

Experimental Study on Centrifugal Pump to Determine the Effect of Radial Clearance on Pressure Pulsations, Vibrations and Noise

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ABSTRACT

This article represents experimental study work carried out on a single stage diffuser type centrifugal pump. The flow-induced pressure pulsations, mechanical vibrations and noise has been monitored during the experimentations for five different flow rates by varying the radial clearance. For each case of radial clearance and flow conditions, overall levels and frequency spectra, in a wide frequency range, have been examined. Vibration and noise both are predominantly due to the hydraulic effects. Impeller vane pass component has generally dominated the spectra. Frequency analysis revealed a good correlation in the overall vibration level and the overall noise level. In the frequency analysis, pressure pulsations are dominating at fundamental frequency and the impeller vane passing frequency. Also in the frequency analysis, level at fundamental frequency dominates the vibration spectra and level at vane passing frequency dominates the noise spectra. Experimental results show that by increasing the radial clearance between impeller and diffuser, lower pulsations, vibration and noise levels has been achieved.

(**Keywords**— Centrifugal Pump, Mechanical Vibrations, Noise, Pressure Pulsations, Radial Clearance)

1. INTRODUCTION

Centrifugal pumps are classified as rotary dynamic type of pumps in which a dynamic pressure is developed which enables the lifting of liquids from a lower to a higher level. Centrifugal pump of today is the result of 250 years evolution. During last four decades or so it has been rapidly superseding the other types of pumping equipments in variety of industrial and engineering applications owing to superior operable characteristics. Pumps are the largest single consumer of power in industry. Faulty pumping equipments can cause a high rate of energy loss with associated performance degradation, high vibration levels and significant noise radiations. The instability in the flowing media could generate pressure pulsations; which could further intensify the problems causing damage to the piping or other components in a hydraulic system. To ensure the safety of pump and associated plant components, the

vibration and noise must be kept within safer limits. Higher vibrations ultimately results in decreased component life due to cyclic loads, lower bearing life, distortion to foundation, frequent seal failures etc. Similarly noise has got huge impact on working environment and comfort conditions of an individual. Exact diagnosis of vibration and noise sources is very difficult in centrifugal pumps as this may be generated due to system or the equipment itself[1-3].

Taking in to consideration the after effects of these influential parameters over the pump performance and efficiency, the researchers have been trying to look in to the dynamics of this mechanical equipment. Investigations on three different pumps for set of flow conditions showed good correlation between vibration and noise[4]. Studies on feed pump outages in nuclear and thermal power plants showed that most of impeller breakages were caused by unusual radial gaps between impeller and diffuser [5]. Impeller breakages often results in pump outage.

Experimental investigations carried out by Chudina have shown that discrete frequency tones of noise spectra that can be used to determine the NPSH required to avoid flowing instability and reduce vibration and noise. However, in some cases, even apparently minor pressure variations cannot be tolerated because of their detrimental effect on the operation of certain equipment in the system[6]. The impeller / volute interaction is an important design parameter in developing high-energy pumps like the double-volute boiler feed pumps and appropriate radial gap selection can reduce the possibility of flow- induced vibration at blade passing frequencies in centrifugal diffuser pumps. Also pressure fluctuation is sensitive to the radial gap between the impeller and the casing [7]. The present work reports the results of the above investigation carried out on diffuser type centrifugal pump illustrating the effect of radial clearance.

2. CENTRIFUGAL PUMP

Centrifugal pump is one of the basic and a superb piece of equipment possessing numerous benefits over its contemporaries. The main advantages of a centrifugal pump includes its higher discharging capacity, higher operating speeds , lifting highly viscous liquids such as oils, muddy

and sewage water, paper pulp, sugar molasses, chemicals etc. against the reciprocating pumps which can handle relatively small quantity of liquid operating at comparative slower range of speeds that is limited to pure water or less viscous liquids free from impurities limited from the considerations of separation, cavitation and frequent choking troubles. The overall maintenance cost of a centrifugal pump is also comparatively lesser due to less wear and tear. While major disadvantage includes vulnerability to a complexities of eddies formations, noise and vibrations and inability to generate higher pressures as executed by the reciprocating pumps.

2.1 Components The main components of a centrifugal pump are impeller, casing, suction pipe and delivery pipe as described below:

2.1.1 Impeller It is a wheel or rotor which is provided with a series of backward curved blades or vanes, as shown in **fig.1**. It is mounted on a shaft which is coupled to an external source of energy (usually an electric motor) which imparts the required energy to the impeller of the system thereby making it to rotate as desired. The impellers may be classified as closed, semi-open and open types.

Closed or shrouded impeller has vanes provided with metal cover plates or shrouds on both sides. These plates or shrouds are known as crown plate and lower or base plate. The closed impeller provides better guidance for the liquid and is more efficient. However, this type of impeller is most suited when the liquid to be pumped is pure and comparatively free from debris.

Semi Open impeller has vanes provided only with the base plate and no crown plate. Such impeller is suitable for the liquids charged with some debris.

An **Open** impeller is that whose vanes have neither the crown plate nor the base plate. Such impellers are useful in the pumping of liquids containing suspended solid matter, such as paper pulp, sewage and water containing sand or grit. These impellers are less liable to clog when handling liquids charged with a large quantity of debris.

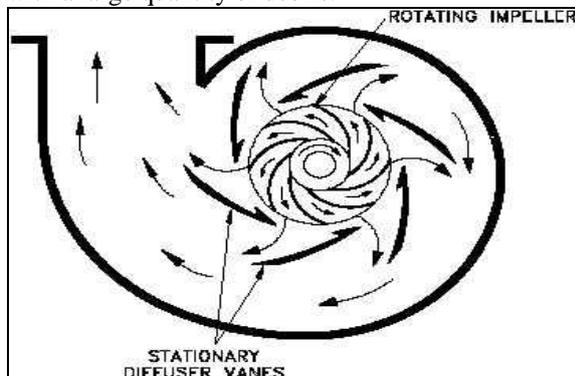


Fig.1 Schematic Line Diagram showing Impeller and Diffuser Vanes

2.1.2 Casing. It is an airtight chamber which surrounds the impeller. It is similar to the casing of a reaction turbine. The two different types of casings commonly adopted are volute and diffuser types.

Volute casing has impeller surrounded by a spiral shaped casing which is known as volute chamber. The shape of the casing is such that the sectional area of flow around the periphery of the impeller gradually increases towards the delivery pipe. This increase in the cross-sectional area results in developing a uniform velocity throughout the casing, because as the flow progresses towards the delivery pipe, more and more liquid is added to the stream from the periphery of the impeller.

Diffuser casing has impeller surrounded by a series of guide vanes mounted on a ring called diffuser ring. The diffuser ring and the guide vanes are fixed in position. The adjacent guide vanes provide gradually enlarged passages for the flow of liquid. The liquid after leaving the impeller passes through these passages of increasing area, wherein the velocity of flow, decreases and the pressure increases. The guide vanes are so designed that the liquid emerging from the impeller enters these passages without shock. After passing through the guide vanes the liquid flows into the surrounding casing.

2.1.3 Suction Pipe It is a pipe which is connected at its upper end to the inlet of the pump or to the centre of the impeller which is commonly known as eye. The lower end of the suction pipe dips into liquid in a suction tank or a sump from which the liquid is to be pumped or lifted up. The lower end of the suction pipe is fitted with a foot valve and strainer. The liquid first enters the strainer which is provided in order to keep the debris away from the pump. It then passes through the foot valve to enter the suction pipe. A 'foot valve' is a non-return or one-way type of valve which opens only in the upward direction. As such the liquid will pass through the foot valve only upwards and it will not allow the liquid to move downwards back to the sump.

2.1.4 Delivery Pipe It is a pipe which is connected at its lower end to the outlet of the pump and it delivers the liquid to the required height. Just near the outlet of the pump on the delivery pipe a delivery valve is invariably provided. A delivery valve is a regulating valve which is of sluice type and is required to be provided in order to control the flow from the pump into delivery pipe.

2.2 Working

The basic principle on which a centrifugal pump works is that when a certain mass of liquid is made to rotate by an external force, it is thrown away from the central axis of rotation and a centrifugal head is impressed which enables it to rise to a higher level. The centrifugal action converts energy of an electric motor or engine via the associated shaft into velocity or kinetic energy and then into pressure of a

fluid that is being pumped. The energy changes occur into two main parts of the pump, the impeller and the volute. The impeller is the rotating part that converts driver energy into the kinetic energy. The volute is the stationary part that converts the kinetic energy into pressure. Liquid enters the pump suction and then the eye of the impeller. Whirling motion is imparted to the liquid by the means of backward curved blades mounted on a wheel known as impeller. When the impeller rotates, it spins the liquid sitting in the cavities between the vanes outward and imparts centrifugal acceleration. As the liquid leaves the eye of the impeller a low pressure area is created at the eye allowing more liquid to enter the pump inlet. The pressure head developed by centrifugal action is entirely due to velocity imparted to the liquid by the rotating impeller and not due to any displacement or impact.

2.3 Disturbing Sources

Vibration is basically the displacement of body back and forth from its static position initiated by a response from the excitation force. Generally increasing vibration levels indicate a premature failure representing the deterioration of an equipment. The noise caused by the vibration can be regarded as the output of a noise producing system in which the input is a force, torque or pressure which excites the vibrating structure. Although a certain amount of noise is to be expected from centrifugal pumps and their drivers, unusually high noise levels (in excess of 100 dB) or particularly high frequencies can be an early indicator of potential mechanical failures or vibration problems in centrifugal pumps. The occurrence of significant noise levels indicates that sufficient energy exists to be a potential cause of vibrations and possible damage to the pump or piping. The main source of vibration and noise in a centrifugal pump can be mechanical, hydraulic or other peripheral sources.

Mechanical Sources includes unbalanced rotating parts, damaged impellers, misaligned pump and driver, bent or warped shaft, loose nut bolts and other fasteners, worn or loose bearings, rubbing parts, misaligned couplings, improper foundation design and layout etc. Hydraulic sources includes transients/ surges, hydraulic unbalance, secondary flows cavitation, wake-effect, pressure pulsations, impeller vane running close to pump cut water etc. Other peripheral sources are harmonic vibration from nearby equipment, operating pump at critical speed etc.

Pressure pulsations is a phenomenon in which the pressure pulses are generated due to the fluid like water impacting on the diffuser surface after leaving the impeller vanes. In centrifugal pump, the centrifugal action throws the fluid towards periphery; at this point fluid possesses very high energy. It is with this energy the fluid strikes the diffuser. Although most of the fluid gets

circulated but some quantity after striking the diffuser moves back and collides with the incoming vane discharge. This causes pressure fluctuations and hence a wave of pressure pulse is generated thus, inducing noise and vibration in the pump. Pressure pulsations are detected at discrete frequencies that are multiples of the rotating frequency and the number of blades; these are also called blade pass frequencies (BPF).

Blade Pass Frequency = No. of blades/vanes \times rpm
Noise and vibration are the important parameters for the condition monitoring of the pump. Condition based maintenance techniques like vibration analysis and noise monitoring are the effective methods of accessing the malfunctioning of pumps [8-12].

3. EXPERIMENTATION

3.1 Test Rig

The experiments were performed on the closed loop centrifugal pump test rig, the schematic diagram is as shown in **fig.2**. The pump used was a single stage horizontal and diffuser type with impeller having eight vanes and diffuser having seven vanes. Radial clearances of the order 6.8mm, 3.7mm, 1.5mm has been used during the experimentation. The rotor was of cantilever type supported on ball bearings. The pump was isolated from each side. It was connected to motor with flexible coupling. The suction and discharge pipes were flexibly connected to pump with hose pipes and rigidly to the tank. The pump drew water from the tank through the suction pipe and discharges water back in to the tank through the discharge pipe. The flow rate of the pump was controlled by throttling valve in the discharge line. A turbine type flow meter measured the flow rate. Bourdon type pressure gauges measure the pressure in suction and delivery line. Through out the experiments, pump were run at the nominal speed of 1440 rpm by a 7.5 KW constant speed motor. The level of water in the tank has been maintained at 0.8 ± 0.02 m above the datum. The instrumentations included accelerometer B&K 4370 type, charge amplifier B&K 2635, 5006 type, vibration meter B&K 2511 type, voltmeter B&K 2425 type, B&K 2215 type precision sound level meter with octave-filters, B&K-2033 type FFT analyzer, pressure transducer, p.c.m. data tape recorder, cassette connecting cables etc.

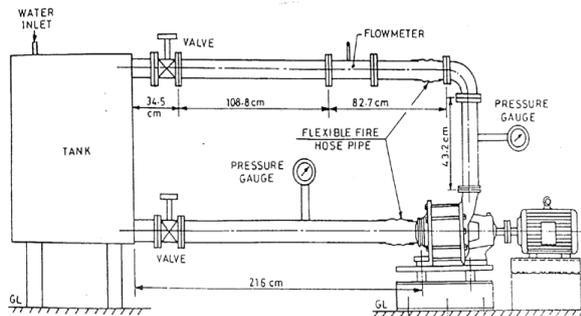


Fig.2. Schematic Diagram of Centrifugal Pump Test Rig

3.2 Experimental Procedure

The first-step in the operation of a centrifugal pump is priming in which the suction pipe, casing of the pump and portion of the delivery pipe up to the delivery valve are completely filled with the liquid which is to be pumped, so that all the air from this portion of the sump is driven out to ensure uninterrupted supply of liquid from the pump. After priming operation, the electric motor is started to rotate the impeller with the delivery valve still kept closed in order to reduce the starting torque for the electric motor. The rotation of the impeller in the casing full of liquid produces a forced vortex which imparts a centrifugal head to the liquid and thus results in an increase of pressure throughout the liquid mass. The increase of pressure at any point is proportional to the square of the angular velocity and the distance of the point from the axis of rotation. Opening of delivery valve forces the liquid to flow out from the pump casing outlet portion. At the eye of the impeller due to the centrifugal action a partial vacuum is created. This causes the liquid from the sump, which is at atmospheric pressure, to rush through the suction pipe to the eye of the impeller thereby replacing the liquid which is being discharged from the entire circumference of the impeller. The high pressure of the liquid leaving the impeller is utilized in lifting the liquid to the required height through the delivery pipe. The readings were carried out under three schemes of pressure pulsations, vibration and noise. A pressure transducer was placed between the impeller and the diffuser casing normally on one side and connected on other side to p.c.m. data tape recorder via. charge amplifier. The signal obtained from pump was fed in to the p.c.m. data tape recorder via. charge amplifier. The voltmeter was connected to the p.c.m. data tape recorder by connecting cables. The recorded signals were fed in to the voltmeter and readings obtained in millivolts were converted in pressure(Pa).The signals from pump were fed in to the tape recorder via cassette and played in recorder. The recorded signals were fed in to FFT analyzer and the signals were analyzed. For reading

the over all vibration level of the signal, the accelerometer was attached to the bearing housing in vertical position on side, while on other side it was attached to the vibration meter through the connecting cable. After performing appropriate settings on the vibration meter the readings were taken by changing the flow rates for the given impeller. The frequency component of the recorded signals were analyzed by the tape recorder connected to FFT analyzer and the signals were analyzed by playing cassette containing recorded signals. The over all noise levels were measured by placing a precision sound level meter at a distance of 1 meter from the casing edge. The readings were taken in linear and A mode. Frequency analysis of noise signal was done with octave filter in linear and A mode.

4.RESULTS AND DISCUSSIONS

The experiments were performed at five different flow rates for three different radial clearances between impeller and diffuser. The results section covers the details of overall levels, frequency spectra of pressure pulsations, vibration and noise for three different cases. Case I represents radial clearance of 6.8mm, Case II represents radial clearance of 3.7mm, Case III represents radial clearance of 1.5mm between impeller and diffuser of the centrifugal pump test rig.

4.1 Pressure Pulsations

The overall pressure pulsations level is plotted in **fig.3.** for different flow rates at delivery throttling. The level is seen to be with in the range 0.6-1.12Pa for Case I, 1.93-2.33Pa for Case II and 1.67-2.84Pa for Case III. The overall pressure pulsations level is more at low flow rates. The reason is that at lower flow rates there occurs many other disturbances like eddies, back flow turbulence etc. Also, the overall pulsations level is minimum when the radial clearance is maximum.

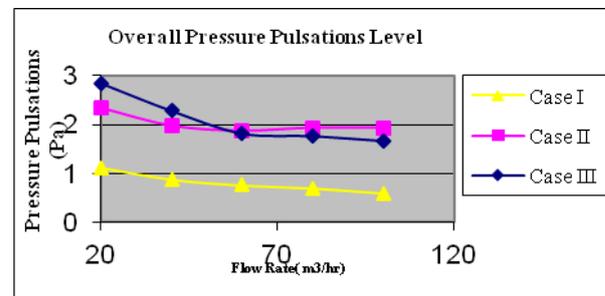


Fig.3. Overall Pressure Pulsations Level at Delivery Throttling for Different Flow Rates

Frequency analysis of pressure pulsations signal was carried out for three different cases at three different harmonics; viz; I harmonics at a frequency of 23.75 Hz, II harmonics at a frequency of 47.50 Hz, VIII harmonics at a frequency of 192.5 Hz.

Table.1. shows that pressure pulsations are maximum at the fundamental frequency for case I. The levels at I and VIII harmonics (Impeller Vane Passing Frequency) are comparable except at high flow rates where fundamental frequency dominates for case II. The levels at fundamental frequency and

Flow Rate, Q (m ³ /h)	Harmonics	Frequency (Hz)	Velocity(mm/sec.)		
			Case I	Case II	Case III
20	1 st	23.75	0.92	0.60	1.15
	2 nd	47.50	0.13	0.14	0.84
	8 th	192.50	0.21	0.29	1.12
40	1 st	23.75	0.94	1.97	1.06
	2 nd	47.50	0.23	1.60	0.84
	8 th	192.50	0.25	1.04	0.62
60	1 st	23.75	0.79	0.60	1.06
	2 nd	47.50	0.31	0.14	0.74
	8 th	192.50	0.20	0.29	0.27
80	1 st	23.75	0.71	1.76	0.92
	2 nd	47.50	0.21	0.41	0.56
	8 th	192.50	0.21	0.22	0.25
100	1 st	23.75	0.60	1.88	0.55
	2 nd	47.50	0.14	0.28	0.34
	8 th	192.50	0.29	0.32	0.18

vane passing frequency are comparable except at higher flow rates where fundamental frequency dominates for case III. The present study shows that with four times increase in the radial clearance, the reduction in maximum value of overall pressure pulsations level at delivery throttling comes out to around 50 %.

Table.1. Frequency Analysis of Overall Pressure Pulsations Level at Three Distinct Harmonics

4.2 Vibrations

The overall vibration level is plotted in **fig.4.** for different flow rates at delivery throttling. The level is seen to be with in the range 1-1.4mm/s for Case I, 1.1-1.45mm/s for Case II, and 1.4-1.6mm/s for Case III. The overall level is low at low flow rates and high at higher flow rates. Greater is the radial clearance more the flow is of erratic type, and the energy with which the fluid makes an impact on diffuser is low. Thus the overall vibration level is minimum at maximum radial clearance.

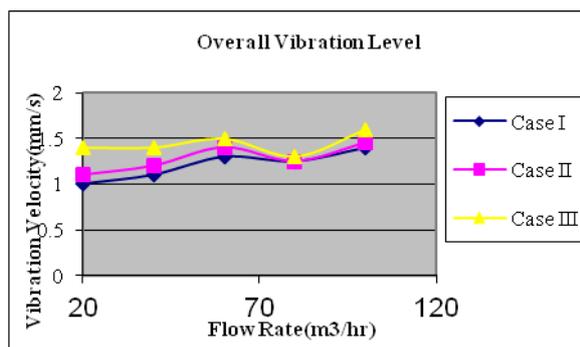


Fig.4. Overall Noise Level at Delivery Throttling for Different Flow Rates

Table.2. shows higher levels at I harmonics that are mainly due to the mechanical and hydraulic unbalance along with pressure pulsations. Hydraulic unbalance can be present either due to uneven spacing between vanes of impeller or stalled areas in the impeller channels. The II harmonics corresponds to misalignment. The VIII harmonics corresponds to the impeller vane passing frequency. Impeller vane pass component is not simply a higher harmonic of fundamental component but much more due to the shock experienced by pump casing. Hydraulic shock occurs as an impeller vane passes a diffuser vane resulting in generation of pressure pulsations. The resulting vibration has the same frequency. The intensity of shock depends on the radial clearance between impeller and diffuser vanes apart from other factors. The Overall levels are primarily governed by impeller vane pass frequency.

Table.2. Frequency Analysis of Overall Vibration Level at Three Distinct Harmonics

Flow Rate Q (m ³ /h)	Harmonics	Frequency (Hz)	Pressure Pulsations (dB)		
			Case I	Case II	Case III
20	1 st	23.75	83.8	95.0	72.6
	2 nd	47.50	70.3	77.9	63.2
	8 th	192.50	76.0	97.0	85.1
40	1 st	23.75	82.1	89.2	74.1
	2 nd	47.50	69.9	76.0	64.8
	8 th	192.50	73.3	90.5	83.6
60	1 st	23.75	83.7	90.4	74.7
	2 nd	47.50	70.6	66.7	60.4
	8 th	192.50	72.2	88.8	72.0
80	1 st	23.75	83.5	90.1	74.6
	2 nd	47.50	70.9	75.6	65.2
	8 th	192.50	69.8	85.0	76.4
100	1 st	23.75	81.0	90.3	76.6
	2 nd	47.50	71.7	75.2	67.9
	8 th	192.50	70.8	76.9	67.0

Wake effect at impeller-diffuser zone causes pressure pulsations which in turn induce noise and vibrations in the pump. Radial clearance affects the pressure pulsations and pump efficiency. Researches have shown that pump reliability is affected by this clearance. Therefore, smaller radial clearance is given prior preference. The present study shows that with four times increase in the radial clearance, the reduction in maximum value of overall vibration level at delivery throttling is around 30 %.

4.3 Noise

During the vibration investigations, only pump vibration was measured as the pump was isolated from all the sides. But in case of noise, the air borne sound pressure (including sound from pump and other components of test rig) was measured. Noise

signal analysis was carried out of the test rig. Overall background noise level was considered to be 58 dB. The overall noise level is plotted in **fig.5** .for different flow rates at delivery throttling. The noise level is seen to be with in the range 79-80dB for Case I, 80-85dB for Case II, and 80-83dB for Case III .The overall noise level is low at low flow rates

and high at higher flow rates. Moreover the overall noise level is minimum at maximum radial clearance . The present study shows that with four times increase in the radial clearance ,the reduction in maximum value of overall noise level at delivery throttling comes out to be around 5dB. The trends matches with that of vibration levels.

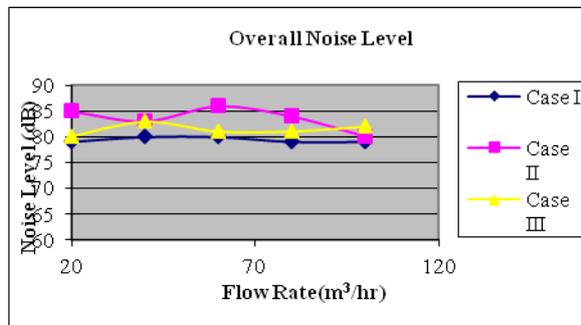


Fig.5. Overall Noise Level at Delivery Throttling for Different Flow Rates

Frequency analysis of noise signals are represented by **Table.3.** and **Table.4.** for cases with maximum and minimum radial clearances for the variations in the flow rates. Levels are higher in the frequency range 63 Hz – 250 Hz contributing to noise primarily and up to 2KHz the level remains comparable. The impeller diffuser interaction effect has the most effect in noise. As the fluid(water) comes out of the impeller and hits the diffuser blades, vibration of casing occurs and as a result pressure wave is generated in the air around it, which is measured. So the noise measured is the air borne noise. Diffuser vane pass frequency also falls in the range of central frequencies but precise

Table.3. Frequency analysis of overall noise level(dB) for Minimum Radial Clearance

Table.4. Frequency analysis of overall noise level(dB) for Maximum Radial Clearance

5. CONCLUSIONS

1. Pressure pulsations are dominating at fundamental frequency and the impeller vane passing frequency (8th harmonics). The overall pressure pulsations level is more at low flow rates and is minimum when the radial clearance is maximum. The reduction in maximum value of overall pressure pulsations level achieved at delivery throttling comes out to be around 50 % for four fold increase in the radial clearance.

2. Vibration is dominating at the fundamental frequency. The overall level is low at low flow rates and high at higher flow rates and is minimum at maximum radial clearance. The reduction in maximum value of overall vibration level achieved at delivery throttling comes out to be around 30 % for four fold increase in the radial clearance.

3. Noise is dominating at impeller vane passing frequency. The overall noise level is low at low flow

Central Frequency, f_c Hz	31.5	63	125	250	500	1000	2000	4000	8000	16000
Flow Rate, Q(m³/h)										
100	69	71	70	69	67	72	67	63	55	45
80	68	71	73	72	68	70	68	65	56	43
60	66	70	71	68	70	72	68	66	56	46
40	68	70	69	68	69	71	70	67	58	48
20	66	70	69	58	64	69	69	65	65	47

contribution to the noise level could be judged by frequency analysis with narrow band filter.

rates and high at higher flow rates. Moreover the overall noise level is minimum at maximum radial clearance . The reduction in maximum value of

Central Frequency, f_c Hz	31.5	63	125	250	500	1000	2000	4000	8000	16000
Flow Rate, Q(m³/h)										
100	69	75	73	74	72	74	72	68	59	49
80	68	66	65	70	73	73	73	72	74	68
60	68	74	71	74	74	74	72	68	59	51
40	68	74	72	74	73	74	73	68	59	50
20	67	74	68	72	70	71	71	67	58	49

overall noise level achieved at delivery throttling

comes out to be around 5 dB for four fold increase in the radial clearance.

4. A small radial clearance may be preferable for pump performance, head and efficiency but, it may initiate strong impeller/volute interaction, resulting in high pressure pulsation inside the pump and consequent higher vibrations and noise. Optimal adjustments of radial clearance in pumps can solve the above problems to a greater extent.

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