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Review

A Review of Pressure Fluctuations in Centrifugal Pumps without or with Clearance Flow

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Abstract: As crucial equipment in the industrial field, the stable operation of centrifugal pumps has drawn noteworthy attention. Relevant studies in the open literature have shown that intense pressure fluctuations have a major effect on the reliability and lifetime of centrifugal pumps. In the present paper, the pressure fluctuations in the centrifugal pumps are discussed in detail from different perspectives. The details of the studies are as follows. Firstly, the pressure fluctuation characteristics in centrifugal pumps are studied without considering clearance flow. Secondly, the pressure fluctuation property is investigated in detail for the pumps, with consideration for clearance flow. The pressure fluctuation characteristics in the wear ring, the pump-chamber clearance region, and the main stream region are studied, and the effect of clearance flow on the external performance of the pumps is analyzed. Thirdly, measures to reduce the pressure fluctuations and forces are summarized to improve the operational reliability of centrifugal pumps. Finally, conclusions and future research perspectives in the field of centrifugal pumps are presented. This review presents the research highlights and progress in the field of pressure fluctuations, which is beneficial to the stable operation of centrifugal pumps in engineering.

Keywords: pressure fluctuations; clearance flow; unsteady flow; centrifugal pumps

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1. Introduction

Centrifugal pumps are widely utilized in engineering circumstances related to power conversion and fluid transport, for example, in petrochemical industry, ocean engineering, aeronautical and astronautical industries, electricity industry, and hydraulic engineering. In almost all of the abovementioned applications, expanding the scope of stable and safe operation and improving efficiency can create enormous economic advantages to meet engineering requirements.

The internal flow characteristics of centrifugal pumps have a significant impact on the external characteristics. The instability of internal flow in centrifugal pumps is caused by rotor–stator interaction, boundary layer flow separation, rotating stall, formation and evolution of vortices, secondary flow, jet-wake structure, clearance flow and its interaction with main flow, etc. [1–3]. Among them, pressure fluctuation is notably observed in centrifugal pumps, which has a significant effect on the stable operation and lifetime of the devices. Under partial flow conditions, strong pressure fluctuations can affect the stability of pump operation through fluid–structure interactions, which can lead to premature mechanical failure in extreme cases, as shown in Figures 1 and 2 [4,5].

Previous studies on pressure fluctuations mainly focused on the main flow areas such as the impeller and volute in centrifugal pumps, and a large number of research results have been achieved as well. However, in addition to the main flow areas, there are also clearance areas such as wear-ring clearance, front and back chambers, and the balance hole. The existence of clearance flow in the pumps interacts with the main flow, resulting in extremely complex internal flow characteristics, and finally changes in characteristics such as pressure fluctuation. Research on clearance flow in centrifugal pumps started relatively late due to the limitation of computational resources as well as research needs. In the last decade, significant progress has been achieved in the area of clearance flow in centrifugal pumps. Related research includes a number of different aspects, from which this review paper is inspired. Therefore, this review paper first analyzes and concludes the distribution characteristics of pressure fluctuations in centrifugal pumps without considering clearance flow, and then studies and summarizes the distribution characteristics of pressure fluctuations in the pumps with clearance flow. Finally, the measures used to reduce pressure fluctuations and forces in pumps are summarized.

Figure 1. Typical impeller shroud failure [4].

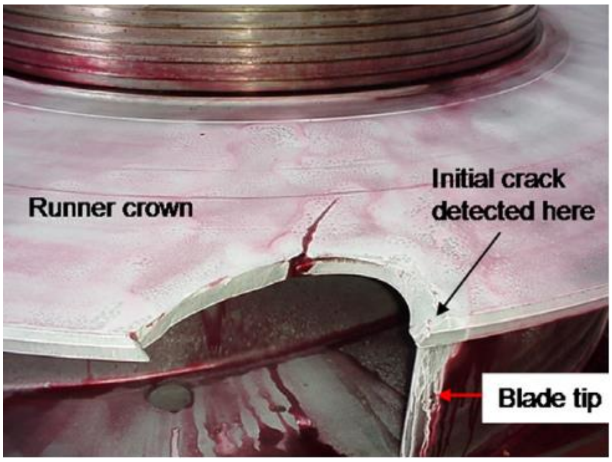


Figure 2. A picture of the broken runner [5].

The typical three-dimensional (3D) model of a centrifugal pump is given in Figure 3, as illustrated in Ref. [6]. The high-pressure fluid flowing out of the impeller outlet flows into the impeller through the clearance areas, which is shown in Figure 4 [7]. Although of small size, it seriously affects the comprehensive performance and operation stability of centrifugal pumps. Figure 5 shows the influence of clearance flow on the pressure fluctuations at the monitoring point near the volute wall. The dimensionless coefficient c_p is commonly used in the study of pressure fluctuations in centrifugal pumps, which is defined as follows:

$$c_p = \left(p - p_{ref}\right)/0.5\rho u_2^2 \quad (1)$$

where p_{ref} denotes the reference pressure and u_2 denotes the impeller circumferential velocity. The results show that the clearance flow attenuates the intensity of pressure fluctuations at the monitoring point near the wall of the volute casing. There is a great difference in the results of pressure fluctuation whether or not the clearance flow is considered, as shown in Figure 5 [8]. The results show that the amplitude of pressure fluctuations at monitoring point P1 in model A considering the clearance flow is significantly lower than that of model B without considering the clearance flow. The amplitude of the blade passage frequency at monitoring point P1 in model A decreased by 56.38% compared to model B. This also illustrates the significant effect of clearance flow on the pressure fluctuation characteristics in the pump. With expanding research on the pressure fluctuation characteristics in the pumps, the influence of clearance has been drawing great attention. Experimental methods, numerical methods, and theoretical analysis methods are widely used in studying clearance flow in centrifugal pumps [9–11].

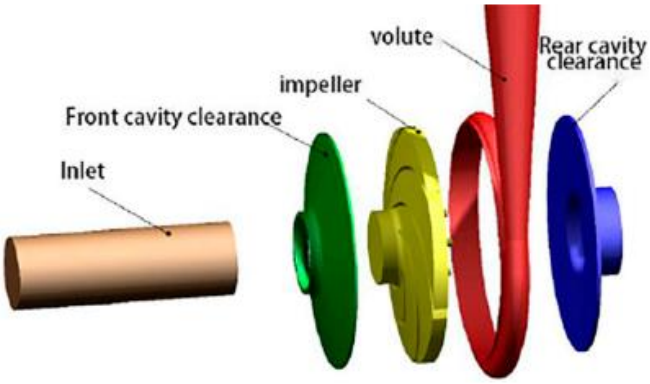


Figure 3. Computational domain of the flow field [6].

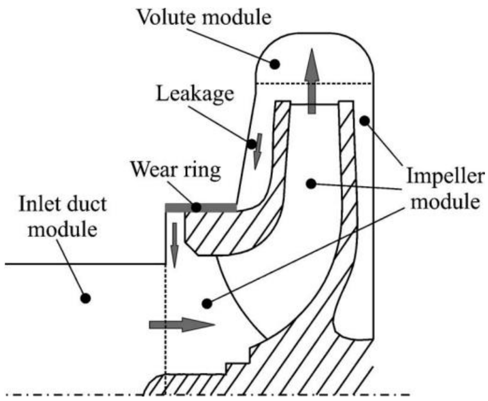
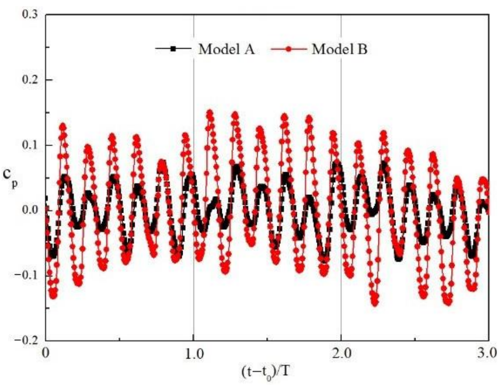
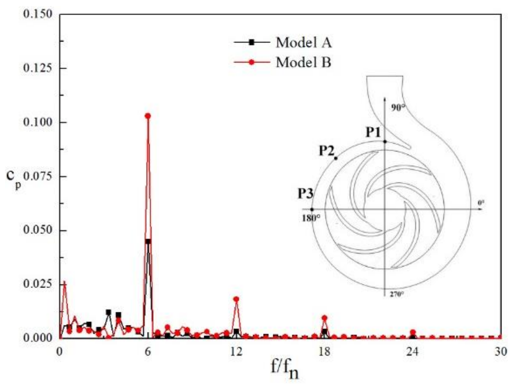


Figure 4. Flow through pump and leakage from volute to impeller eye [7].



(**a**) Pressure fluctuation at P1



(**b**) Pressure spectra at P1

Figure 5. Pressure fluctuation and frequency spectra at selected monitor points (model A includes the clearance region and model B does not contain the clearance region) [8].

Extensive studies have been carried out on the characteristics of pressure fluctuations inside the centrifugal pumps with or without considering clearance flow. Each study is usually conducted for a specific parameter, while centrifugal pumps have a complex structure and a diversity of factors affecting pressure fluctuation. However, there are relatively fewer studies on pressure fluctuations that comprehensively summarize the various influences from different aspects, including clearance flow. Therefore, a comprehensive and systematic review that synthesizes the related research is urgently needed and meaningful. This paper systematically summarizes the progress of research on pressure fluctuations in centrifugal pumps and proposes potentially valuable research directions to provide guidance for researchers in related fields. The following aspects are discussed and summarized in this review paper: (a) pressure fluctuations in centrifugal pumps without clearance flow; (b) pressure fluctuations in centrifugal pumps with clearance flow; and (c) precautions and countermeasures.

2. Pressure Fluctuations in Centrifugal Pumps without Clearance Flow

The strong hydrodynamic interaction at the impeller outlet strongly influences the unsteady flow and pressure distribution in centrifugal pumps. Limited by computational resources and research needs, early studies of centrifugal pumps mainly considered the main over-flow components, such as the impeller and volute; the clearance regions were often neglected.

2.1. Study of the Effect of Flow Conditions on Pressure Fluctuations

Centrifugal pumps have a wide range of flow rates and the pressure field distribution varies significantly at different flow rates. As a result, much research has focused on the effect of changes in flow rate conditions on the intensity of pressure fluctuations in centrifugal pumps. Wu et al. [12] investigated the pressure fluctuations by using numerical calculation and dynamic pressure transducers. Results show that broadband pressure fluctuations are caused exclusively by flow instabilities, especially at part-load condition. The strong pressure fluctuation between the impeller and the volute tongue has a significant effect on the pump performance. Therefore, Zheng et al. [13] focused on the evolution of pressure fluctuation characteristics near the volute tongue at various flow rates. By studying the processes of the blades close to and far from the tongue, it was found that the intensity of the pressure fluctuation is closely related to the impeller outlet vortex structure and the position of the blades relative to the tongue. In addition, Ma et al. [14] also carried out a study of the pressure fluctuation characteristics in a centrifugal pump at different flow conditions and found that the amplitude and the intensity of the pressure fluctuation is closely related to the flow rate and spatial location.

Stall can be a common flow structure in centrifugal pumps, which may seriously affect the pressure fluctuation of the machinery [15–17]. Zhao et al. [18] studied the relationship between pressure fluctuation characteristics and rotating stall in centrifugal pumps. The results suggest that the interaction of the stall cell with the volute tongue also influences pressure fluctuations. Coherent analysis of rotational stall detection in centrifugal pumps based on pressure fluctuation signals was carried out by Zhang et al. [19]. The correlation between the flow condition and the low frequency signal was obtained by applying root mean square (RMS) analysis, which is defined as follows:

$$RMS = \sqrt{\frac{1}{2}\left(\frac{1}{2}A_0^2 + \sum_{n=2}^{n-1} A_{n-1}^2 + \frac{1}{2}A_n^2\right)} \quad (2)$$

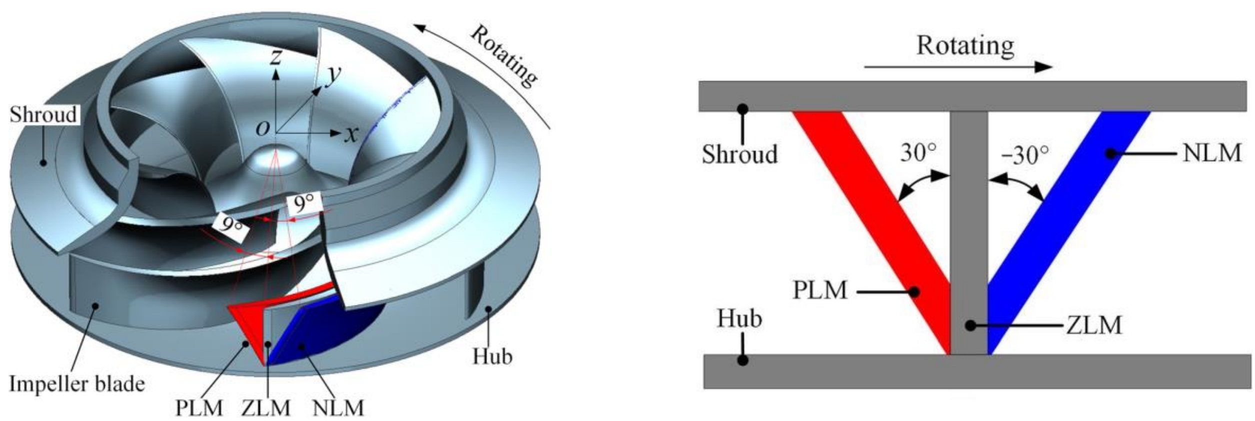
where A_n indicates the pressure amplitude at a typical frequency. RMS represents the entire fluctuation energy of a specific frequency band. The results demonstrate that the unsteady pressure signal is remarkably affected by the rotating stall characterized by an increase in the amplitude of the fluctuations and an increase in the low frequency component generated in the pressure spectrum. In addition to steady operating conditions, centrifugal pumps inevitably experience transient conditions such as startup and shutdown, and other flow change processes, which have a significant impact on the pressure fluctuation characteristics of centrifugal pumps [20–24].

2.2. Study of the Influence of Structure Parameters on Pressure Fluctuations

Studies on the influence of the structure parameters of centrifugal pumps on the pressure fluctuations have focused on the inlet structure, impeller structure, guide-vane structure, and volute structure.

In terms of inlet structure influence studies, Ye et al. [25,26] conducted a study of the effect of straight inlet sections versus nonstraight inlet sections on pump performance and pressure distribution. There has been some research on the inlet guide vane on unsteady flow and pressure fluctuation characteristics in centrifugal pumps, and certain research results have been obtained [27–29]. Liu et at [30] used a combination of numerical calculations and experiments to investigate the effect of inlet guide-vane geometry on pressure fluctuation characteristics of centrifugal pumps. The results of the study show that the intensity of pressure fluctuations in the pumps can be effectively reduced by arranging the guide-vane structure with six blades on the inlet pipe.

As an important working and flowing component of centrifugal pumps, changes in the impeller structure have a great impact on the strength of pressure fluctuations. Some research has been carried out on the effect of different blade numbers, blade thickness, splitter blade, and different vane layouts on the pressure fluctuation characteristics in the pumps [31–36]. In addition, some research has been carried out on the gap drainage impeller, and good results have been obtained [37,38]. Zhang et al. [37] used a combination of the hybrid Reynolds-average Navier–Stokes / large-eddy simulation (RANS/LES) method and experiment to investigate the effect of twisted gap drainage blades on pressure fluctuation characteristics and performance. The results show that the 3D-gap blades can effectively improve the hydraulic performance of the centrifugal pump and reduce the intensity of pressure fluctuations. Zeng et al. [39] studied the effect of two different trailing-edge lean-mode methods of the blades on the pressure fluctuation characteristics of centrifugal pumps with guide vanes, as shown in Figure 6. The results show that the impeller structure with positive lean mode (PLM) has a significant effect in reducing the intensity of pressure fluctuations in the pumps.



(**a**) impeller (**b**) different lean modes

Figure 6. Geometric differences in the tested impeller (ZLM stands for zero lean mode; NLM stands for negative lean mode) [39].

In the previous research, the large amplitude of pressure fluctuation was identified near the tongue region, which greatly affects the pressure fluctuation level of the pump [40]. The effect of the number of grooved volute casing parameters on the performance of the centrifugal pump and the pressure fluctuation characteristics was investigated by

Shen et al. [41]. The results show that as the number of grooves increases, the intensity of pressure fluctuation in the pump can be significantly reduced.

Other research on pressure fluctuations of pumps are summarized in Table 1.

Table 1. Related research in pumps without clearance flow.

References	Object	Brief Conclusion
Li et al. [42]	high-speed micro centrifugal pump	In cavitation or noncavitation conditions, the main frequency of pressure fluctuation is still dominated by the blade-passing frequency.
Liu et al. [43]	double suction centrifugal pump	Inlet splitter can effectively reduce the intensity of pressure fluctuation.
Jin et al. [44]	double suction centrifugal pump	Impeller types that are staggered in the circumferential direction may be beneficial for pressure fluctuations.
Binama et al. [45]	pump as turbine	The blade-passing frequency and its harmonics are the main frequencies in the pump as turbine (PAT). Blade trailing edge positions may increase or decrease the pressure fluctuation intensity.
Chai et al. [46]	pump as turbine	The pressure fluctuation amplitude is greatest at initial startup time. As the speed increases, the pressure fluctuation amplitude decays rapidly in the volute, but decays slowly in the impeller.

3. Pressure Fluctuations in Centrifugal Pumps with Clearance Flow

Clearance flow has a significant impact on the external characteristics of centrifugal pumps. The difference in flow scale between clearance flow and the main flow causes a sharp increase in the total number of meshes in order to obtain accurate numerical calculation results for the whole flow field in centrifugal pumps. Therefore, numerical calculation for the pumps requires ample computing resources and consumes much computing time. With the development of high-performance computing in recent years, the foundation for the study of clearance flow in centrifugal pumps has been established. At the same time, experimental studies are also widely used in the study of pressure fluctuations in pumps with clearance flow. The study of pressure fluctuations in centrifugal pumps with clearance flow is discussed and summarized in the following subsections.

3.1. Study of Pressure Fluctuation Characteristics in the Wear Ring

Wear-ring clearance is an important part of the internal clearance in centrifugal pumps. Wear-ring clearance includes the front and rear wear-ring clearances. Wear-ring clearance is composed of a pair of sealing rings mounted on the impeller and casing. The wear-ring clearance can effectively reduce the loss of high-energy fluid at the impeller outlet, and thus minimizes the volume loss. Bruurs et al. [47,48] used a combination of numerical calculations and theoretical analysis to study the pressure distribution in a multistage centrifugal pump. The effect of wear-ring clearance variation on transient flow in a centrifugal pump was analyzed by Liu et al. [49]. The results obtained show that the distribution of unsteady pressure inside the front sidewall gap is closely related with the wear-ring clearance and radial position, and maximum pressure fluctuations appear at part-load conditions. The characteristics of the static pressure distribution in the front chamber with different wear-ring clearances were also obtained, and the sudden pressure change is captured at the front wear-ring clearance, as shown in Figure 7.

Gao et al. [50] carried out the numerical analysis and experimental research on the performance and hydraulic excitation characteristics of a centrifugal pump with different wear-ring clearances. Four pressure monitoring points were placed at the wear-ring clearance to obtain pressure fluctuation characteristics at different wear-ring clearances. By analyzing the experimental results, it was found that the main frequency of the pressure fluctuation at the wear ring remained consistent with the blade-passing frequency. As the wear-ring clearance increases, there exists a wear-ring clearance that allows the pressure fluctuation amplitude to take an extreme value. With the assistance of computational fluid dynamics (CFD) and experimental techniques, complex pressure fluctuation characteristics under different flow conditions can be quickly and efficiently analyzed. The pressure fluctuation monitoring points are distributed in four azimuths (A–D) at the back pump-chamber wall and two azimuths (E–F) at the front pump chamber wall, as shown in Figure 8 [51]. There are three pressure monitoring points arranged at each azimuth of the back pump-chamber wall. In the E azimuth of the front pump chamber, E2 and E3 are the front pump-chamber pressure monitoring points, and E1 is the pressure monitoring point at the wear-ring clearance. The distribution of pressure monitoring points in Figure 8 is a layout method often adopted for pressure fluctuation measurement in the clearance area of centrifugal pumps. The number and location of specific monitoring points can be adjusted according to the research requirements.

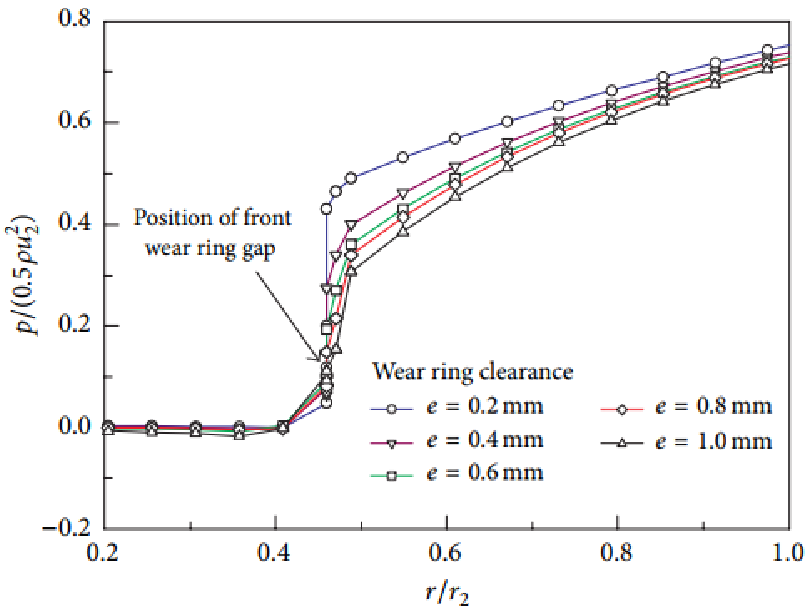


Figure 7. Comparisons of static pressure distributions inside the front sidewall gap with wear-ring clearance variation under the design flow condition [49].

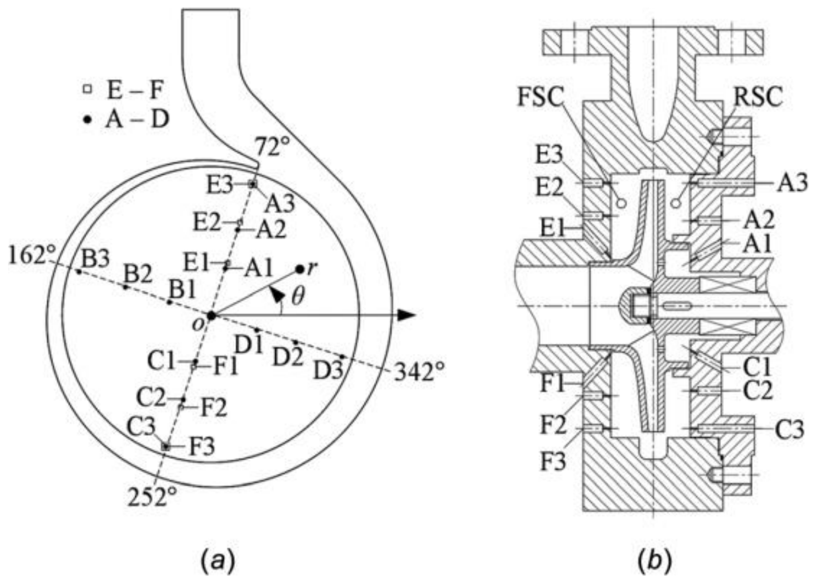
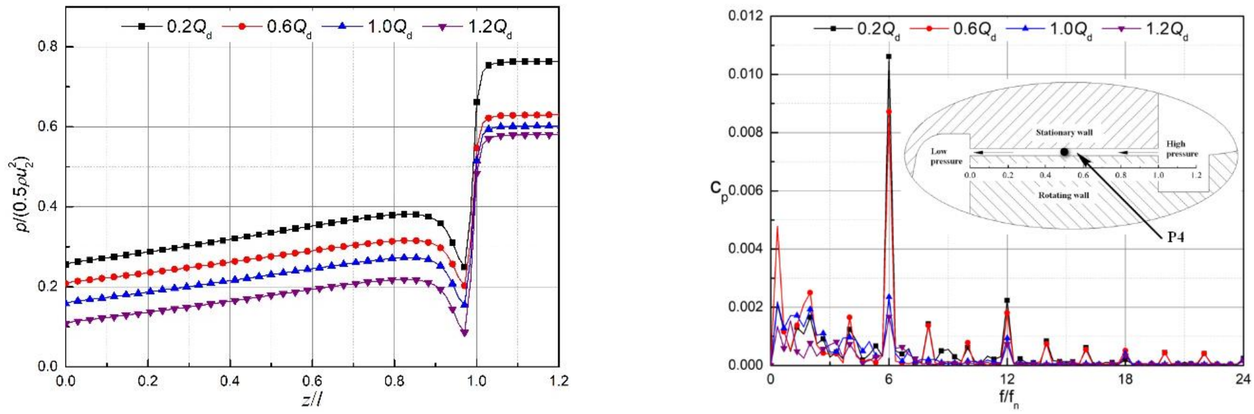


Figure 8. Pressure measuring points: (**a**) front view and (**b**) sectional view (FSC stands for front shroud chamber; RSC stands for rear shroud chamber [51].

In recent years, Zheng et al. [52] have studied by experimental and numerical methods the distribution characteristics of pressure fluctuation characteristics at different locations in the centrifugal pump under various flow conditions. The static pressure distribution inside the wear ring is presented in Figure 9a. There is a sudden decrease in static pressure at the inlet of the wear ring, followed by a certain degree of pressure recovery, which is closely related to the small scale and the sudden change in geometry at the wear ring. As can be seen in Figure 9b, the dominant frequency for pressure fluctuation in the wear-ring clearance is the blade-passing frequency, whose amplitude decreases with the increase in the flow rate.



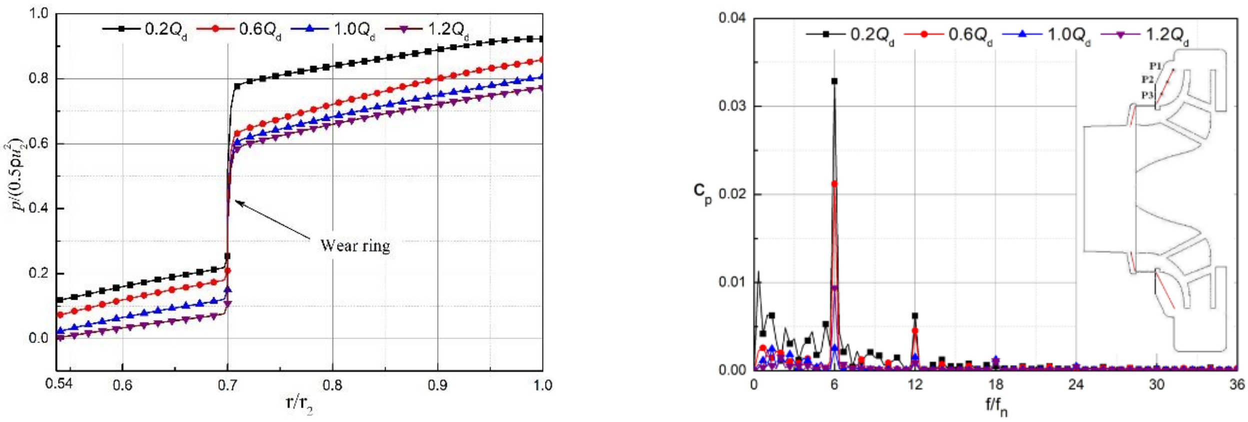
(**a**) Pressure distribution (**b**) Pressure fluctuation distribution

Figure 9. Distribution of wear-ring pressure and pressure fluctuation characteristics [52].

On the whole, the pressure distribution in the chamber of centrifugal pumps is subject to abrupt changes at the wear ring due to the tiny scale of the wear ring and its geometric structure. The pressure fluctuation at the wear ring is still governed by the blade-passing frequency. In addition, a combination of numerical calculations and experiments has proven to be an efficient method to study the pressure fluctuations in wear-ring clearance.

3.2. Study of Pressure Fluctuation Characteristics in Pump Chambers

The pump chambers consist of a front chamber and a back chamber. The most common and effective experimental method for obtaining pressure fluctuations in the pump chambers is through the use of a pressure transducer to collect pressure data from the pressure measuring holes in the walls of the pump chambers. The pressure fluctuation characteristics inside an axial-clearance variable centrifugal pump were studied by using experimental and computational methods [53]. It was found that the pressure intensity inside the front pump chamber does not rise or fall monotonically with increasing front axial clearance size. The blade-passing frequency is the dominant frequency for pressure fluctuation in most areas of the front pump chamber, while the remaining areas are influenced by the back-blades. The study of pressure fluctuation in the small sidewall gaps of a centrifugal pump show that several frequency components appear as dominant frequencies at different locations in the sidewall gap, but the relatively strong pressure fluctuations are dominated by the rotating frequency [54]. The pressure distribution characteristics and pressure fluctuations in the front chamber of a centrifugal pump are shown in Figure 10 [52]. The existence of a clearance in the pumps allows the high-energy fluid from the impeller outlet to flow to the impeller inlet via the wear ring. Therefore, as the radial radius decreases and the flow rate increases, the pressure in the front chamber shows a decreasing trend and an abrupt pressure drop that occurs at the wear-ring position. The pressure fluctuation in the front chamber is still dominated by the blade-passing frequency, and the intensity of the pressure fluctuation decreases as the radial radius of the probing points decreases. The internal pressure fluctuation characteristics of centrifugal pumps with a vaned diffuser were experimentally investigated by Liu et al. [55]. The results of the study show that the dominant frequency of pressure fluctuation in the front chamber is still the blade-passing frequency.



(**a**) Pressure distribution in radial direction (**b**) Pressure fluctuation distribution

Figure 10. Distribution of pressure and pressure fluctuation characteristics in the front cavity [52].

Studies have shown that the front chamber has a greater impact on pump performance than the back chamber. The study of pressure fluctuation characteristics in the back chamber is slightly less than that in the front chamber. The study of the back chamber mainly focuses on the internal flow and the pressure field distribution [51,56,57]. The effect of the balance hole diameter on the flow characteristics of the back chamber in a centrifugal pump has also been carried out [58]. This study also illustrates that the experimental approach is an effective way to obtain data on the pressure characteristics in the pump chamber.

The flow in the pump chamber is influenced by the rotating wall surface, the stationary wall surface, and the narrow size structure such as the clearance. In general, previous studies have shown that the front chamber has a stronger effect on centrifugal pump performance than the back chamber. The static pressure in the front chamber increases with increasing radial radius. The frequency of pressure fluctuations in the pump chamber is mainly dominated by the blade-passing frequency for chambers without back-blades. Additionally, the intensity of the pressure fluctuations increases with the increase in radial radius.

For the study of pressure characteristics in the pump chambers, an experimental approach allows direct and effective acquisition of pressure fluctuations in the clearance. At the same time, the numerical calculation method can obtain the flow structures inside the pumps. The combination of numerical calculation and experimental method is an efficient technique to study the pressure fluctuation characteristics inside the pump chambers.

3.3. Other Research on the Pressure Fluctuation Characteristics

The study of the pump as turbine has attracted increasingly more scholars [59]. Lin et al. [60] studied the flow separation and pressure characteristics in the impeller of a pump as turbine (PAT) under a design condition. Hu et al. [61] studied the flow transient characteristics inside the pump as turbine. The research results indicate that the pressure fluctuation at the monitoring point in the volute shows a periodic distribution, and the number of peaks and troughs corresponds to the number of blades. With the increasing requirements of equipment, high-speed centrifugal pumps have also attracted the attention of increasingly more scholars. Wang et al. [62] studied the effect of weak compression on the pressure fluctuation caused by rotor–stator interaction in a high-speed centrifugal pump. The results of the study show that there is a slight increase in pump performance affected by the weak compressibility effect, in addition to the magnitude of pressure, the fluctuation is also affected to some extent by the weak compressibility effect.

Some studies have also been conducted on the pressure fluctuation characteristics in axial flow and mixed flow pumps. Chen et al. [63] investigated the effect of suction and discharge configurations on the unsteady flow in an axial-flow reactor coolant pump. Studies have shown that the pressure fluctuation in the impeller is greatly influenced by the changes in the suction and discharge configurations. Yang et al. [64] analyzed the distribution of pressure fluctuation characteristics in an axial flow pump with a guide vane. The results showed that the dominant frequency at each monitoring probe is essentially the blade-passing frequency, and the secondary dominant frequency is twice the blade-passing frequency. Liu et al. [65] investigated the unsteady flow characteristics in a PAT at pump mode for different blade rotation angles and found that the dominant frequency of the pressure fluctuation under certain conditions is determined by the oscillatory characteristics of the tip-leakage vortex (TLV).

Some studies have also been conducted on the pressure fluctuation characteristics in multistage pumps. Zhang et al. [66] studied the pressure fluctuation in a multiphase pump with different gas volume fractions and obtained the dominant frequencies in the impeller and guide vane. The distribution characteristics of pressure fluctuations in the full flow field of a two-stage centrifugal pump were studied by Wang et al. [67]. The results show that the main frequency of pressure fluctuation in the impeller corresponds to the diffuser blade frequency, while the main frequency of pressure fluctuation in the diffuser and volute corresponds to the impeller blade frequency. Zhai et al. [68] investigated the unsteady flow characteristics of a ten-stage centrifugal pump with blade-type guide vanes and found that the dominant frequency of pressure fluctuation in each stage guide vane is the blade passage frequency.

Other research on clearance flow and pressure fluctuations in pumps is summarized in Table 2.

Table 2. Related research in pumps with clearance flow.

References	Object	Brief Conclusion
Zhang et al. [69]	multiphase pump	The dominant frequency and maximum amplitude of pressure fluctuations increase with the increase in tip clearance.
Yu et al. [70]	pump–jet propulsor	The pressure fluctuation amplitude on the blade surface increases significantly with the increase in tip clearance.
Shen et al. [71]	axial flow pump	The rotation of the impeller dominates the pressure pulsations in tip region.
Shi et al. [72]	full tubular pump	The dominant frequency of pressure pulsation in a full tubular pump decreases with the increase in flow rate, and the pressure pulsation at impeller inlet is dominated by blade-passing frequency.
Lu et al. [73]	centrifugal pump	The main frequency amplitude of pressure fluctuation near the tongue gradually decreases with the occurrence and development of tongue cavitation.

3.4. Study of Pressure Fluctuation Characteristics in the Mainstream Area

In order to study the extent of the effect of clearance on pressure fluctuations in centrifugal pumps, studies have been carried out on the pressure fluctuation characteristics of pumps with and without clearance flow. Zheng et al. [8] investigated the pressure fluctuation characteristics at the volute wall of two centrifugal pump models with and without clearance at low-flow conditions. The results show that for both centrifugal pump models, the blade-passing frequency is still the main frequency of the pressure fluctuation. The difference lies in the magnitude of the main frequency of the pressure fluctuation amplitude. The clearance flow causes the loss of high-energy fluid at the impeller outlet, which reduces the intensity of the pressure fluctuation in the pump. Research has been carried out in the area of geometry on pump pressure fluctuation characteristics. Using the LES method, Posa [74] studied the effect of the diffuser inlet angle on pressure fluctuations in a centrifugal pump. Studies have shown that reducing the angle of incidence by changing the orientation of the diffuser blades under off-design conditions can be beneficial to pump performance and pressure fluctuations. Studies have also been conducted on the pressure fluctuation characteristics in the pump with respect to the trailing edge structure of the blades [75].

In terms of off-design operating conditions, Zhang et al. [76] used the delayed detached eddy simulation (DDES) method to study the evolution of unsteady flow in a centrifugal pump under partial flow conditions and the pressure fluctuation characteristics. The results of the study show that the pressure spectrum is affected under rotating stall conditions, including the blade passage frequency and low frequency components. Studies have also been conducted on the pressure fluctuation characteristics in a double-suction centrifugal pump with respect to the flow rate and rotational speed [77,78].

Many scholars have studied the pressure fluctuation characteristics in the mainstream region of the whole flow field inside the centrifugal pump, and some conclusions have been reached. In general, the clearance flow causes a loss of energy in pumps and a certain impression on the amplitude of pressure fluctuations in the centrifugal pumps.

3.5. Study of the Effect of Clearance Flow on Pump External Characteristics

In early research, the clearance flow of centrifugal pumps was rarely studied. The fluid domain between the impeller hub/shroud and casing was usually neglected during the geometric simplification of centrifugal pump models. The existence of clearance flow in pumps can cause leakage of high-energy fluid from the impeller outlet, which has a large impact on the external characteristics of centrifugal pumps and their internal flow characteristics. Therefore, detailed analysis on clearance flow characteristics and their influence on the external characteristics of centrifugal pumps are of great significance.

Accurate calculation of clearance flow in pumps requires a complex computational mesh and extensive computational resources. The quality of the structured meshing of the whole flow field plays an important role in studying the effect of clearance flow on pump performance. Li et al. [79] used Integrated Computer Engineering and Manufacturing (ICEM) software for structured meshing of the whole flow field inside a centrifugal pump, detailing the requirements for the delineation of high-quality meshes. The meshes of important over-flow components such as volute casing and the impeller were optimally delineated, and the meshes of near-wall surfaces and boundary layers were encrypted. The total number of meshes for the final calculation reached 17.8 million, and the detailed structure of the mesh is shown in the Figure 11. The effect of different mesh node numbers of the wear-ring clearance on the flow characteristics inside a centrifugal pump was carried out [52]. The results suggest that a smaller number of mesh nodes in the wear-ring clearance may lead to deviations in the turbulent kinetic energy data, as shown in Figure 12. Therefore, numerical calculation of the whole flow field in centrifugal pumps demands higher requirements for the whole flow field computational mesh.

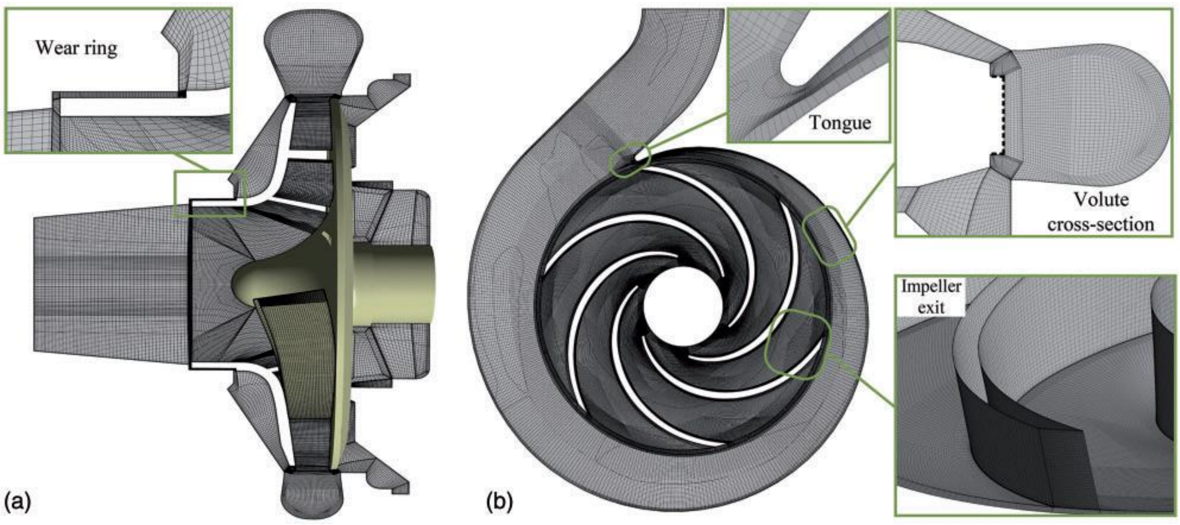


Figure 11. Grid view of a centrifugal pump: (**a**) axial section view and (**b**) middle section view [79].

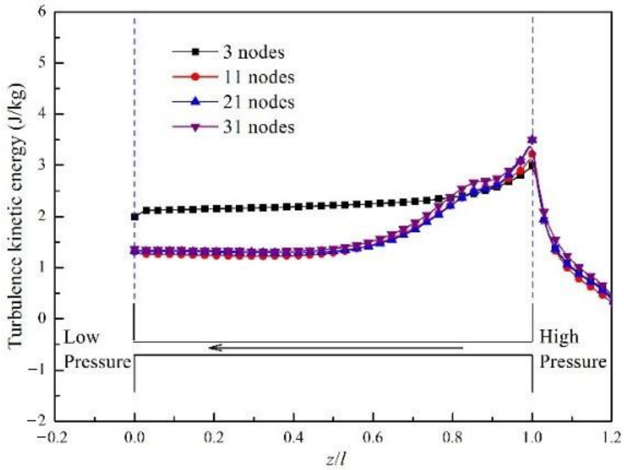
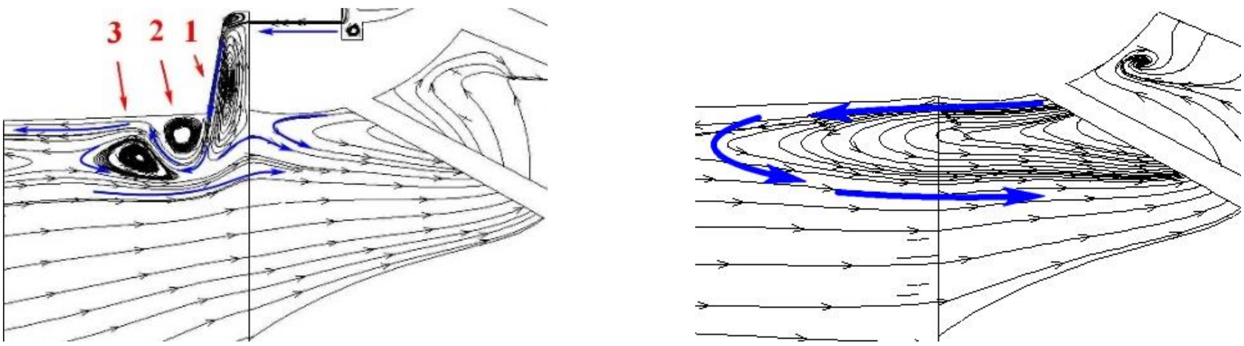


Figure 12. Turbulent kinetic energy distribution on the center line of the wear ring [52].

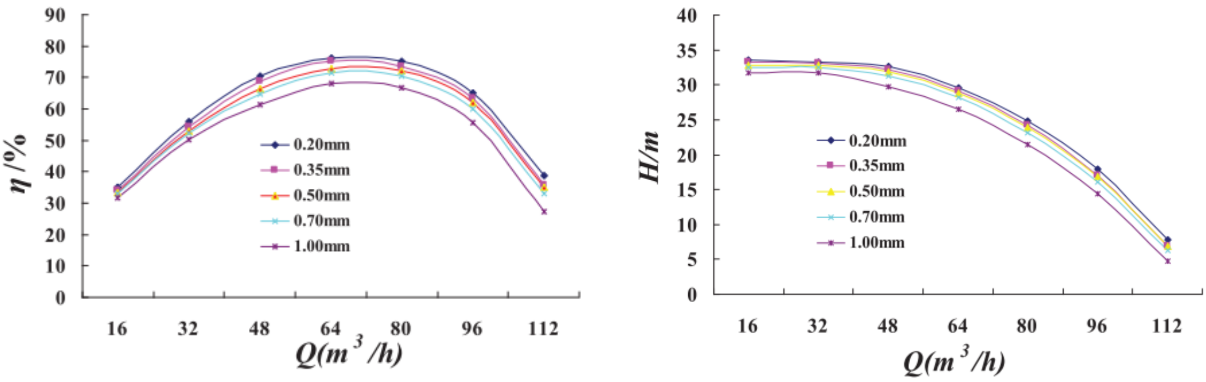
The study of the external characteristics of centrifugal pumps with and without clearance and the internal flow field has been carried out by Jiang et al. [80]. The result shows that the head and efficiency of a pump with clearance are lower compared to the simplified centrifugal pump model without clearance area, and the variability of the calculated results is also reflected in the internal flow field. The effect of clearance flow on external characteristics and internal flow field of centrifugal pumps carried out by Zheng et al. [8] also proves that the effect of clearance flow must be considered, as shown in Figure 13. There is a significant difference in the flow structure of the impeller inlet for the pump with or without considering clearance flow. There is a multivortex structure in front of the impeller inlet of pump model A considering clearance flow, and the vortices are indicated by the numbers 1, 2, and 3. The multivortex structure in front of the impeller inlet of model A is a significant flow phenomenon that distinguishes it from model B, which does not consider clearance flow. Therefore, in studying the internal flow field and the external characteristics of centrifugal pumps, the effect of the clearance flow must be considered.



(**a**) Model A (with clearance area) (**b**) Model B (without clearance area)

Figure 13. Absolute velocity distribution within the cross-section of a centrifugal pump [8].

As an important part of the leakage channel, the wear-ring clearance also has a vital impact on centrifugal pump performance [50,81–85]. Shi et al. [83] used a combination of numerical calculations and experiments to study the effect of wear-ring clearance variation on pump external characteristics. Figure 14 shows the results of efficiency and head under different wear-ring clearance at various flow rates. The parameter Q (m^3/h) indicates the flow rate of the centrifugal pump. It was found that the pump head and efficiency decrease with the increase in the wear-ring clearance. In addition, the effect of the front wear-ring clearance on pump energy performance is stronger than that of the back wear-ring clearance.



(**a**) pump efficiency (**b**) head

Figure 14. Comparison of the performance characteristic under different clearances [83].

In addition to the size of the wear-ring clearance, the structure of wear-ring clearance also has an important impact on pump performance. Yan et al. [86] studied the effect of different wear-ring clearance sizes and structure on pump external performance. Results suggested that with the increase in the clearance width, the mechanical loss, volume loss, and hydraulic loss of the pump increase, and the efficiency of the pump under each working condition decreases by different degrees. As far as the wear-ring clearance structure is concerned (Figure 15), the pump performance with the labyrinth seal is generally higher than that with the flat-ring seal. Jia et al. [6] investigated the effect of the incidence angle of the wear-ring clearance on pump performance, as shown in Figure 16. The results of the study show that as the angle of incidence of the wear-ring gap decreases, the higher the head and efficiency of the pump.

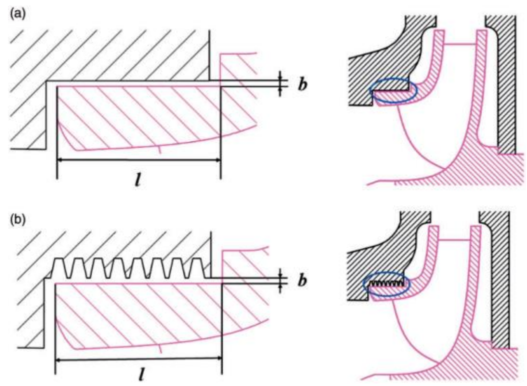


Figure 15. The diagram of wear-wing clearance: (**a**) flat-ring seal and (**b**) labyrinth seal [86].

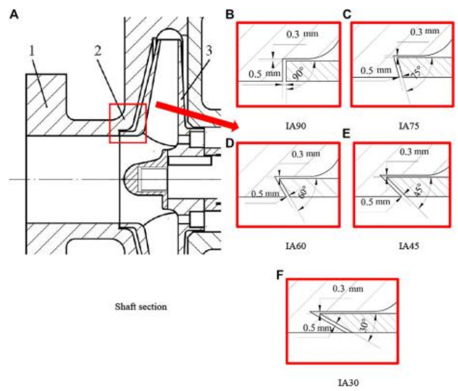


Figure 16. Diagram of incident angle for different wear-ring clearances [6].

Variations in the chamber clearance also have an impact on the external performance of centrifugal pumps. The effect of axial clearance variation on the external performance of centrifugal pumps was studied by Cao et al. [87]. The results show that the increase in front cavity clearance leads to a decrease in efficiency and head. The volumetric efficiency is the most sensitive to the variation in axial clearance and is the key factor for the variation in total efficiency among hydraulic, volumetric, and mechanical efficiencies. In addition, the balance hole also has an impact on the performance of pumps. Related studies have shown that with the increase in the balance hole, the head and efficiency of the pump tends to decline [88].

Insufficient pump mesh quality may lead to deviations in the internal flow field calculation results. Therefore, numerical calculation of the full flow field inside a centrifugal pump has extremely high mesh requirements, which are necessary to provide a guarantee for subsequent accurate analysis data for the pumps. The existence of the clearance, especially wear-ring clearance, causes the loss of high-energy fluid at the impeller outlet, which in turn affects the external characteristics of pumps. The effect of the front wear-ring clearance on the pump external characteristics is higher than that for the back wear-ring clearance. With the increase in wear-ring clearance, the pump head and efficiency are reduced. In addition, a suitable wear-ring structure can improve the pump performance to a certain extent.

4. Precautions and Countermeasures

Strong pressure fluctuations have an important impact on the reliability of centrifugal pump operation, so it is necessary to consider the appropriate measures to limit the intensity of pressure fluctuations in pumps. The strong pressure fluctuations generated during the operation of the centrifugal pump also cause changes in the pressure field inside the pump. Changes in fluid pressure in pump chambers directly cause variation in the force on the impeller, which in turn has an impact on the operational reliability of centrifugal pumps. Complex unsteady clearance flows may cause the equilibrium between radial and axial forces to break down and put additional loads on the bearings. Under the influence of strong rotation, the unbalanced forces may eventually lead to failures or even accidents. Therefore, the method for reducing pressure fluctuations in pumps should be studied along with the measures to reduce axial and radial forces.

4.1. Initiatives to Reduce the Intensity of Pressure Fluctuations in Pumps

Much research has been carried out concerning rotor–stator interaction in centrifugal pumps, and the distribution of pressure fluctuations has been obtained. Previous studies have shown that the large intensity of pressure fluctuations in centrifugal pumps has a great impact on the stable operation of centrifugal pumps, and the intensity of pressure fluctuation is closely related to the flow conditions, structure parameters, and other factors. Thus, the reduction in pressure fluctuations in pumps is one of the important research directions to be considered in the future design of pumps.

There have been some attempts to reduce the intensity of pressure fluctuations in pumps by changing the volute structure. The pressure fluctuation in a centrifugal pump with a slope volute was studied by experimental tests and numerical simulations [89,90]. A comparison shows that the slope volute could significantly reduce the pressure fluctuation level compared to a conventional spiral volute pump, as shown in Figure 17. Recommendations on geometric modification aimed at reducing pressure fluctuation and improving stable operation of centrifugal pumps were presented by Spence et al. [4]. The suggestions should be taken in consideration at the design stage.

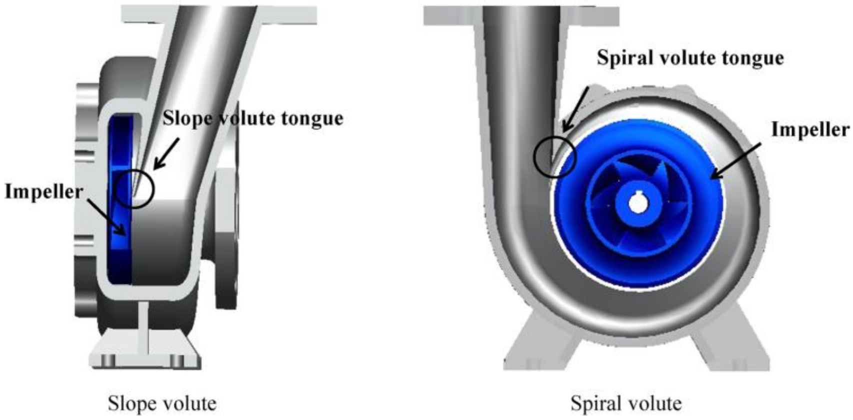


Figure 17. Structure comparison of the slope volute and the conventional spiral volute [89].

Attempts on using impeller blades to reduce the pressure fluctuation amplitude have been carried out. The study of the blade profile on pressure fluctuation in a centrifugal pump was carried out by means of experimental and computational verification. The results showed that a proper blade profile would be beneficial in reducing the large amplitude of pressure fluctuations in the pumps [91–96]. A staggered impeller has also proven to be an effective way to reduce pressure fluctuations in centrifugal pumps [97–100]. Studies of the effect of a gap-drainage impeller on centrifugal pump performance and pressure fluctuation have also shown that a reasonable open seam scheme can effectively reduce the intensity of pressure fluctuation in the pump [38,101]. In addition, the bionic structure is also gradually applied to the centrifugal pump. It was shown that the layout of the bionic structure extracted from the surface of the dung beetle on the blade surface improves the pressure fluctuation characteristics in the pump [102].

Changing the inlet structure for reducing the pressure fluctuation amplitude has been carried out. A suitable inlet layout of the splitter blade can effectively reduce the peak value of pressure fluctuation in a double suction centrifugal pump [43]. The conclusions show that the intensity of pressure fluctuation in the pump can be effectively decreased by arranging the guide vanes at the inlet pipe [29,30].

Precautions should be taken at the design stage of centrifugal pumps to reduce the large amplitude of pressure fluctuations resulting from unsteady flow and to increase the device life. Direct and inverse iteration methods were applied in the centrifugal pump impeller design by controlling blade wrap angle (Tan et al. [103]). The results show that it improves the comprehensive performance and reliability of operation of centrifugal pumps.

Research has been carried out and certain conclusions have been obtained in reducing pressure fluctuations in centrifugal pumps. In this section, different methods to reduce the strong pressure fluctuations are discussed and summarized for the optimal design of the pump. However, only the basic relationship among the intensity of pressure fluctuations, flow conditions, and individual structural parameters has been obtained, and the quantitative and comprehensive relationship still deserves further investigation.

4.2. Initiatives to Reduce Forces in Pumps

Much research has been carried out concerning the axial and radial forces in centrifugal pumps, and the internal pressure distribution was obtained [104–107]. Previous studies have shown that the large force has a large effect on the stable operation of centrifugal pumps. Therefore, reducing the axial and radial forces in pumps is also one of the important research directions.

Some scholars have conducted research on reducing the axial force in pumps. The prediction of axial forces in a multistage pump was investigated by Bruurs et al. [47,108]. The pressure distribution on the series impeller of a multistage pump is given in Figure 18. Liu et al. [109,110] studied the influence of the balance hole on the internal axial force of a single-stage centrifugal pump, and results showed that the increase in the balance hole is beneficial for reducing the axial force, but also affects the external characteristics of pump. The study of balance drum clearance on the total axial force on the impeller of a multistage centrifugal pump shows that the proper value for balance drum clearance can effectively reduce the axial force on the impeller [111]. Dong et al. [112] studied particle flow in a centrifugal pump and the axial force within the pump chamber and found that adding particles can reduce the total axial force of the centrifugal pump at the same flow rate, when compared with clear water pump. Appropriately increasing the diameter of the particles contributes to the decrease in the total axial force of the centrifugal pump. In addition, research has been conducted on axial force reduction in mixed-flow pumps. Mixed-flow pumps with guide vanes have also been studied in terms of optimal design to reduce axial forces [113].

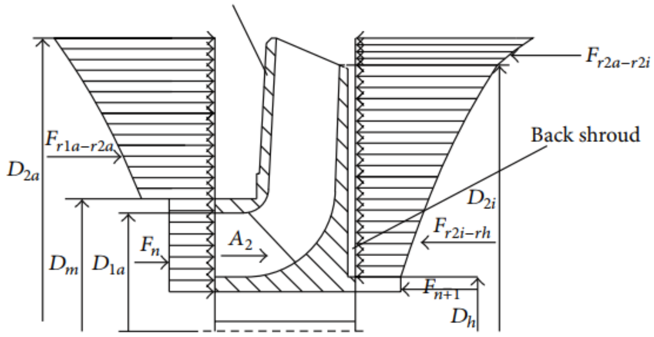


Figure 18. Distribution of axial force on one impeller [108].

Much research has been conducted on reducing the radial force in pumps. Song et al. [114] studied the effect of staggered impellers on radial forces and pressure fluctuation in a double-suction centrifugal pump. Results show that the staggered arrangement impeller can effectively reduce the amplitude of radial force fluctuation. The effect of flow rate on radial forces in a centrifugal pump was analyzed and studied by Cui et al. [115]. The results of the study show that the radial force on the impeller can be reduced at the design conditions. Zhou et al. [116] investigated the effect of volute geometry on the radial force characteristics of a centrifugal pump during start-up. The conclusions show that the double volute geometry structure can effectively reduce the radial force in the centrifugal pump compared to the single volute. Research has also been conducted in the area of impeller trimming; variation in radial forces within a double-suction centrifugal pump can achieve a reduction in radial forces while broadening the range of pump applications [117]. The effect of rotation center eccentricity on radial force in a single-blade centrifugal pump was carried out by Wang et al. [118], as shown in Figure 19. It was found that an optimal eccentricity can effectively reduce the radial force in the pump. This study provides another direction for reducing the radial forces in the pump.

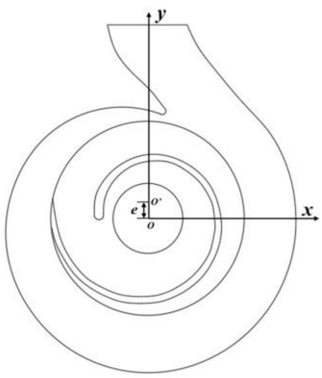


Figure 19. Diagram of the eccentricity of the impeller [118].

Relevant studies have been carried out on reducing axial and radial forces in centrifugal pumps, and some conclusions have been obtained. However, only the fundamental correlation between axial force and radial force with flow conditions and individual structure parameters has been obtained, and a comprehensive and integrated correlation between them still needs to be further investigated.

5. Conclusions and Outlook

As essential equipment, centrifugal pumps have a wide range of applications in all areas of industry. Intense unsteady pressure fluctuations have outstanding influence on the operational stability of centrifugal pumps. In some extreme cases, strong pressure fluctuations in centrifugal pumps may cause premature mechanical failures, such as wear-ring abrasion and impeller failure, jeopardizing the operation of the entire pump system. Therefore, a comprehensive and in-depth study on the pressure fluctuations in centrifugal pumps is necessary and relevant. An extensive and detailed literature review on the pressure fluctuation characteristics in centrifugal pumps with clearance flow is reported. The main conclusions are summarized as follows:

(1) The distribution characteristics of pressure fluctuations in centrifugal pumps, methods to reduce the intensity of pressure fluctuations, and measures to reduce the forces on the pumps are discussed in detail.

(2) The existence of clearance flow causes the loss of internal high-energy fluid, reducing the intensity of pressure fluctuations in pumps and leading to a decrease in external characteristics. The main frequency of pressure fluctuation in the clearance area is mainly dominated by the rotor–stator interaction between the impeller and the volute.

(3) The strength of the pressure fluctuations is tightly associated with the flow conditions. Operating under design conditions effectively reduces the strength of pressure fluctuations in pumps.

(4) The intensity of pressure fluctuations in centrifugal pumps is closely related to the structure parameters. Valid methods to reduce the intense pressure fluctuations in centrifugal pumps are investigated in detail, such as blade profile modification, staggered impellers, volute structure, and inlet guide vanes.

(5) The studies related to axial and radial forces in the centrifugal pumps are summarized and effective measures to reduce the forces, such as increasing the balance hole diameter, adding particles, impeller trimming, and center eccentricity adjustment.

Based on these results and discussions, the following understanding and outlook on future research lines are proposed.

(1) To obtain accurate external characteristics of the centrifugal pumps and the internal flow field characteristics, the effect of clearance flow in pumps must be considered.

(2) Accurate numerical results for the whole flow field of centrifugal pumps require a more accurate and high-quality pump mesh.

(3) A combination of numerical calculations and experiments will be an effective method for studying the characteristics of pressure fluctuations in centrifugal pumps.

(4) The establishment of comprehensive relationships between the pressure fluctuation strength and the axial and radial forces with the flow conditions and structure parameters should be studied and achieved. This will provide an important reference for decreasing the intensity of pressure fluctuations in the pumps, reducing the axial and radial forces on the impeller, improving the stability of pump operation, and providing an important reference for the optimal design of centrifugal pumps.

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Nomenclature

c_p (-)	Pressure coefficient
p (Pa)	Static pressure
p_{ref} (Pa)	Reference pressure
ρ (kg/m^3)	Water density
u_2 (m/s)	Impeller circumferential velocity
H (m)	Pump head
η (%)	Pump efficiency
Q (m^3/h)	Flow rate
A_n (Pa)	Pressure amplitude
3D	Three-dimensional
RMS	Root mean square
LES	Large eddy simulation
PAT	Pump as turbine

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