developed. It was necessary for the solar pumps to follow the radiation curve daily to maximize the use of available solar power. By using the simulation tool, the optimized position is decided and accordingly the stage is deactivated, and speed is varied. Breakpoint of the shaft is decided at a certain number of impeller. The number of stages to be activated depends upon the level of solar radiation. The shaft is divided in two parts by using a mechanical clutch which can engage and disengage the two parts under automatic control. The efficiency of the solar pumping system that is the amount of water pumped during the day depends upon the selection of shaft break point. The break point depends upon peak power value (peak power value depends upon the photo-voltaic solar panels surface when the daily radiation is fixed). Once the peak power value and minimum power demand is determined, breakpoint is determined. A 3 phase AC pump with 46 stages was taken. The breakpoint was fixed at 20th impeller due to which two working modes were possible;

With 20 stages (leaving the remaining idle)

With 46 stages

The pumps motor is combined with a variable speed AC-DC inverter. Due to variability of speed, variable number of working stages are allowed by shaft breakpoint. The pumping system is optimized by working at low speed full stages during early morning and late afternoon and increasing the shaft speed while decreasing the number of working stages during the middle hours of the day (when the power output from the solar panels is highest). After carrying out all the calculations for a 46 stages pump with a nominal peak power value (3000w & 100m head), followings results were observed;

9 to 10% improvement in the yearly water yield.

Marginal improvement in efficiency

If pump is correctly selected, profitable.

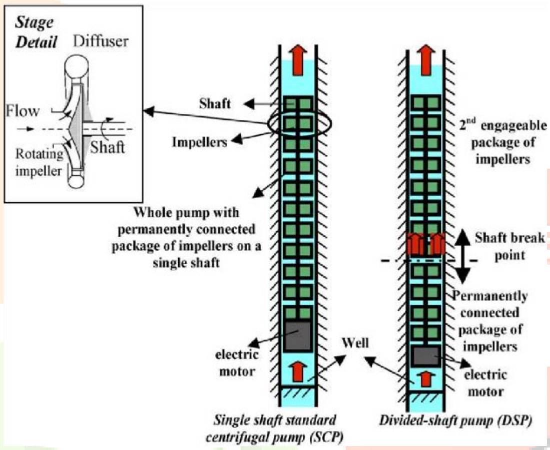


Fig 1. Schematic of standard single-shaft centrifugal pump (SCP) and divided shaft pump (DSP) with detailed section of **one** stage and the related impeller

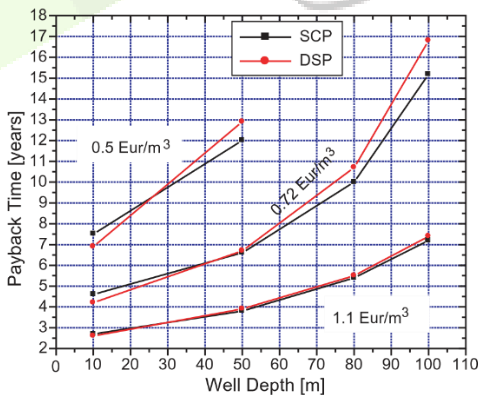


Fig 2. Payback time vs. well depth at different specific water price level for DSP and SCP for 28-impeller pump

Mario Savar, et al. [3] studied working of centrifugal pump in desalination plant and found out that centrifugal pumps do not operate at their optimal point for various reasons. In this paper impeller trimming was studied as one of the method to adjust the pump operating point to actual need. Pumps used in industry are often oversized due to 'rounding up' or due to future plant capacity expectation. Impeller trimming is based on affinity law which states that pumps are similar if they satisfy geometric and kinematic similarity conditions.

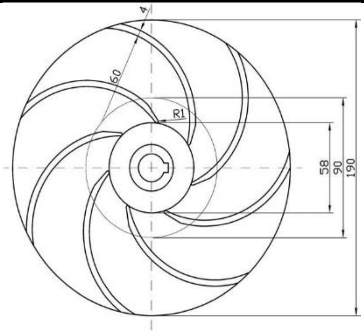


Fig 3. Dimensions of impeller before trimming

In this experiment impeller was trimmed from diameter of 190mm to diameter of 130mm in step of 10mm. After each trimming operation impeller was placed in the same casing and pump characteristics was recorded. Non-dimensional numbers viz. head coefficient ψ=(2gH/u_2) and flow coefficient φ=(Q/uA) were used to plot a characteristics graph for pump. It was observed that as amount of impeller trimming increases, efficiency decreases due to increase in gap between impeller and stator. It was advisable to limit the trimming to 75% of original diameter. It was concluded that even though geometrical conditions were not preserved, there was very less deviation from the affinity law.

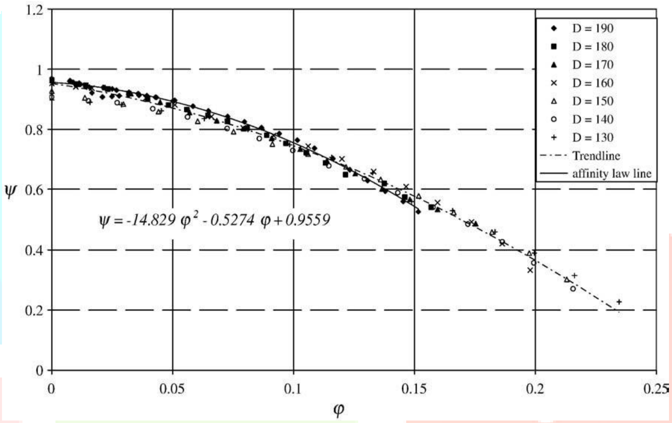


Fig 4. Head coefficient ψ vs. flow φ coefficient diagram

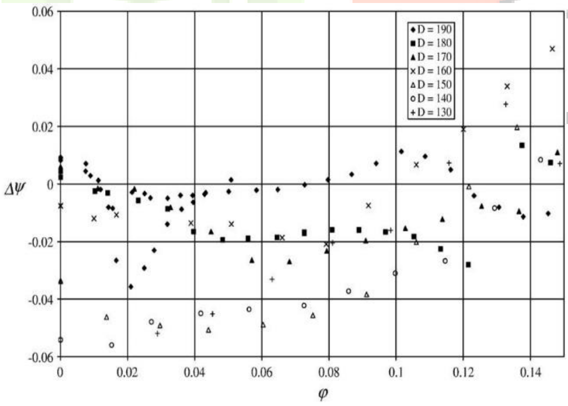


Fig 5. Dissipation about affinity law line

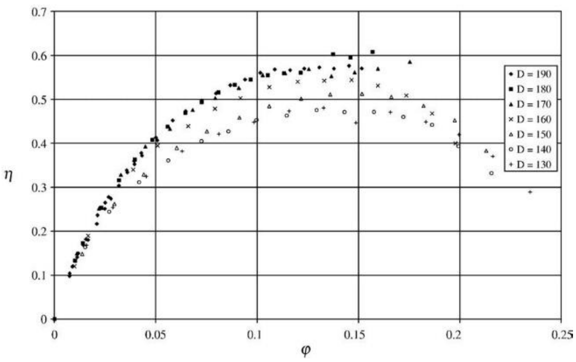


Fig 6. Efficiency vs. flow coefficient diagram

S. R. Shah, et al. [4] investigated the use of Computational Fluid Dynamics (CFD) to study fluid flow inside the centrifugal pump. CFD analysis is used to predict performance of centrifugal pump at design and at off-design condition, for parametric study, for cavitation and diffuser pump analysis and to predict performance of pump running in turbine mode. CFD is used to study complex internal flow at different operating conditions. 3D model of centrifugal pump is used to study interaction between impeller and spiral casing. RANS (Reynolds Averaged Navier Stroke) equation was used to carryout steady state simulation of pump.

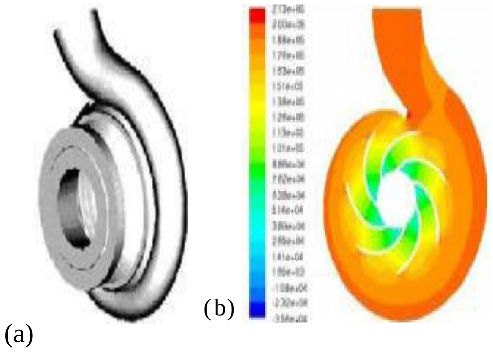


Fig 7. (a) Three-dimensional model of centrifugal pump (b) static pressure contours in the pump.

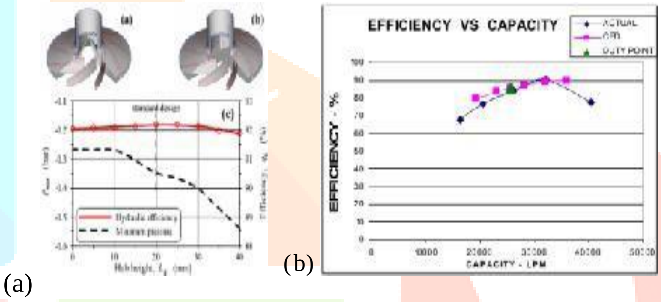


Fig 8. (a) Modified shroud geometry and its effect on head and efficiency (b) efficiency vs. capacity curve

CFD analysis was also used to predict flow behavior in different parts of centrifugal pump before manufacturing them. For this different configuration of controllable design variables and impeller shape was used. It was observed that hydraulic efficiency can be improved by optimizing the impeller geometry. For studying cavitation effects, models like homogenous two-phase RANS equation, air-vapour-liquid 2-phase medium (TE model) and constant enthalpy vapourization (CEV) were used. The results showed excellent agreement with experimental observations. Interaction between components was studied by using viscous Navier Stroke equation along with sliding mesh technique. Amplitude of fluctuating pressure field at blade passing frequency was captured and is shown in fig. no. 1. It was seen that pressure in diffuser passage fluctuates with the basic frequency of the impeller blade passing frequency. For proper dimensioning of multistage centrifugal pump, contribution of each component to the axial load, leakage flows in shroud chambers, balancing drums and residual axial thrust was studied using CFD analysis and it was observed that axial thrust is highly affected by leakage mass flow and local rotating speed inside the cavity. Pumps used for handling Non-Newtonian fluid (slurry, blood, etc.) were studied using k-ε turbulence model. Analysis showed that solid concentration and wall shear stress increases from upstream to downstream. CFD analysis of pump as turbine (PAT) showed resemblance with experimental results in case of head drop, efficiency and discharge away from BEP (Best Efficiency Point) after using structured grid. Mini-pump (diameter 5mm to 50mm) were studied using k-ε turbulence model and experimental results showed that CFD analysis can be effectively used for analysis of mini-pumps with reasonable accuracy. It was concluded that CFD approach can be effectively used for the analysis of flow in the centrifugal pump with percentage of error less than 10%.

Yang Sun-Sheng, et al. [5] studied the effect of impeller trimming on performance of PAT (pump as turbine). As manufacturers do not provide characteristics curve of their pump working as turbine, other methods such as performance based on its pump mode characteristics, geometric parameters or CFD analysis have been used to determine characteristics of PAT. In this experiment, energy dissipated pump was used to consume energy generated by PAT and to regulate PAT's rotational speed. After measuring inlet, outlet pressure and other parameters, PAT's head, output power, efficiency and performance curve were obtained. After trimming, PAT's geometric parameters such as diameter (D_2), impeller inlet width (b_2), blade wrap angle (u), and blade inlet angle (β) were changed. CFD code Ansys-CFX software was used to analytically study the effects of impeller trimming on PAT's performance. Five sections viz. PAT's volute, impeller, front and back chambers, and outlet pipe were considered separately for mesh generation. Structured hexahedral grid with k-ε turbulence model was used. PAT's geometric parameters such as outlet diameter, blade wrap angle, blade inlet angle was changed and studied separately.

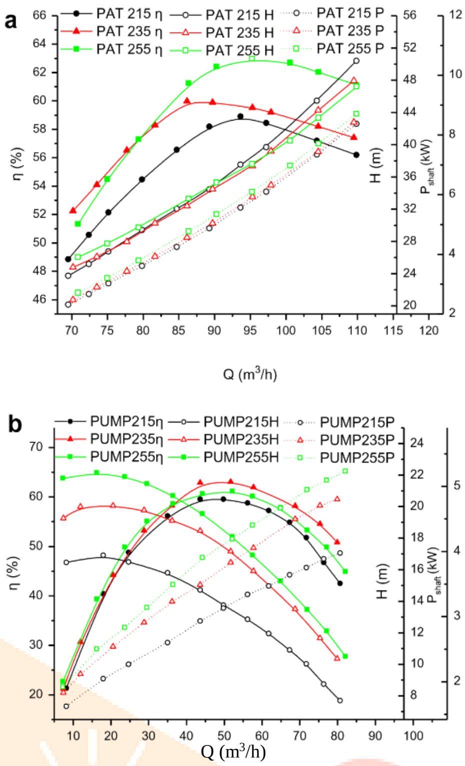


Fig 9. (a) performance curves of impeller in turbine mode (b) performance curves of impeller in pump mode

The CFD analysis results and experimental data was compared to determine the accuracy of CFD analysis and it was concluded that CFD analysis can be used reasonably to study PAT's performance. After experimental and numerical investigation, it was concluded that numerical results are slightly higher than experimental results, due to neglection of volumetric leakage loss, through balancing holes and mechanical seals. Through CFD analysis it was observed that, as outlet diameter decrease from 255mm to 215mm flow rate and efficiency decreases at BEP. Also, the optimal blade wrap angle is 130°, highest efficiency is obtained at 13mm impeller inlet width. It was also observed with increase in blade inlet angle, flow rate at BEP increases.

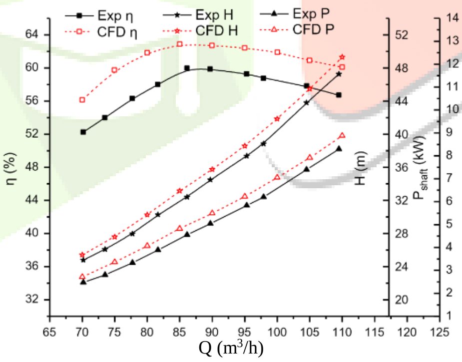


Fig 10. Experimental and numerical performance curves

Shahram Berakhshan, Ahmad Nourbakhsh [6] studied the characteristics of centrifugal pump working as turbine by varying specific speed. PATs are being used in small hydropower plant stations because they are relatively simple machines and they are available in most developing countries. The main problem with PAT is proper selection according to the application. In this paper, some relations were derived to predict BEP of PAT by using experimental data. The experiment consisted of PAT, generator, pump, valve, flow meter, etc. Four industrial centrifugal pumps with specific speeds from 14 to 56 (m, m^3/s) were used. After measuring all parameters head, flow rate, output power and efficiency were calculated. The results showed that low specific speed pumps can operate as turbine in different specific speeds. Various relations between BEP of pump and BEP of PAT were derived and it was observed they are valid for low specific speed centrifugal pumps. Experimental data showed that the dimensionless characteristics curves of PATs based on BEP were approximately the same as that of pump mode. It was concluded that, centrifugal pump can operate as turbine without any mechanical problem. Also, for same specific speed, pump working as turbine with higher head and discharge is more efficient than its pump mode and pump with bigger impeller is more efficient than PAT. The given method was verified with experimental data and it was seen that it is applicable for centrifugal pump with specific speed < 60 (m, m^3/s). The procedure given in this paper for selection of PAT is valid for pumps with N_{st} < 150 (m, KW).

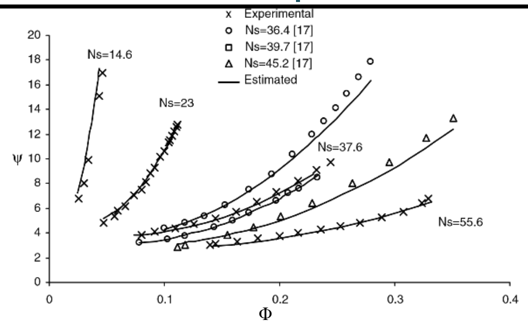


Fig 11. Measured and estimated PAT's dimensionless head curves

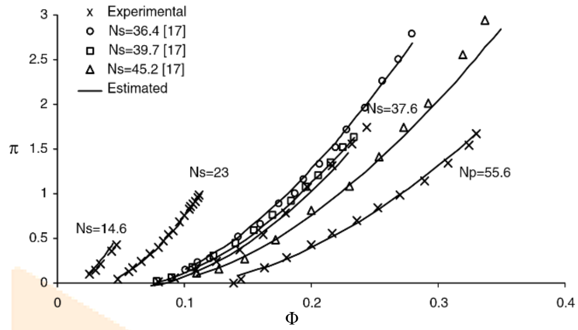


Fig 12. Measured and estimated PAT's dimensionless power curves

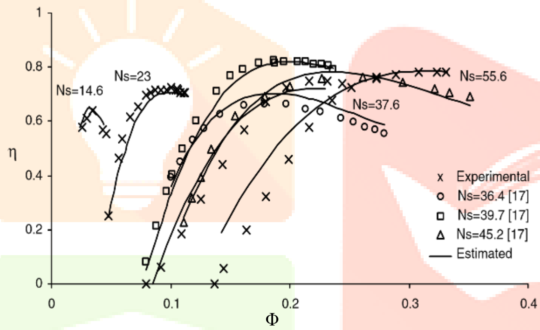
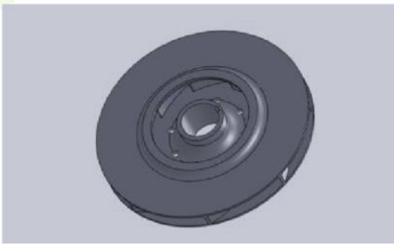
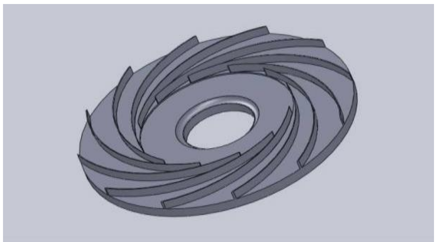


Fig 13. Measured and estimated PAT's efficiency curves

Vishnu R. Nair, et al. [7] carried out Computational Fluid Dynamic (CFD) analysis to study de-staging and other methods of improving performance of centrifugal pump. The numerical study was carried out on a 146KW 5 stage centrifugal pump used in combined power plant using ANSYS Fluent software. The power plant was first studied for power consumption to analyze how much power was being wasted due to inefficient operation of pumps.


(a)


(b)

(c)

Fig 14: Solidworks model of (a) impeller (b) diffuser (c) volute/casing

3D model of centrifugal pump was created using Solidworks. The design specifications of each part were given. After solid modeling, incompressible fluid flow inside the centrifugal pump was studied using k-ε turbulence model. Each stage of multistage centrifugal pump was studied individually for the pressure variations to save time and for better accuracy. Impeller, diffuser and the shaft domain were considered as rotating frame of reference with rotating speed of 1485 rpm. After observing the results of CFD analysis, it was concluded that even though other methods such as impeller trimming, installation of VSD gives satisfactory performance improvement de-staging is preferable because it is simple to implement.

III. Conclusions

Centrifugal pumps consume sizable amount of power for their operation. However, their operation is not efficient due to various reasons viz. improper selection of pump for given operation, oversized or undersized pumps, pump not working at BEP, frequent load variation on the system, etc. It is mandatory to improve the performance of pump to reduce the power used by pump and to make the system more efficient. The characteristics curve of pump can be studied using experimental data or by numerical analysis. CFD analysis is a powerful tool to predict the performance of pump at design and off-design conditions. The comparison of numerical and experimental data has shown reasonable agreement. The study of pumps has shown that efficiency of systems is poor and power consumption is very high at off-design condition. The performance of pump decreases drastically when working at part load condition and when the load on the system varies frequently. After analyzing the working conditions, proper selection of performance improving methods is very important task. Impeller trimming, installation of VSD, de-staging are some of the popular methods used to improve performance of pump. Pump working as turbine has been area of interest for many developers. Pump can be used as turbine due to its simple construction and easy operation. CFD analysis has also been used to predict the performance of pump working as turbine. This application of pump is being limited to low specific speeds since at high speed PATs become inefficient.

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