Influence of the Impeller Diameter and Off-Bottom Clearance on the Flow Velocity Distribution Characteristics Near the Bottom inside a Flotation Machine

Shuling Gao *, Lingguo Meng *, Dezhou Wei, Qiang Zhao, Xuetao Wang and Duanxu Hou

School of Resources and Civil Engineering, Northeastern University, Shenyang 110819, China; dzwei@mail.neu.edu.cn (D.W.); 1510468@stu.neu.edu.cn (Q.Z.); taoxuawang11@126.com (X.W.); houduanxu@163.com (D.H.)
* Correspondence: gaoshuling@mail.neu.edu.cn (S.G.); 1810389@stu.neu.edu.cn (L.M.)

Abstract: The solid particle suspension inside a flotation machine is significantly dependent on the flow field, particularly the flow hydrodynamics characteristics near the bottom of the flotation machine. In this study, a laser Doppler anemometer (LDA) was utilized to investigate the influence of the impeller diameter and the impeller off-bottom clearance of a flotation machine on the flow velocity distribution characteristics near its bottom. The results showed that centripetal, centrifugal, and transitional spiral ascending vortexes were generated for different cases of the impeller variables. The impeller diameter and the off-bottom clearance were found to have a significant and interactive influence on the flow pattern, radial and axial velocities, velocity vector distribution, and axial fluctuating root mean square (RMS) velocity characteristics. When the centripetal flow was generated with a large impeller diameter and a small off-bottom clearance, the vortex stability was improved, the low-velocity distribution area was reduced near the bottom center, and the high axial RMS velocity distribution area was extended and became more consistent. The latter provided an advantageous condition for the momentum transfer between the liquid flow and the solid particles, as well as the airflow. However, the axial RMS velocity in the centrifugal flow formed in other cases of the impeller variables was less than that in the centripetal flow. Although the increase in the impeller off-bottom clearance contributed to increasing the velocity magnitude, this is certainly disadvantageous to the service life of the impeller blades, as expected from the high-velocity area extension. These results may provide a reference for the impeller design and optimization of a KYF (Kuang Yuan Flotation) flotation machine, as well as a basis for further investigation on the behavior of the dispersed phases inside a flow field.

Keywords: flotation machine; impeller diameter; impeller off-bottom clearance; flow pattern; RMS velocity

1. Introduction

Froth flotation is a method that is used to separate useful minerals and gangue by utilizing air bubbles to carry solid particles upward, which provides an effective method for sorting various complex refractory ores [1]. The success of a flotation process benefits from the provision of an appropriate fluid dynamics environment and the perfect particle suspension by the flotation equipment [2].

Particle suspension or mixing not only determines the method of interaction between particles and bubbles but also has an important impact on entrainment; therefore, it has always been a concern in laboratory and industrial flotation machines. Manjunath and Sanja investigated particle behavior in a flotation tank with a 457 mm diameter using electrical resistance tomography (ERT) and found that the impeller size and off-bottom clearance contributed to increasing the velocity magnitude, this is certainly disadvantageous to the service life of the impeller blades, as expected from the high-velocity area extension. These results may provide a reference for the impeller design and optimization of a KYF (Kuang Yuan Flotation) flotation machine, as well as a basis for further investigation on the behavior of the dispersed phases inside a flow field.
of entrainment in some flotation cells [4]. Moreover, they found that experimental data collected from Outokumpu tank flotation cells of three different sizes (3, 100, and 150 m$^3$) were fitted using the proposed exponential model, and the solids content in the top region was dependent on the cell size. Yianatos found that the short-term mixing in a 130 m$^3$ industrial flotation machine could evaluate the probability of particle–bubble contact near the impeller zone [5], which obtained a better understanding of how the mixing takes place in a large-sized flotation cell. In order to make the particles in different tank sizes have similar suspension effects, the critical suspension speed ($N_{js}$) has usually been used as the magnification parameter in the scale-up process of a flotation machine [6–8].

In recent decades, with the rapid scale-up of flotation machines, the requirement for realizing efficient particle suspension inside their flotation cells has gradually increased [9]. Generally speaking, solids suspension is superior in the impeller zone with the high-intensity turbulence but poorer in the upper static zone. Therefore, solids suspension must be taken into consideration when the laboratory flotation machine with high turbulence is expanded to industrial cells with less turbulence.

Solid particles concentrate near the bottom of the flotation cell in a flotation machine [10], and some of them that are not adsorbed by the bubbles will be sucked into the impeller agitation region by the lower circulation driving. During this process, most of the hydrophobic particles will rise to the foam zone along with the bubbles, whereas the hydrophilic particles will fall to the bottom of the tank and gradually accumulate over time. Concurrently, some coarse mineral particles will tend to be mixed in the accumulated materials, and thus, will not be captured by the bubbles. The collision and adsorption processes between the solid particles and the bubbles can occur only when the particles are fully suspended [3]. Fundamentally, solid particle suspension in a flotation machine depends on the flow characteristics at the clearance between the impeller bottom and the bottom of the flotation tank [11].

Until now, a relatively limited number of studies have been published on the effect of the structural parameters on the solids suspension in a flotation machine compared to the research on stirred tanks. It is worth noting that the structures of a flotation machine and a stirred tank are similar, except for the presence of a stator in the former. Although a stator weakens the rotational strength of the liquid flow in a flotation machine to a certain extent, the loop structures of the upper and lower circulation formed by a flotation machine and a stirred tank are almost identical. Therefore, optimization of the flow field characteristics in a flotation machine can be realized based on the influence of its structural parameters on the flow field characteristics in a stirred tank.

Over the last 20 years, researchers have focused on studying the influence of different structural parameters on the $N_{js}$ in a stirred tank. Armemante et al. [12] found decreasing the impeller off-bottom clearance can significantly reduce $N_{js}$ when using a radial impeller. Montante et al. [13] first discovered that the flow pattern in a stirred tank showed a transition from a double loop to a single loop as the impeller off-bottom clearance decreased. A similar experimental phenomenon was also reported by Galletti et al. [14]. Further studies by Ochieng et al. [15] and Zhu et al. [16] suggested that a single-loop flow can shorten the mixing time of the materials and reduce the energy consumption in a stirred tank. On this basis, Basavarajappa et al. [17] compared the influence of a Rushton turbine and a flotation impeller on the flow characteristics in a lab-scale stirred tank. They suggested that the abovementioned flow pattern transition from a double-loop to a single-loop flow can also be observed using a flotation impeller. Moreover, they found that the flow pattern is mainly affected by the impeller off-bottom clearance and the impeller diameter and that an impeller with a larger diameter is more prone to promote the flow pattern transition. These studies indicate that the structural parameters of an impeller are critical to the flow pattern of the fluid flow characteristics and that the flow pattern transition has a further impact on the particle suspension and mixing in a stirred tank. However, for flotation machines, there is still a lack of research on the influencing factors of local flow pattern transitions and the mechanism of different flow patterns for solid particle suspension.
Here, a brief analysis of the motion characteristics of the bottom flow in a flotation machine is provided. The impeller in a flotation machine acts like a partially open pump [18]. The bottom liquid flow is continuously sucked into the impeller because of the pressure drop in the center of the impeller. Under the action of agitation and pumping of the impeller, the bottom flow forms an ascending spiral swirl. The axial velocity directly reflects the pumping capacity of an impeller. The increase in the axial velocity can increase the impeller circulation volume [19]. The tangential velocity of a swirl tends to initially increase and subsequently decrease in a radially outward direction [20], and its direction depends on the rotation direction of the impeller. Until now, there are few reported studies on the radial flow velocity near the bottom of a flotation machine. However, considering the complex three-dimensional nature of this bottom flow, clearly, the radial velocity cannot be ignored. Figure 1 shows the effect of the radial velocity on the bottom rising vortex.

In an ideal case, a fluid particle rising along a spiral path is assumed to be below the impeller. As shown in Figure 1a, the fluid particle undergoes a centripetal spiral ascension motion, with the direction of the radial velocity being toward the axis. In contrast, as shown in Figure 1b, when the direction of the radial velocity is away from the axis, the fluid particle presents a centrifugal spiral ascension motion. The difference in the flow pattern determines the trajectory of the particles to a certain extent, which will affect the suspension and the mixing of the particles near the bottom. Actually, fluid particles do not necessarily move around the axis. Hadane et al. investigated the influence of a stator on the flow field characteristics of a flotation machine using computational fluid dynamics (CFD) simulations [20]. It was observed from their simulation results that the rotational motion apparently disintegrates near the stator in the tank center and that the center of the vortex formed below the impeller also deviates from the axis. Clearly, the center of an ascending vortex spiral is dominated by the vertical ascending motion when the main suction region is located at the bottom of the impeller. The misalignment of the center of the vortex and the tank center suggests that the main suction position deviated from the center of the impeller, which will be detrimental to the uniform dispersion of the particles. This phenomenon might be caused by the instability of the bottom flow field. Concurrently, the bottom flow instability adds complexity to the measurement of the hydrodynamic parameters inside a flotation machine. Theoretically, the radial velocity at the center of a vortex is zero. Once the flow at the axial center has a radial velocity, it can be considered that the center of the vortex is not coincident with the axis, i.e., the bottom flow is unstable.

In order to obtain the flow field information of the fluid, optical techniques, such as laser doppler anemometer (LDA) and particle image velocimetry (PIV), are generally adopted [21]. As they are non-intrusive measurement devices, LDA and PIV will not affect the flow pattern of the fluid; therefore, higher measurement accuracy can be obtained. Darelius et al. [22] used an LDA to measure the distribution of velocity and turbulence characteristics in a high shear mixer and found that the axial velocity component near the wall region was directed upward and the fluctuating velocities were at the same level in the tangential and axial directions. Kysela et al. [23] also utilized an LDA to measure the mean axial ensemble-averaged velocity and analyzed the turbulence energy spectrum for three impeller speeds. Darabi et al. [24] investigated the influence of cell geometry on the flow pattern and turbulence characteristics in a lab-scale Denver flotation machine based on the high-speed stereo-PIV technique. Furthermore, the flow velocities measured using LDA and PIV are often utilized to verify the numerical simulation of fluid inside flotation machines [19,25,26]. Although LDA and PIV have been proven to be reliable for the measurement of the flow velocity of a liquid phase system, it cannot be applied to measure non-transparent systems, such as a high concentration slurry in the flotation machine.

As a typical representative of aerating mechanically agitated flotation machines, KYF (Kuang Yuan Flotation) flotation machines have been extensively used in mineral processing plants [27]. Compared to the tank designs of cylindrical and inverted cones [26,28], a U-shaped tank structure is adopted in a KYF flotation machine to enhance the circulation of the bottom pulp. This unique U-shaped tank significantly reduces the bottom space of
the flotation machine, which allows the particles to accumulate at the center of the tank bottom. Therefore, the flow characteristics at the impeller suction area play a key role in particle suspension.

![Motion trajectory of fluid particles below the impeller](image)

**Figure 1.** Motion trajectory of fluid particles below the impeller: (a) radial velocity toward the axis and (b) radial velocity away from the axis.

In this study, the flow velocities of the fluid near the bottom of a lab-scale KYF flotation machine were measured using an LDA to investigate the influence of the impeller diameter and the impeller off-bottom clearance on the flow velocity distribution. Based on the experimental results, the flow patterns at different impeller parameters were analyzed. Moreover, the difference in several flow hydrodynamics parameters (vortex stability, radial and axial velocities, velocity vectors, and axial fluctuating root mean square (RMS) velocity) were discussed to identify the more advantageous parameters for a dispersed phase suspension.

### 2. Experimental Design

#### 2.1. Geometry of the Flotation Machine and Impeller Parameter Selection

A 50 L laboratory KYF flotation machine (JiLin Provincial Machine Factory of Ore Exploration, Changchun, China) with polymethyl methacrylate walls was adopted to conduct this study, as shown in Figure 2. The flotation machine can be divided vertically into three parts. The upper part (H₁ = 180 mm) was asymmetric, tilting toward the overflow weir, to discharge foams. The middle part (H₂ = 50 mm) and the bottom part (H₃ = 185 mm) had a symmetrical columnar structure (T = 400 mm) and a U-shaped structure, respectively.

Backward impeller blades (β = −40°) were adopted to increase the impeller circulation volumes [19]. A stator was connected to the tank body by four support columns. The impeller off-bottom clearance, C, is defined as the vertical distance from the impeller bottom to the lowest point of the U-shaped tank bottom. The impeller off-bottom clearance was set at four values (24, 28, 32, and 36 mm) when the impeller diameter, D, was varied from 150 to 175 and 200 mm. This was done to investigate the flow velocity distribution change caused by the variation in the two impeller parameters. Actually, when the impeller diameter was enlarged, the proportionality of the motion unit of the flotation machine to the static cell was changed accordingly. Considering the structural features of the KYF flotation machine (the horizontal cross-section was a square with a side length of 400 mm and its bottom was U-shaped), a scalable parameter, such as the “impeller diameter” / “cell diameter,” was not adopted in this paper. The other structural parameters were kept constant during the whole measurement: impeller cavity diameter (dₐ = 45 mm), blade height (h = 106 mm), and blade thickness (dₜ = 9 mm).
2.2. Method for Measuring the Fluid Velocity in a Flotation Machine

The LDA (2D-LDA), manufactured by Dantec (Copenhagen, Denmark), was used to measure the flow velocity near the bottom of the KYF flotation machine. The medial vertical plane was selected for the measurement, which can be seen in Figure 3. A schematic of the experimental system is displayed in Figure 4. Distilled water was used in the measurement process. The composition of the tracer particles was polystyrene with a density of 1.03–1.05 g·cm⁻³. The mean diameter of the tracer particles was 15.9 µm. These are popular tracer particles for characterizing fluid velocities because of their good diffusibility and followability [29–31]. The optical axis of the laser was consistently perpendicular to the incident plane to avoid the disadvantageous influence of the refraction on the measurement process.

The coordinate graph of the flotation tank near the bottom is presented in Figure 5. The measured point was set to move outward from the axis (r = 0 mm) with a step length of 2 mm. It should be noted that the terminal point of each measuring line was not close to the tank wall but near the stator support columns because they hindered the laser incidence. It is also worth noting that the axial position of the laser intersection varied with the impeller off-bottom clearance. Therefore, the length of the measuring line segment gradually shrunk with the reduction in the impeller off-bottom clearance. The correspondence between the vertical position and both the length of the measuring line segment and the impeller off-bottom clearance can be seen in Table 1. The vertical distance between the impeller blade bottom and the measuring line was always 6 mm. Finally, the measured data were processed offline to analyze the mean velocity, as well as the fluctuating RMS velocity, which was corrected using the time-weighted deviation method.
Figure 2. Schematics of the KYF (Kuang Yuan Flotation) flotation machine and impeller with relevant dimensional details.

Figure 3. Half medial vertical plane in the KYF flotation machine.

Figure 4. Schematic of the experimental system.

Figure 5. Coordinate diagram of the flotation tank near the bottom with D = 175 mm and C = 32 mm.

3. Results and Discussion

3.1. Influence of the Impeller Diameter and Impeller Off-bottom Clearance on the Radial Velocity Distribution of Fluid 6 mm below the Impeller Blade Bottom

To investigate the interactive influence of the impeller diameter and the impeller off-bottom clearance on the flow velocity distribution near the bottom, the latter was set to 24, 28, 32, or 36, respectively, in each impeller application. Considering that the adjustment of the impeller speed has no significant effect on the flow pattern in a fully turbulent regime [13,17,32], the impeller speed was uniformly set as 400 r/min to support the particle suspension during the measurement. In this study, the positive direction of the radial velocity was set to be radially outward, and vice versa. The results are shown in Figure 6.
Because only the flow velocities of fluid (water) were measured, the aeration valve of the flotation machine was kept closed to ensure that there was no aeration during the whole measurement. Before the measurement, the fluid with a small amount of tracer particles was stirred for 5 min to ensure that the tracer particles diffused fully. The measuring time for each measured point was approximately 20 s to ensure that enough tracer particles could be caught by laser to gain more precise measurement data.

Table 1. Correspondence between the axial position and the length of the measuring line segment and the impeller off-bottom clearance.

| Impeller Off-Bottom Clearance (mm) | Axial Position of Measured Line Segment (mm) | Length of Measured Line Segment (mm) |
|-----------------------------------|---------------------------------------------|-------------------------------------|
| 24                                | 18                                          | 32                                  |
| 28                                | 22                                          | 50                                  |
| 32                                | 26                                          | 60                                  |
| 36                                | 30                                          | 66                                  |

3. Results and Discussion

3.1. Influence of the Impeller Diameter and Impeller Off-Bottom Clearance on the Radial Velocity Distribution of Fluid 6 mm below the Impeller Blade Bottom

To investigate the interactive influence of the impeller diameter and the impeller off-bottom clearance on the flow velocity distribution near the bottom, the latter was set to 24, 28, 32, or 36, respectively, in each impeller application. Considering that the adjustment of the impeller speed has no significant effect on the flow pattern in a fully turbulent regime [13,17,32], the impeller speed was uniformly set as 400 r/min to support the particle suspension during the measurement. In this study, the positive direction of the radial velocity was set to be radially outward, and vice versa. The results are shown in Figure 6.

As can be established from Figure 6a, when the impeller with a diameter of 150 mm was employed, the direction of the radial velocity of the fluid 6 mm below the impeller blade bottom was negative when the impeller off-bottom clearance was set to 28, 32, and 36 mm. However, the direction was positive when the clearance was reduced to a relatively low value, 24 mm, evidencing a remarkable influence of the impeller off-bottom clearance on the fluid motion behavior. In the impeller off-bottom clearance range from 24 to 36 mm, the radial velocity of the fluid varied with its radial position and the set value of the clearance. Similarly, after a certain radial position (approximately 15–20 mm), the magnitude of the radial velocity generally increased with an increasing radial position. However, the measured values of the radial velocity of the fluid derived at each invariable radial position presented a positive correlation with the bottom clearance magnification, including the maximum velocities at the external, as well as the radial velocity at the axis (r = 0 mm). Maximum radial velocities of 0.24, −0.25, −0.33, and −0.37 m·s\(^{-1}\) (presented in Table 2) and the radial velocities at the axis of 0, −0.07, −0.13, and −0.25 m·s\(^{-1}\) were found at the impeller off-bottom clearances of 24, 28, 32, and 36 mm, respectively. Based on the radial velocities of the fluid at the axis of the impeller obtained at varying off-bottom clearances, the center of the ascending spiral vortex deviated from the axis of the impeller when the impeller off-bottom clearance was larger. However, the vortex became increasingly stable when the clearance was reduced, causing the vortex center and the axis of the impeller to coincide at a clearance of 24 mm. Therefore, it can be deduced that a demarcation point of the fluid flow direction was caused by the adjustment of the impeller off-bottom clearance.
Figure 5. Coordinate diagram of the flotation tank near the bottom with D = 175 mm and C = 32 mm.

Radial velocity (m·s⁻¹) vs radial position (mm) for different clearances (C) at the impeller bottom:
- C = 24 mm
- C = 28 mm
- C = 32 mm
- C = 36 mm

Figure 6. Radial flow velocity distribution on a horizontal line at 6 mm below the impeller blade bottom at varying impeller diameters (D) and impeller off-bottom clearances (C). Note: the dotted line represents a zero radial velocity.
Table 2. Maximum radial velocity (m·s⁻¹) that was found at each measuring line at the related impeller diameter and off-bottom clearance.

| Impeller Off-Bottom Clearance (mm) | Impeller Diameter (mm) |
|-----------------------------------|------------------------|
|                                   | 150        | 175        | 200        |
| 24                                | 0.24       | 0.18       | −0.37      |
| 28                                | −0.25      | 0.17       | 0.26       |
| 32                                | −0.33      | 0.25       | 0.35       |
| 36                                | −0.37      | −0.21      | 0.45       |

When the impeller diameter was increased to 175 mm, the distribution curve of the radial velocity of the fluid, as displayed in Figure 6b, was different from that for the impeller diameter of 150 mm, in that the former presented more scattered measuring data. The fluid flowed outward at the impeller off-bottom clearance of 24 mm, with the radial velocity increasing with the radial distance, except for a slight decrease at the external rim scope. However, the maximum radial velocity of 0.18 m·s⁻¹ was decreased compared to that derived at the impeller diameter of 150 mm (with the same clearance of 24 mm). When the impeller off-bottom clearance was set to a higher value of 28 mm, the fluid also flowed outward with a decreasing radial trend. However, the fluid at the inner radial scope flowed outward and that at the outer scope flowed inward at the clearances of 32 and 36 mm, suggesting the fluid motion transition was caused by the increase in the impeller diameter and its off-bottom clearance.

It is seen in Figure 6c that as the impeller diameter was increased to 200 mm, the fluid particles flowed inward at the impeller off-bottom clearance of 24 mm, which was in the opposite direction to those generated at a lower impeller diameter (with the same clearance of 24 mm). All the fluid particles flowed outward when the off-bottom clearance was higher, which was a further advancement of the fluid motion transition. In addition, the radial velocity of the fluid was approximately 0 m/s at the axis (r = 0 mm) at each clearance, which suggests that the vortex near the bottom of the flotation tank became more stable by applying an impeller with a large diameter.

According to the aforementioned description and analysis of the radial velocity distribution curves presented in Figure 6, it can be deduced that the impeller diameter and its off-bottom clearance indeed had a significant impact on the fluid flow pattern near the bottom of the flotation machine. The fluid flow passage at the lower circulation near the bottom of the flotation machine may have been shrunk by increasing the impeller diameter or reducing the impeller off-bottom clearance, thereby improving the vortex stability in the impeller suction region. Furthermore, the radial velocity of the fluid was increased by some degree when the impeller diameter was set to 200 mm, which suggests a larger positive momentum transfer between the liquid flow and the solid particles, as well as the airflow.

Additionally, the flow pattern transition was found by adjusting the impeller off-bottom clearance at impeller diameters of 150 or 200 mm. However, this type of flow pattern transition was insensitive to the impeller diameter of 175 mm, which might be a critical state of the flow pattern transition. For illustration, the fluid flow near the bottom of the flotation tank was classified into two patterns according to its radial motion direction: The centripetal flow toward the axis and the centrifugal flow toward the contrary direction. To validate the influence of the two impeller structural parameters on the flow hydrodynamics, the vertical velocities, as well as the velocity vectors in the suction area inside the flotation machine, were investigated further.

3.2. Influence of the Impeller Diameter and Its Off-Bottom Clearance on the Axial Velocity Distribution of the Fluid 6 mm below the Impeller Blade Bottom

The axial velocities of the fluid particles 6 mm below the impeller blade bottom were measured simultaneously at the same settings of the impeller diameter and its off-bottom clearance as in the aforementioned radial velocity measurement. In this part of the study,
the positive direction of the axial velocity of the fluid was set to be vertically upward. The results are shown in Figure 7.

![Figure 7](image-url)

**Figure 7.** Axial flow velocity distribution on a horizontal line at 6 mm below the impeller blade bottom at varying impeller diameters (D) and impeller off-bottom clearances (C).

As shown in the three subgraphs in Figure 7, the axial velocity of the fluid 6 mm below the impeller blade bottom is typically positive and presents a remarkable increasing trend from external to internal, suggesting an increase in the suction force. Subsequently, the velocity amplification decreases till those radial positions approximating the axis. Therefore, an axial velocity maximum exists at each measuring line, similar to that seen in Table 3. The axial velocity is relatively higher than the radial velocity presented in Figure 6, particularly when an impeller with a larger diameter is employed and the impeller off-bottom clearance is high.
Table 3. Maximum vertical velocity (m·s\(^{-1}\)) that was found at each measuring line at the related impeller diameter and off-bottom clearance.

| Impeller Off-Bottom Clearance (mm) | Impeller Diameter (mm) |
|-----------------------------------|------------------------|
|                                   | 150        | 175        | 200        |
| 24                                | 0.38       | 0.80       | 1.0        |
| 28                                | 0.40       | 0.86       | 1.05       |
| 32                                | 0.42       | 0.95       | 1.13       |
| 36                                | 0.48       | 1.13       | 1.23       |

Regarding the trend of the variation with the impeller off-bottom clearance at a fixed impeller diameter, a large clearance was associated with a high axial velocity of the fluid. It is very interesting that the velocity difference caused by the off-bottom clearance variation became more remarkable when the diameter of the impeller was increased from 150 to 175 and 200 mm. However, when the impeller off-bottom was invariant, the axial velocity of the fluid rose with an increasing impeller diameter, where this type of velocity amplification effect was overwhelmingly significant compared to that resulting from the clearance variation.

The axial flow velocity distribution on a horizontal line located at 6 mm below the impeller blade bottom at varying impeller diameters and off-bottom clearances validated the idea that a higher kinetic energy input can be achieved with a larger impeller diameter when the impeller speed is identical in all the experiments. Moreover, a large impeller off-bottom clearance was associated with a long velocity acceleration distance, resulting in a high velocity at the measuring line. Therefore, both of the impeller parameters had similar correlations to the axial and radial velocity distributions of the fluid near the bottom of the flotation machine. Considering the comprehensive request in flotation practice, a larger impeller diameter is more advantageous in comparison to a large impeller off-bottom for contributing to a more active momentum transfer and a more stable vortex.

3.3. Velocity Vectors Analysis of the Fluid Near the Bottom of the Flotation Machine in the Half-Medial Vertical Plane

The effects of the impeller diameter and its off-bottom clearance on the velocity vectors of the fluid in the half-medial vertical plane near the bottom of the flotation machine were investigated and are presented in this section. The velocity vector analysis was focused on the impeller suction area, namely, the bottom flow field inside the flotation machine with the impeller off-bottom clearances of 24 and 36 mm for contrast. Therefore, the axial measurement scope ranged from 16 to 24 and 36 mm. The distribution of the velocity vectors (the resultant velocity of the radial and axial velocities) of the fluid in the impeller suction zone is presented in Figure 8.
Figure 8. Diagram of the velocity vectors at the bottom of the KYF flotation machine.
It is found from Figure 8 that the low-velocity region was mainly distributed at the scope above the tank bottom (r = 0–20 mm) and some scopes near the sidewall (r = 20–65 mm), where the particle suspension was weak. However, the low-velocity region varied with the flow patterns. When the centrifugal flow was generated in the suction zone, the low-velocity region mainly existed at the center of the tank bottom, similar to that shown in Figure 8a,f, but not in Figure 8c, where the low-velocity region extended to the sidewall, although it presented a centrifugal flow. However, when the centripetal flow was formed, the low-velocity area was mainly distributed near the sidewall, with a distribution reduction at the bottom center, which can be observed simultaneously in Figure 8b,d,e. For minerals processor design or optimization, the aim should be to form centripetal flow via regulation of the impeller parameters, as well as other available variables, to reduce the low-velocity distribution area near the center of the tank bottom such that the suspension state of the solid particles will be correspondingly improved. Moreover, Figure 8d shows a partial centrifugal flow close to the axis. From the low velocities for different cases, a larger impeller diameter and a lower impeller off-bottom clearance are more advantageous for particle suspension.

It can also be observed more intuitively from Figure 8 that the flow velocities of the fluid particles near the impeller bottom were relatively high and rose with the increase in the impeller off-bottom clearance, which is in accordance with the results discussed in Section 3.2. The maximum resultant velocities of the radial and axial velocities for different cases are listed in Table 4, where it was found that the larger the impeller diameter or its off-bottom clearance was, the higher the maximum velocity became. Moreover, this type of enlarging effect of the impeller diameter on the fluid velocities was more remarkable when the impeller off-clearance was set to 24 mm. In addition, the high-velocity area was significantly extended when the clearance varied from 24 to 36 mm at the impeller diameter of 200 mm. It is understandable that the kinetic energy carried by the fluid will be partially converted to the pressure potential energy of the impeller when the fluid flow encounters the rotating impeller. Therefore, the increase in the impeller off-bottom clearance will accelerate the damage of the impeller blades, which will result in poor performance of the flotation machine.

Table 4. Maximum resultant velocities (m·s⁻¹) of the radial and axial velocities at the related impeller diameter and off-bottom clearance.

| Impeller Off-Bottom Clearance (mm) | Impeller Diameter (mm) |
|-----------------------------------|------------------------|
|                                   | 150  | 175  | 200  |
| 24                                | 0.66 | 1.13 | 1.43 |
| 36                                | 0.82 | 1.49 | 1.45 |

The transition of the flow patterns in the bottom flow field of the flotation tank may be considered relevant to the pressure distribution generated when the impeller rotates at a high speed. Two low-pressure regions can be formed during the operation of the impeller. One is formed in the impeller cavity, as the mass of the fluid flow discharged around the blade, reducing the pressure at the center. The other one is formed behind the blade by the relative movements of the blade and the fluid [33]. When the pressure in the impeller cavity is less than the pressure behind the blade, the fluid is inclined to move toward the center of the impeller to form a centripetal flow. Conversely, the fluid is more inclined to move toward the blade to generate a centrifugal flow.

Moreover, the suction instability will break the uniformity of the pressure distribution near the impeller, resulting in the deviation of the vortex near the bottom. This is expected to be disadvantageous for the solid particle and air bubble dispersion in the fluid flows. Furthermore, the unstable flow pattern will weaken the mixing degree of the particles, and it may damage the local impeller blades, which is not conducive to an effective flotation process. Although the flow pattern transition is highly complex, precise data were derived
by the current study, enabling the transition to be clearly identified. More comprehensive approaches are required to be adopted to gain deeper insights into the transition mechanism of the flow patterns near the bottom inside the flotation machine.

3.4. Axial Fluctuating RMS Velocity Distribution in the Bottom Flow Field

Turbulence is of fundamental significance for solid particle suspension in a flotation tank. Anisotropic turbulence has been found by Galletti et al. not only in impeller regions but also near the bottom of a tank [34]. Among all the fluctuating components of turbulence, the axial component of the fluctuating velocity plays a key role in lifting the solid particles from the bottom of a tank and into the strong circulating flow [35]. Based on the relevant literature and the aforementioned investigations conducted on the flow velocity of the fluid near the bottom of a flotation tank, the axial fluctuating RMS velocities of the fluid in different flow patterns were measured. The corresponding distribution graphs are presented in Figures 9 and 10. It should be noted here that the flow patterns at the impeller diameter of 175 mm were not included in the investigation because of their mixed and transitional conditions.

Figure 9. Axial root mean square (RMS) velocity distribution in the centripetal flow.

Figure 10. Cont.
By comparing the distributions of the axial RMS velocity in different flow patterns, it was established that the fluctuating component of the turbulence at the scope above the tank bottom \((r = 0–20 \text{ mm})\) in a centripetal flow was larger than that in a centrifugal flow, regardless of the impeller diameter being 150 or 200 mm. Therefore, it was deduced that the centripetal flow was more advantageous for solid particle suspension in a fluid and it is beneficial for increasing the collision probability of particles and bubbles. Moreover, the axial RMS velocities of the fluid with an impeller diameter of 200 mm and an impeller off-bottom clearance of 24 mm presented in Figure 9b are higher than those for a smaller impeller diameter and larger impeller off-bottom clearance, which is also shown in Figure 9a. Based on the comprehensive effect of the two impeller structural parameters on this turbulence component in the centripetal flow, the impeller diameter was found to be more effective for improving the flow characteristics, namely, an increase in the flow velocities and an intensification of the vortex stability. When the centrifugal flow was formed, the axial RMS velocity rose by a combined effect of the increase in the impeller diameter and the enlargement of the impeller off-bottom clearance, which is shown in Figure 10.

It can also be found from the subgraphs in Figures 9 and 10 that the maximum values of the axial RMS velocity were distributed at the regions under the impeller blade tip, which were associated with trailing vortices. The maximum axial fluctuating RMS velocities for different cases are shown in Table 5, according to which, the centripetal flow was found to be more advantageous for particle suspension and mixing. Similarly, the distribution area of high axial RMS velocities was broader and more consistent when a centripetal flow was generated with an impeller diameter of 200 mm and a clearance of 24 mm.

Table 5. Maximum axial fluctuating RMS velocity \((\text{m·s}^{-1})\) with the related impeller diameter and its off-bottom clearance.

| Impeller Off-Bottom Clearance (mm) | Impeller Diameter (mm) |
|-----------------------------------|-------------------------|
|                                   | 150                     | 200                     |
| 24                                | 0.53 (centrifugal flow) | 0.94 (centripetal flow) |
| 36                                | 0.94 (centripetal flow) | 0.86 (centrifugal flow) |

3.5. Extrapolation of Solid Particle Suspension Via the Flow and Residence Time Inside the Flotation Machine

In an ideal particle suspension state, most of the particles are suspended in the impeller zone and a small part is suspended in the upper quiescent zone, which can effectively prevent entrainment. However, uniform dispersion of the particles is not the optimal working condition for flotation [20,36]. Two inherent disadvantageous effects are imposed on the particle suspension when the radial impeller is used in a KYF flotation machine. One is that the intense turbulence generated by the radial impeller stirring surrounds the impeller only; it does not exist near the bottom of the flotation machine. The other one
is that the particles are promoted to accumulate at the center of the tank by the lower circulation flow, causing them to fall without any resuspension [35].

It has been reported in many studies that reducing the radial impeller off-bottom clearance can promote the flow pattern transition from a double loop (radial flow) to a single loop (axial flow) in a stirred tank, improving the particles’ suspension state near the tank bottom [12,13,15–17]. However, this type of transition is not observed inside the KYF flotation machine even when the impeller off-bottom clearance is reduced to a small value.

Nevertheless, in this study, two flow patterns of the vortex under the impeller were observed by adjusting the impeller diameter and the impeller off-bottom clearance. An intense axial fluctuating velocity was generated above the center of the tank bottom in the centripetal flow but not in the centrifugal flow. It was confirmed that the centripetal flow was more appropriate for particle suspension in the KYF flotation machine without the consideration of air bubbles.

Residence time distribution studies are important for evaluating the quality of mixing and determining deviations from ideal flotation machine performance [37,38]. According to the experimental results of this article, the impeller diameter and the off-bottom clearance were found to have a significant and interactive influence on the fluid patterns. The change of flow pattern will have a complex impact on the residence time distribution. A few related studies [18,39,40] have shown that a high degree of solids suspension and shorter mixing times can be realized when a larger impeller–tank (D/T) aspect ratio is used. It can be inferred that a wider impeller will decrease the residence time to some extent. However, the effect of the impeller off-bottom clearance on the material mixing is not linear, as seen in the investigation conducted by Patel et al. [41]. They found that a satisfactory mixing quality can be obtained within an appropriate range of impeller off-bottom clearance. In the present investigation, flow velocities of fluid near the bottom of the KYF flotation machine are improved when the impeller off-bottom clearance is increased from 24 mm to larger values; therefore, shorter residence times can also be realized by using a larger impeller off-bottom clearance. Furthermore, increasing the impeller off-bottom clearance will inevitably expand the circulation range of the bottom fluid such that it favors bypass flows [42]. Therefore, it can be inferred that a larger impeller off-bottom clearance is beneficial for the flotation process in terms of reducing the residence time and favoring bypass flows.

Regarding the shortcomings of this investigation, it should be noted that the study reported in this paper only considered a single-phase flow, which does not accord with the real scenarios of the gas–liquid–solid system used in the flotation practice. Generally, aeration will weaken the impeller pumping capacity, owing to the formation of gas cavities behind the blade [40], which changes the pressure distribution and the vortex flow patterns near the impeller. A measuring technique and a numerical approach of a multiphase flow will be applied in future work to investigate the correlation between the liquid flow characteristics and the presence of dispersed phases.

4. Conclusions

(1) The present study focused on the flow velocity distribution near the bottom of a KYF flotation machine to obtain the detailed flow hydrodynamics parameter variation with impeller variables. Centripetal and centrifugal vortices, as well as transitional spiral ascending vortices, were observed in different cases of the impeller diameter and the impeller off-bottom clearance, respectively.

(2) The impeller diameter and the off-bottom clearance were found to have significant effects on the flow patterns, radial and axial velocities, velocity vector distribution, and axial fluctuating RMS velocity characteristics. In the case of a large impeller diameter or a small off-bottom clearance, the fluid flow passage at the lower circulation inside the flotation machine shrunk. This resulted in a remarkable improvement in the vortex stability, which was beneficial for producing a uniform solid particles suspension.
(3) The axial velocity of the fluid near the bottom inside the flotation machine was higher than the radial velocity, particularly in the case of a large impeller diameter and a large off-bottom clearance. However, when the impeller off-bottom clearance was increased, the velocity amplification effect was not as remarkable as that caused by the impeller diameter increase. Moreover, the high-velocity area located near the impeller bottom was notably extended in the case of a large off-bottom clearance, which will cause inevitable damage to impeller blades.

(4) The low-velocity region distributed at the suction zone inside the flotation machine weakened the solid particle suspension. It varied with the flow patterns. When a centripetal flow was generated at a large impeller diameter and a small off-bottom clearance, the low-velocity distribution region area was significantly reduced near the bottom center.

(5) The fluctuating component of the turbulence, namely, the axial RMS velocity, was higher in the centripetal flow than that in the centrifugal flow. The distribution area of the high axial RMS velocity was broader and more consistent in the centripetal flow generated with a large impeller diameter and a small off-bottom clearance. Thus, forming a centripetal flow near the bottom inside the flotation machine via the adjustment of the impeller variables is of extreme importance for the suspension of the solid particles, as well as the dispersion of air bubbles.

Author Contributions: Conceptualization, S.G. and L.M.; methodology, S.G.; software, X.W.; validation, D.W., Q.Z, and D.H.; formal analysis, S.G.; investigation, L.M.; resources, S.G.; data curation, L.M.; writing—original draft preparation, S.G.; writing—review and editing, S.G.; visualization, S.G.; supervision, S.G.; project administration, S.G.; funding acquisition, S.G. All authors have read and agreed to the published version of the manuscript.

Funding: This project was financially supported by the National Natural Science Foundation of China (51974065) and the Fundamental Research Funds for the Central Universities (N180102032, N180408018).

Data Availability Statement: All data presented is original.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

D Impeller Diameter (mm)
C Impeller off-bottom clearance (mm)
H1 Height of the upper part of the KYF flotation machine (mm)
H2 Height of the middle part of the KYF flotation machine (mm)
H3 Height of the U-shaped structure of the KYF flotation machine (mm)
T Width of the flotation tank (mm)
h Height of the impeller (mm)
β Inclination angle of the blade (°)
ds Impeller cavity diameter (mm)
dd Blade thickness (mm)
r Radial position (mm)
Njs Critical impeller speed (rpm)

References

1. Wei, D.Z. Solid Materials Separation; Metallurgical Industry Press: Beijing, China, 2015.
2. Amini, E.; Bradshaw, D.J.; Xie, W. Influence of flotation cell hydrodynamics on the flotation kinetics and scale up, part 1: Hydrodynamic parameter measurements and ore property determination. Miner. Eng. 2016, 99, 40–51. [CrossRef]
3. Manjunath, B.; Sanja, M. CFD-DEM simulations and electrical resistance tomography (ERT) studies of solid-liquid flows in flotation cells. In Proceedings of the 27th International Mineral Processing Conference, Santiago, Chile, 20–24 October 2014.
4. Zheng, X.; Franzidis, J.P.; Johnson, N.W.; Manlapig, E.V. Modelling of entrainment in industrial flotation cells: The effect of solids suspension. Miner. Eng. 2005, 18, 51–58. [CrossRef]
5. Yianatos, J.B.; José, M.L.; Moys, M.H.; Diaz, F.J. Short time mixing response in a big flotation cell. Int. J. Miner. Process. 2008, 89, 1–8. [CrossRef]
6. Lima, O.A.; Deglon, D.A.; Filho, L.S.L. A comparison of the critical impeller speed for solids suspension in a bench-scale and a pilot-scale mechanical flotation cell. Miner. Eng. 2009, 22, 1147–1153. [CrossRef]
7. Westhuizen, A.P.V.D.; Deglon, D.A. Solids suspension in a pilot-scale mechanical flotation cell: A critical impeller speed correlation. Miner. Eng. 2008, 21, 621–629. [CrossRef]
8. Westhuizen, A.P.V.D.; Deglon, D.A. Evaluation of solids suspension in a pilot-scale mechanical flotation cell: The critical impeller speed. Miner. Eng. 2007, 20, 233–240. [CrossRef]
9. Mesa, D.; Brito-Parada, P.R. Scale-up in froth flotation: A state-of-the-art review. Sep. Purif. Technol. 2019, 210, 950–962. [CrossRef]
10. Shi, S.X.; Yu, Y.; Yang, W.W.; Zhou, H.X. Flow field test and analysis of KYF flotation cell by PIV. Appl. Mech. Mater. 2013, 331, 200–204. [CrossRef]
11. Schubert, H. On the turbulence-controlled microprocesses in flotation machines. Int. J. Miner. Process. 1999, 56, 257–276. [CrossRef]
12. Armemante, P.M.; Nagamine, E.U. Effect of low off-bottom impeller clearance on the minimum agitation speed for complete suspension of solids in stirred tanks. Chem. Eng. Sci. 1998, 53, 1757–1775. [CrossRef]
13. Montante, G.; Lee, K.C.; Brucato, A.; Vanneskis, M. An experimental study of double-to-single-loop transition in stirred vessels. Can. J. Chem. Eng. 1999, 77, 649–659. [CrossRef]
14. Galletti, C.; Brunazzi, E.; Vanneskis, M.; Paglianti, A. Spectral and wavelet analysis of the flow pattern transition with impeller clearance variations in a stirred vessel. Chem. Eng. Sci. 2003, 58, 3859–3875. [CrossRef]
15. Ochieng, A.; Onyango, M.S.; Kumar, A.; Kiriamiti, K.; Musonge, P. Mixing in a tank stirred by a Rushton turbine at a low clearance. Chem. Eng. Process. 2008, 47, 842–851. [CrossRef]
16. Zhu, Q.; Xiao, H.; Chen, A.; Geng, S.; Huang, Q. CFD study on double-to-single-loop flow pattern transition and its influence on macro mixing efficiency in fully baffled tank stirred by a Rushton turbine. Chin. J. Chem. Eng. 2019, 27, 993–1000. [CrossRef]
17. Basavarajappa, M.; Draper, T.; Toth, P.; Ring, T.A.; Miskovic, S. Numerical and experimental investigation of single phase flow characteristics in stirred tanks using Rushton turbine and flotation impeller. Miner. Eng. 2015, 83, 156–167. [CrossRef]
18. Souza Pinto, T.C.; Braga, A.S.; Leal Filho, L.S.; Deglon, D.A. Analysis of key mixing parameters in industrial Wemco mechanical flotation cells. Miner. Eng. 2018, 123, 167–172. [CrossRef]
19. Shi, S.; Zhang, M.; Fan, X.; Chen, D. Experimental and computational analysis of the impeller angle in a flotation cell by PIV and CFD. Int. J. Miner. Process. 2015, 142, 2–9. [CrossRef]
20. Hadane, A.; Khamar, L.; Benjelloun, S.; Nounah, A. Hydrodynamic study of a phosphate flotation cell by CFD approach. Chem. Eng. Process. 2019, 135, 190–203. [CrossRef]
21. Meng, J.; Tabosa, E.; Xie, W.; Runge, K.; Bradshaw, D.; Manlapig, E. A review of turbulence measurement techniques for flotation. Miner. Eng. 2016, 95, 79–95. [CrossRef]
22. Darelus, A.; Rasmussen, A.; Niklasson Björn, I.; Folestad, S. LDA measurements of near wall powder velocities in a high shear mixer. Chem. Eng. Sci. 2007, 62, 5770–5776. [CrossRef]
23. Kysela, B.; Konfršt, J.; Chara, Z. LDA measurements and turbulence spectral analysis in an agitated vessel. EPJ Web Conf. 2013, 45, 01051–01056. [CrossRef]
24. Darabi, H.; Koleini, S.M.J.; Soltni, F.; Abdollahy, M.; Ghadiri, M. Investigation of cell geometry effect on the turbulence characteristics and flotation performance using particle image velocimetry technique. Powder. Technol. 2020, 376, 458–467. [CrossRef]
25. Tiitinen, J.; Vaarno, J.; Grönstrand, S. Numerical modeling of an outokumpu flotation device. In Proceedings of the Third International Conference CFD in the Minerals and Process Industries, CSIRO, Melbourne, Australia, 10–12 December 2003; pp. 167–170.
26. Kuang, J.; Feng, Y.; Yang, W.; Wett, P.; Schwarz, P.; Qiu, T. CFD modelling and PIV validation of flow field in a flotation cell. In Proceedings of the 11th International Conference on CFD in the Minerals and Process Industries, Melbourne, Australia, 7–9 December 2015.
27. Shen, Z.; Chen. J. Flow Field Simulation and Its Applications; Science Press: Beijing, China, 2012.
28. Koh, P.T.L.; Schwarz, M.P.; Zhu, Y.; Bourke, P.R.; Franzidis, J.P. Development of CFD models of mineral flotation cells. In Proceedings of the Third International Conference on Computational Fluid Dynamics in the Minerals and Process Industries, Melbourne, Australia, 10–12 December 2003; pp. 171–175.
29. Puga, H.; Teixeira, J.C.; Barbosa, J.; Ribeiro, S.; Prokic, M. The combined effect of melt stirring and ultrasonic agitation on the degassing efficiency of AlSi9Cu3 alloy. Mater. Lett. 2009, 63, 2089–2092. [CrossRef]
30. Deen, N.G.; Hjertager, B.H.; Solberg, T. Comparison of PIV and LDA measurement methods applied to the gas-liquid flow in a bubble column. In Proceedings of the 10th international symposium on Application of Laser Techniques to Fluid Mechanics, Lisbon, Portugal, 10–13 July 2000.
31. Kaftori, D.; Hetsroni, G.; Banerjee, S. Particle behavior in the turbulent boundary layer II velocity and distribution profiles. Phys. Fluids. 1995, 7, 1107–1121. [CrossRef]
32. Li, Z.; Bao, Y.; Gao, Z. PIV experiments and large eddy simulations of single-loop flow fields in Rushton turbine stirred tanks. Chem. Eng. Sci. 2011, 66, 1219–1231. [CrossRef]
33. Vlaev, S.D.; Staykov, P.; Popov, R. Pressure distribution at impeller blades of some radial flow impellers in saccharose and xanthan gum solutions: A CFD visualization approach. Food Bioprod. Process. 2004, 82, 13–20. [CrossRef]
34. Galletti, C.; Brunazzi, E.; Pintus, S.; Paglianti, A.; Vanneskis, M. A study of reynolds stresses, triple products and turbulence states in a radially stirred tank with 3-d laser anemometry. Chem. Eng. Res. Des. 2004, 82, 1214–1228. [CrossRef]
35. Ayranci, I.; Márcio, B.M.; Madej, A.M.; Derksen, J.J.; Nobes, D.S.; Kresta, S.M. Effect of geometry on the mechanisms for off-bottom solids suspension in a stirred tank. *Chem. Eng. Sci.* **2012**, *79*, 163–176. [CrossRef]
36. Xie, W.; Meng, J.; Nguyen, A.V. Experimental quantification of turbulence and its applications in the study of multiphase flotation pulps. *Int. J. Miner. Process.* **2012**, *156*, 163–176. [CrossRef]
37. Yianatos, J.; Díaz, F.; Rodríguez, J. Industrial flotation process modelling: RTD measurement by radioactive tracer technique. *IFAC Proc.* **2002**, *35*, 55–60. [CrossRef]
38. Yianatos, J.; Contreras, F.; Díaz, F. GAS holdup and RTD measurement in an industrial flotation cell. *Miner. Eng.* **2010**, *23*, 125–130. [CrossRef]
39. Takenaka, K.; Takahashi, K.; Bujalski, W.; Nienow, A.; Paolini, S.; Paglianti, A.; Etchells, A. Mixing time for different diameters of impeller at a high solid concentration in agitated vessel. *J. Chem. Eng. Sci. Jpn.* **2005**, *38*, 309–315. [CrossRef]
40. Panneerselvam, R.; Savithri, S.; Surender, G.D. CFD modeling of gas-liquid-solid mechanically agitated contactor. *Chem. Eng. Res. Des.* **2008**, *86*, 1331–1344. [CrossRef]
41. Patel, D.; Ein-Mozaffari, F.; Mehrvar, M. Dynamic performance of continuous-flow mixing of pseudoplastic fluids exhibiting yield stress in stirred reactors. *Ind. Eng. Chem. Res.* **2011**, *50*, 9377–9389. [CrossRef]
42. Yianatos, J.; Bergh, L.; Vinnett, L.; Panire, I.; Díaz, F. Modelling of residence time distribution of liquid and solid in mechanical flotation cells. *Miner. Eng.* **2015**, *78*, 69–73. [CrossRef]