

Article

Effects of Diameter Parameters on Gas Flow Field Characteristics in Cyclones: An Experimental Investigation

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Abstract: The flow field characteristic is crucial for the separation process of cyclones, which includes time–mean and dynamic characteristics. The structural parameters of the cyclone have an important influence on the internal flow field characteristics, among which the cylinder diameter and vortex finder diameter are important structural parameters. This experimental study aimed to assess the effects of diameter parameters on the flow field characteristics of cyclones, especially the dynamic characteristics, which have received less attention in the literature. A hot wire anemometer (HWA) was employed in measuring the instantaneous tangential velocities in cyclones with different cylinder and vortex finder diameters. Time and frequency domain analyses of the measured data revealed that the diameter parameters of cyclones affected not only the distributions of the time–mean and instantaneous tangent velocities but also the intensity and dominant frequency of the instantaneous tangential velocity fluctuations. First, the maximum tangential velocity in the cyclone increased slightly when the cylinder diameter was increased and decreased significantly when the vortex finder diameter was increased. Second, the tangential velocity fluctuation intensity characterized by the standard deviation (S_d) increased on the same dimensionless axial section when the cylinder diameter was increased and the vortex finder diameter was decreased. It was also found that the increases in cylinder diameter and vortex finder diameter led to the dominant frequencies in the cyclone being reduced. Based on the results of this study, the dominant frequency calculation model for cyclones was improved. The conclusions presented in this study may provide valuable insights into the dynamic characteristics of flow fields in cyclones for future improvements to separation performance.

Keywords: cyclone; flow field; cylinder diameter; vortex finder diameter; dynamic characteristics; dominant frequency



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1. Introduction

Cyclones are one of the most widely used gas–solid separation devices in many scientific and engineering fields due to their simple structure and high efficiency. The main separation principle of the cyclone is to remove the dust particles from the swirling flow system by utilizing high centrifugal forces [1–3]. Therefore, the swirling flow field is crucial for the separation process of cyclones. However, due to the complexity of the three-dimensional swirling flow, the flow field in the cyclone is not yet fully understood [4–6]. It has long been the focus of many experimental [3,7–9], theoretical, and computational studies [10–13].

Many published research works have shown how the structure form and parameters of the cyclone affect the internal flow field distribution, as well as the performance (including separation efficiency and pressure drop) [14–18]. For a single parameter or multiple parameters, many relevant studies have been conducted, such as those on cyclone length and diameter [19,20], vortex finder dimension [21–23], inlet and outlet size [24,25], and

cyclone hopper geometry [26,27]. Notwithstanding, most previous studies have focused on the flow field time–mean characteristics, few studies have paid close attention to the flow field dynamic characteristics, and the influence of structural factors on the dynamic characteristics has been mostly neglected in many of these studies. Dynamic characteristics play just as important a role in the particle separation process as time–mean characteristics, which can obviously increase the gas swirling flow turbulence intensity, as well as the fine particle diffusion [28–30]. Consequently, it is not sufficient to fully understand the flow field in the cyclone and further the mechanism of the gas–solid separation process without considering the dynamic characteristics.

In past decades, many means of measurements have been used to measure the flow fields for cyclones, such as laser Doppler velocimeters (LDVs) [3,4], hot wire anemometers (HWAs) [30,31], and particle image velocimeters (PIVs) [32,33]. Most of the measurements taken in these studies provided general features of the flow field distribution in cyclones, and some of the studies indicated the existence of dynamic characteristics of gas swirling flow, which is manifested by the fluctuation of instantaneous parameters over time. In addition, numerical simulations with computational fluid dynamics (CFD) of the flow field in cyclones have also shown that instantaneous parameters fluctuate with time [34–36]. In addition, Sun Liqiang [30], Gu Xiaofeng [37], and Jia Mengda [38] conducted spectral analyses of the instantaneous parameters that proved the existence of the dominant frequency in the cyclone and attributed this frequency to the swing of the swirling flow; these studies have deepened our understanding of the flow field dynamic characteristics.

Hoekstra [3], Sun Liqiang [27], and Derksen [34] considered that dynamic behaviors of the gas swirling flow in the cyclone can be characterized by the Strouhal number, $St = \frac{fD}{V_i}$, where St is a fixed value at higher Reynolds numbers. The above model describes the relationship between the dominant frequency in the cyclone (the swing frequency of the swirling flow) and some structural parameters and operational parameters. However, further experimental validation of the applicability of the model in different cyclones is lacking, and the parameters considered are not comprehensive enough; for example, an important structural parameter, the cyclone vortex finder diameter, is not considered in the model. Hosseini [39], Gao Zhuwei [40], and Zhang Zhengwei [41] have confirmed that the vortex finder diameter has an important influence on the flow field in the cyclone. Therefore, the influence of structural parameters on the dynamic characteristics in the cyclone should be taken into consideration, and then, the frequency calculation model should be improved.

This experimental study aimed to investigate the effects of diameter parameters on the flow field characteristics in the cyclone, especially the dynamic characteristics. An HWA system was employed to measure the instantaneous velocities in cyclones with different cylinder diameters and vortex finder diameters. The properties of the time and frequency domain, such as the time–mean and instantaneous velocity distributions, the standard deviation, and the dominant frequency distributions were analyzed based on the experimental measurements. The effects of the cylinder diameter and the vortex finder diameter on the flow field characteristics were discussed. Furthermore, the dominant frequency calculation model for cyclones was improved. This research aims to deepen our understanding of the flow field dynamic characteristics in cyclones for future improvements to the performance.

2. Experiments

2.1. Cyclone Geometry

Reverse cyclones were designed as the models for our dynamic measurement experiments. The cyclones were made of Plexiglas for easy observation during measurements. Figure 1 and Table 1 provide details of the geometric parameters. The details of Cyclone I are listed in Table 1 as the basic model for this study. To analyze the effects of the cylinder diameter parameters, Cyclone II and Cyclone III were built with different cylinder diameters, which were scaled according to the structural parameter dimensions of Cyclone I.

Moreover, to analyze the effects of the vortex finder diameters, Cyclone IV and Cyclone V were designed with the same structural dimensions as Cyclone I except for the vortex finder diameters.

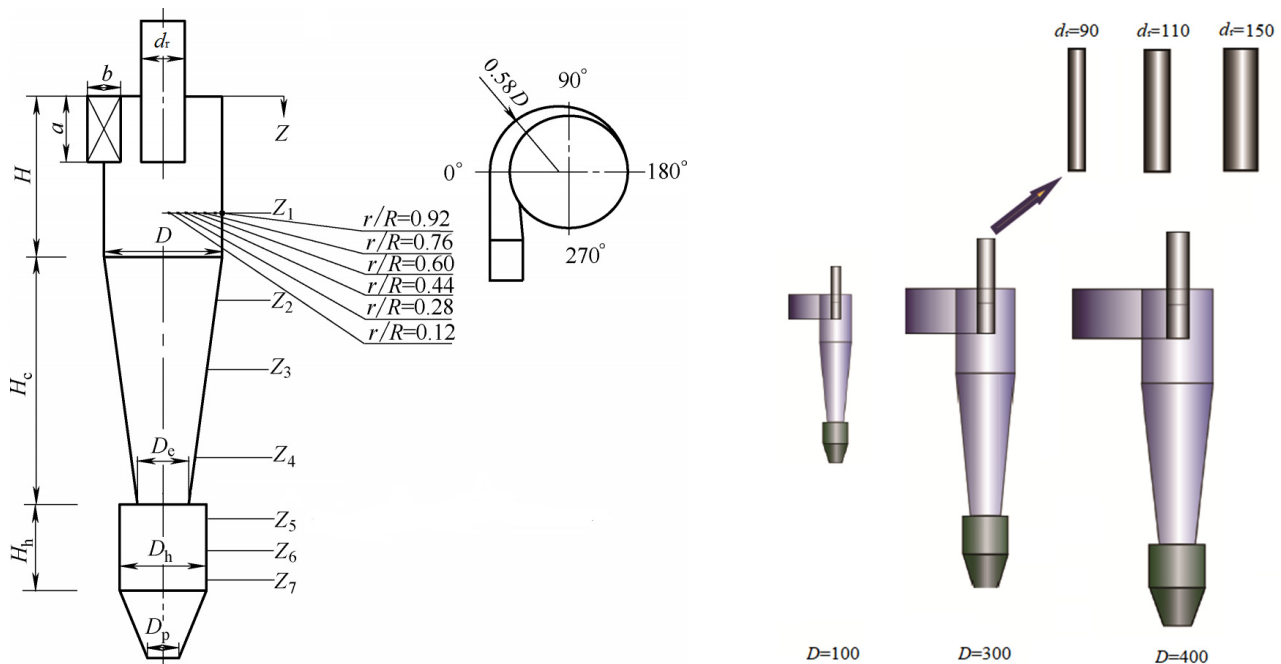


Figure 1. Dimensions of cyclones.

Table 1. Geometric parameters of cyclones.

Geometric Parameter (mm)	Cyclone I	Cyclone II	Cyclone III	Cyclone IV	Cyclone V
Cylinder diameter, D	300	100	400	300	300
Vortex finder diameter, d_r	110	35	145	90	150
Rectangular entrance, $a \times b$	178×84	59×28	238×112	178×84	178×84
Vortex finder height, S	178	59	238	178	178
Cylindrical body height, H	430	143	574	430	430
Cone height, H_c	660	220	880	660	660
Dust outlet diameter, D_e	130	43	174	130	130
Hopper size, $D_h \times H_h$	220×230	70×77	294×307	220×230	220×230

The z axis was downward, which originated from the center of the cylinder's upper end. Seven measuring sections ($Z_1(z/D = 1.23)$ for the cylinder, Z_2 – Z_4 ($z/D = 1.93, 2.53, 3.30$) for the cone, and Z_5 – Z_7 ($z/D = 3.97, 4.05, 4.13$) for the hopper) were established along the axial direction of the cyclones. There were several measuring points at each section along the radial direction (cross 0° – 180°). Figure 1 presents the six measuring points with different r/R values at the Z_1 section.

2.2. Experimental Setup

Figure 2 shows a schematic diagram of the experimental setup. The experimental setup comprised an experimental system and a measuring system. The experimental system includes the cyclone model, the fan, and auxiliary lines. The measuring system mainly includes the hot wire anemometry, the computer, and the coordinate controller. The experiments were conducted under negative pressure conditions. The centrifugal fan inhaled the atmospheric pressure and ambient temperature gas (air) into the cyclone, and a buffer tank was installed between the centrifugal fan and the cyclone outlet pipe to avoid the influence of airflow instability. A butterfly valve and a pitot tube were used to ensure a

constant inlet velocity. The hot wire anemometry (IFA300, TSI Inc., Seattle, WA, USA) was mainly employed to measure instantaneous velocities in the cyclone. The hot wire probe was inserted into the cyclone through measuring holes in its wall and the position was fixed by using the coordinate frame during the measuring procedure.

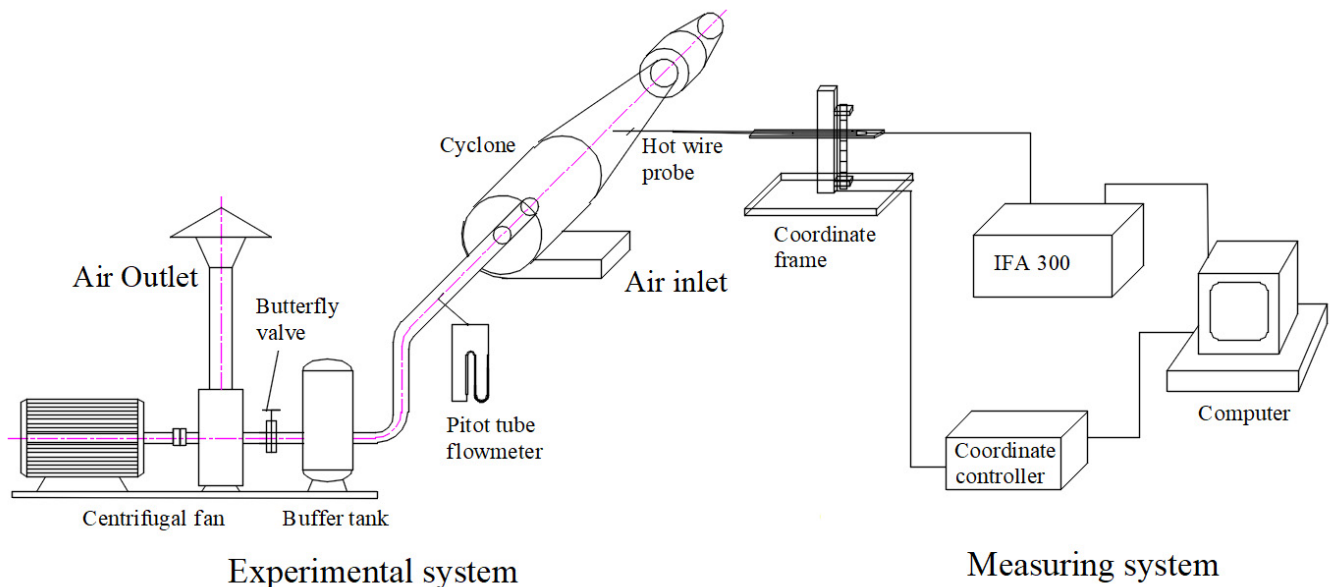


Figure 2. Schematic diagram of experimental setup.

This study focuses more on the instantaneous velocity of the flow fields at different positions in cyclones; therefore, the measurement system needed to have a higher sampling frequency and faster response times, and the HWA is ideal compared with the LDV and PIV. A key feature of the HWA is the ability to measure rapidly changing velocity with a high spatial and temporal resolution due to the hot probe's (micrometers in diameter) low thermal inertia [42,43]. However, for LDV and PIV, there are limits to the optical accessibility and seeding of air flow because the measurement process requires tracer particles. The accuracy of the measurements is affected by the distribution of tracer particles in a swirling gas flow and is especially dependent on the tracer particle concentration and size. In addition, the cyclone itself has a particle separation effect: the concentration of particles in the region near the cyclone center is low, which cannot satisfy the high velocity acquisition requirements [44].

The distribution of the velocity in the cyclone conforms to the Rankine vortex structure, containing tangential, axial, and radial velocity. The centrifugal acceleration generated by the tangential velocity is the main driving force that makes the particles move outward to the wall, and it plays a leading role in the capture and separation of the particles. The axial velocity is downflowing on the outside and upward flowing on the inside; the interface shape of the upper and downstream flow is similar to that of the cyclone. Radial velocity is the smallest velocity component of the cyclone flow field, its value is much less than the tangential velocity and axial velocity, and the distribution is more complex, so it is difficult to measure accurately. Therefore, the tangential velocity is the most central component of the three-dimensional swirling flow field. Our dynamic measurement experiments selected the instantaneous tangential velocity V_t as the parameter of interest to characterize the flow field dynamic characteristics, which requires the hot probe to be arranged vertically with the tangential velocity during the measurements. A constant inlet velocity was set at 6.8 m/s for all experiments, the HWA had a sampling frequency of 1000 Hz, and the sampling time was 15 s.

3. Results and Discussion

3.1. Effects of the Cylinder Diameter

3.1.1. Time-Mean and Instantaneous Tangential Velocities

Figure 3 shows the time-mean tangential velocity profiles of cyclones with different cylinder diameters. The distribution patterns of dimensionless tangential velocity ($\bar{V}_t/V_i$) in cyclones with different cylinder diameters showed a basically Rankine vortex structure, which is consistent with some results reported in the literature [1,3,4]. However, for cyclones with different cylinder diameters, due to the differences in the gas swirling flow curvature and the residence time in cyclones, the maximum tangential velocity increased slightly when the cyclone cylinder diameter was increased. It is worth noting that the tangential velocity changed less at the lower cone section Z_4 ($z/D = 3.30$), which differed from the others. This is because the type of cyclone used for this study is one with a hopper, and the lower cone section Z_4 ($z/D = 3.30$) is close to the dust outlet. The other study by the authors of this article [27] showed that the hopper has an important effect on the instantaneous tangential velocity near the dust outlet region. A decrease in cone size and backflow from the hopper resulted in dramatic instantaneous tangential velocity fluctuations in the cone space near the dust outlet; the time-mean tangential velocity was not greatly altered at different radial positions and the Rankine vortex structure was relatively unclear.

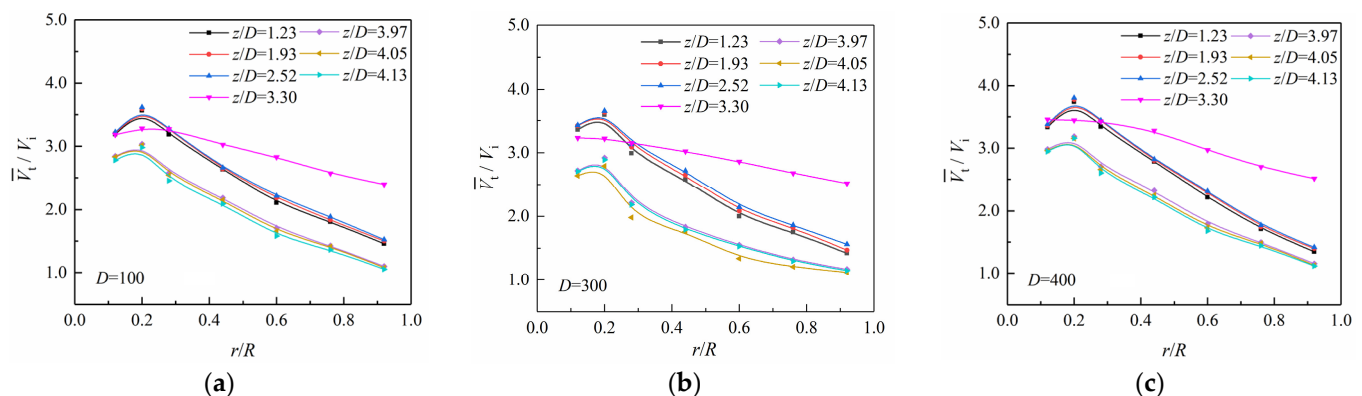


Figure 3. Time-mean tangential velocity profiles in cyclones with different cylinder diameters. (a) $D = 100$ mm; (b) $D = 300$ mm; (c) $D = 400$ mm.

Figure 4 shows the instantaneous tangential velocity profiles of cyclones with different cylinder diameters. Here, we selected two measurement sections of the cylinder Z_1 ($z/D = 1.23$) and the lower cone Z_4 ($z/D = 3.30$) in different cyclones for analysis. The instantaneous tangential velocity fluctuations in cyclones with different cylinder diameters are relatively similar in the radial and axial directions, which showed low-frequency fluctuations superimposed onto the turbulence pulsation velocity at high frequency. In the radial direction, the instantaneous tangential velocity fluctuations considerably increased and exhibited a certain quasi-periodic behavior as the measuring points moved to the cyclone geometric center. In the axial direction, the instantaneous tangential velocities for all measuring points at the lower cone section Z_4 ($z/D = 3.30$) were close, and the fluctuations were larger. However, it can be seen from the data comparison that the instantaneous tangential velocity fluctuation increased and the fluctuation frequency decreased as the cylinder diameter increased; specific details can be seen in the analysis in Sections 3.1.2 and 3.1.3. Moreover, the fluctuations became violent near the cyclone dust outlet regardless of whether the cylinder diameter was changed under the influence of the hopper backflow.

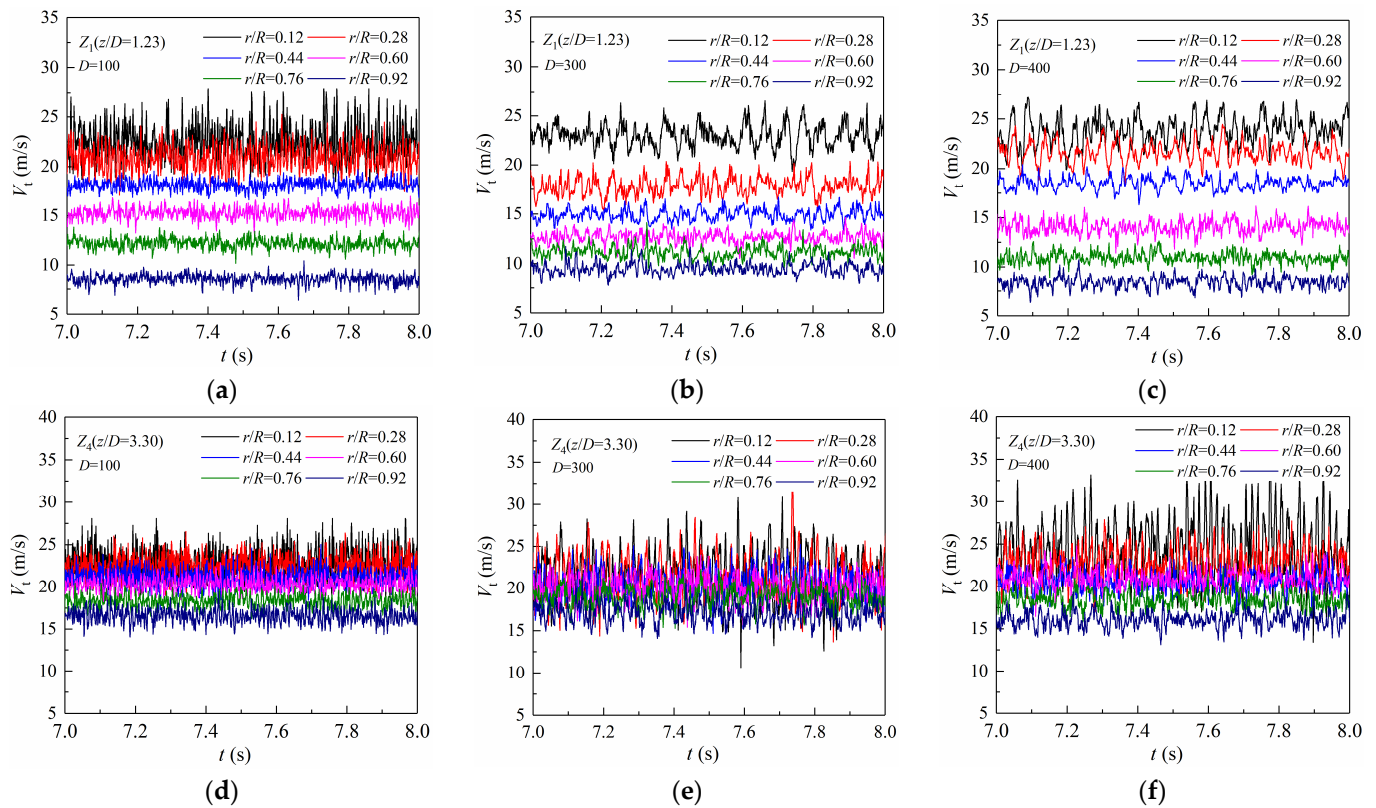


Figure 4. Instantaneous tangential velocity profiles in cyclones with different cylinder diameters. (a) $D = 100$ mm, $z/D = 1.23$; (b) $D = 300$ mm, $z/D = 1.23$; (c) $D = 400$ mm, $z/D = 1.23$; (d) $D = 100$ mm, $z/D = 3.30$; (e) $D = 300$ mm, $z/D = 3.30$; (f) $D = 400$ mm, $z/D = 3.30$.

3.1.2. Fluctuation Intensity

Standard deviation (S_d) is a standard measure of the dispersion of the data distribution, which is mainly used to measure the data value deviation from the arithmetic mean. For the instantaneous tangential velocity in the cyclone, the S_d removes the stable component and provides the degree to which the instantaneous tangential velocity fluctuation data value deviates from its mean value. Therefore, the fluctuation intensity of the instantaneous tangential velocity in the time domain can also be described by its S_d . The S_d calculation formula is as follows:

$$S_d = \sqrt{\frac{1}{N} \sum_{i=1}^N (V_{ti} - \bar{V}_t)^2} \quad (1)$$

Figure 5 shows the S_d calculated from the measured tangential velocities in cyclones with different cylinder diameters. The S_d distributions showed the same regularity in the radial and axial directions in different cyclones. For the separation spaces, the S_d values were the largest near the cyclone geometric center region, then decreased as the radial position moved to the wall, while they increased along the axial direction for the same dimensionless radial position. For the hopper, the S_d values decreased compared to the separation spaces and, as a result of the gas swirling flow, passed through a suddenly changing cross-section dust outlet. The S_d values were larger near both the center and the wall.

However, the S_d increased at the same dimensionless axial section when the cylinder diameter was increased. This indicates that the cylinder diameter of the cyclone increased, the fluctuation intensity of the instantaneous velocity increased, and the turbulent intensity increased. This is due to the different confinement effects of the cyclone space size on the tangential velocity fluctuations. When the cyclone cylinder diameter was smaller, the distribution space of gas swirling flow was small and had a strong confinement effect on the

instantaneous tangential velocity fluctuations. As the diameter increased, the distribution space of gas swirling flow increased, the confinement effect decreased, and the fluctuation intensity increased.

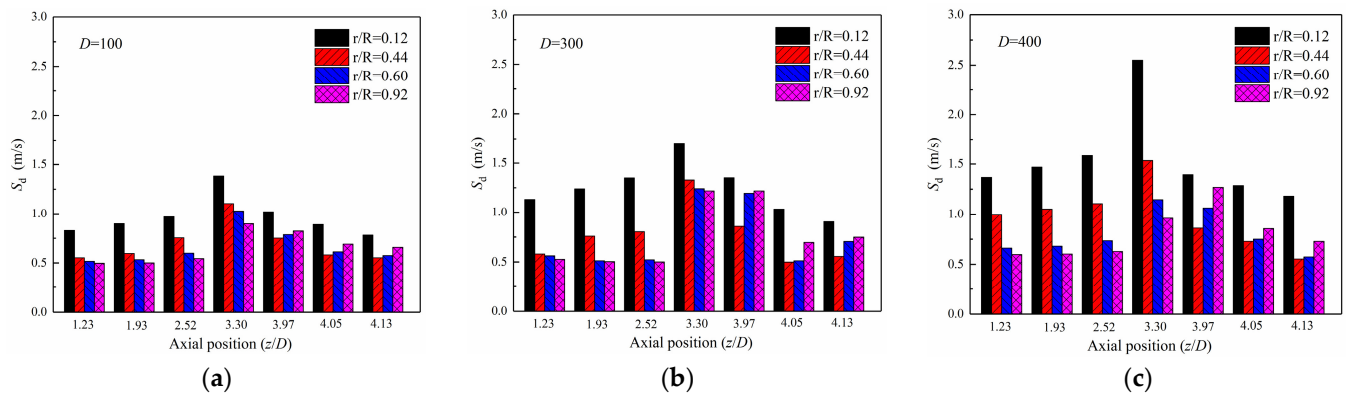


Figure 5. S_d of tangential velocity fluctuation in cyclones with different cylinder diameters. (a) $D = 100$ mm; (b) $D = 300$ mm; (c) $D = 400$ mm.

3.1.3. Frequency Domain Characteristics

Spectral analysis can decompose the complex time series waveform into several single harmonic components with Fourier transform to obtain the frequency structure of the signal and the amplitude, phase, and energy of each harmonic. From Figure 4, it can be seen that fluctuations in the instantaneous tangential velocity exhibit a certain quasi-periodic behavior. Therefore, the measured instantaneous tangential velocities were processed by using a fast Fourier transform (FFT) to analyze the frequency domain characteristics. Figure 6 shows the results of the spectral analysis (power spectral density (PSD) relative frequency) of the measured data at the measuring sections for cyclones with different cylinder diameters. As per the spectral analyses of the measured data shown in Figure 6, the phenomenon of two dominant frequencies appeared in cyclones with different cylinder diameters. One entire space dominant frequency f_1 was presented at all sections of the cyclones, and another obvious local dominant frequency f_2 was only presented at some sections up and below the dust outlet, as shown in Figure 6g–l. The f_1 and f_2 with high PSD values in the spectral graph reflect quasi-periodic fluctuations in the gas swirling flow. The dominant frequency distributions indicated that the velocity fluctuations in cyclones had two sources: one was the gas swirling flow swing in the separation spaces and the other was the gas swirling flow swing in the hopper. (The cause of the phenomenon of two dominant frequencies was analyzed in detail in our previous study [27]. When the cyclone had no hopper, only one entire dominant frequency was presented.) Other frequencies with a low PSD can also be observed in the spectral graphs, which reflect the irregular and random characteristics of the turbulence flow itself.

The f_1 and f_2 in cyclones with different cylinder diameters were extracted separately, as shown in Figure 7a–c. Although there were two dominant frequencies, the values of the dominant frequencies in cyclones with different cylinder diameters were different. According to the Strouhal number, $St = \frac{fD}{V_i}$, the dominant frequency of the gas swirling flow is inversely proportional to the cyclone cylinder diameter. Figure 7d shows the variation in f_1 and f_2 with the cyclone cylinder diameter. When $D = 100$ mm, f_1 and f_2 were 81 Hz and 190 Hz; when $D = 300$ mm, f_1 and f_2 were 20 Hz and 56 Hz; and when $D = 400$ mm, f_1 and f_2 were 16 Hz and 43 Hz. Both the f_1 and f_2 obtained in cyclones decreased when the cylinder diameter was increased, but they were not strictly inversely proportional. This is because the friction losses produced by cyclones with different cylinder diameters at the same inlet velocity were different, and there were some differences in the confinement effect of the cyclone space size on the tangential velocity fluctuations, while the St of each cyclone with different cylinder diameters calculated by using the above formula was different.

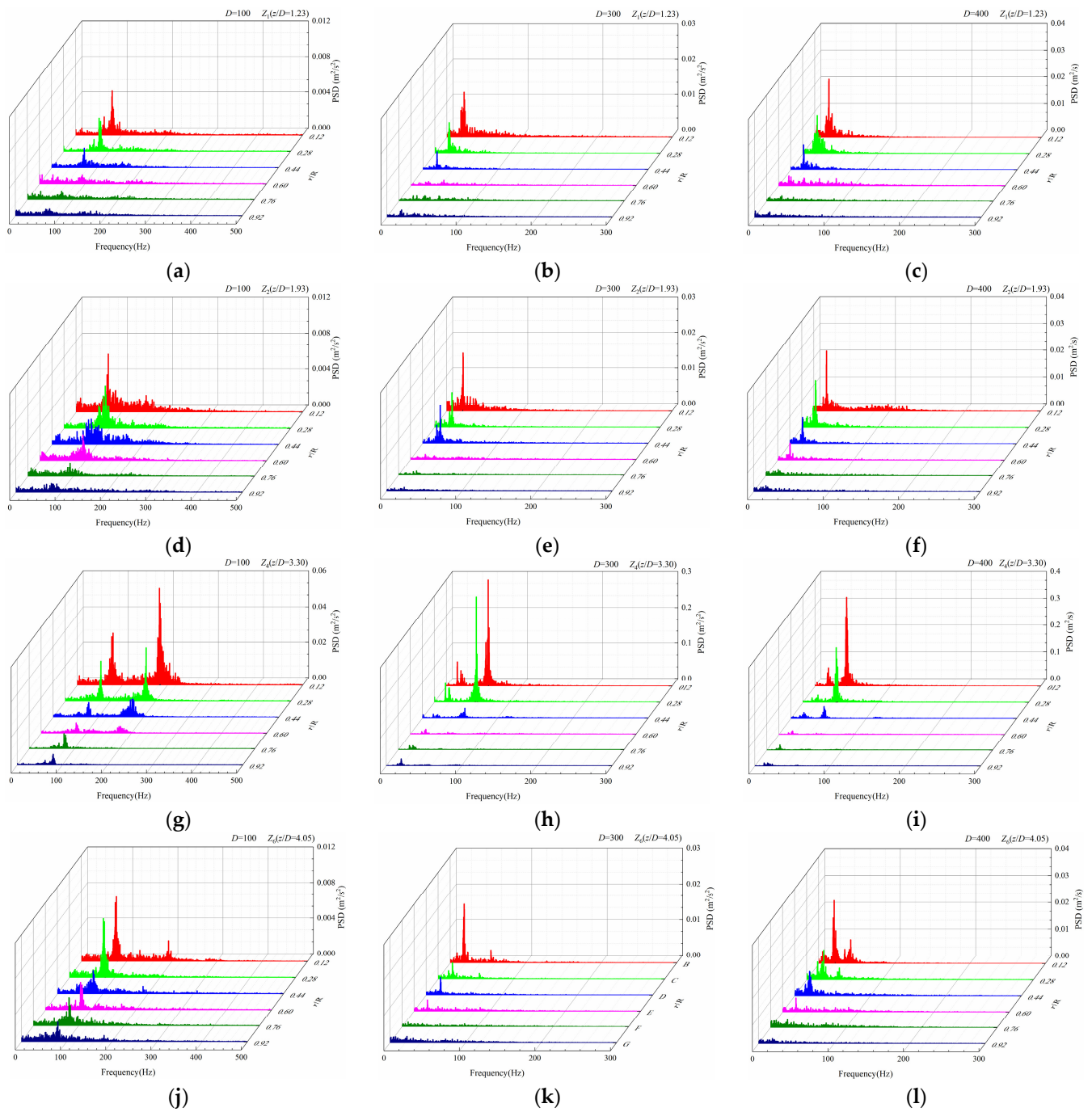


Figure 6. Spectral analysis of measured data for cyclones with different cylinder diameters. (a) $D = 100$ mm, $z/D = 1.23$; (b) $D = 300$ mm, $z/D = 1.23$; (c) $D = 400$ mm, $z/D = 1.23$; (d) $D = 100$ mm, $z/D = 1.93$; (e) $D = 300$ mm, $z/D = 1.93$; (f) $D = 400$ mm, $z/D = 1.93$; (g) $D = 100$ mm, $z/D = 3.30$; (h) $D = 300$ mm, $z/D = 3.30$; (i) $D = 400$ mm, $z/D = 3.30$; (j) $D = 100$ mm, $z/D = 4.05$; (k) $D = 300$ mm, $z/D = 4.05$; (l) $D = 400$ mm, $z/D = 4.05$.

3.2. Effects of the Vortex Finder Diameter

3.2.1. Time-Mean and Instantaneous Tangential Velocities

Figure 8 shows the time-mean tangential velocity profiles at four measuring sections selected for cyclones ($D = 300$ mm) with different vortex finder diameters ($d_r/D = 0.3$, $d_r/D = 0.367$, and $d_r/D = 0.5$). The distribution patterns in different vortex finder cyclones also reflected the Rankine vortex structure. However, the maximum tangential velocity decreased significantly when d_r/D was increased, and the interface between the rigid vortex

and the quasi-free vortex (radial position of the maximum tangential velocity) gradually increased, and all were less than d_r .

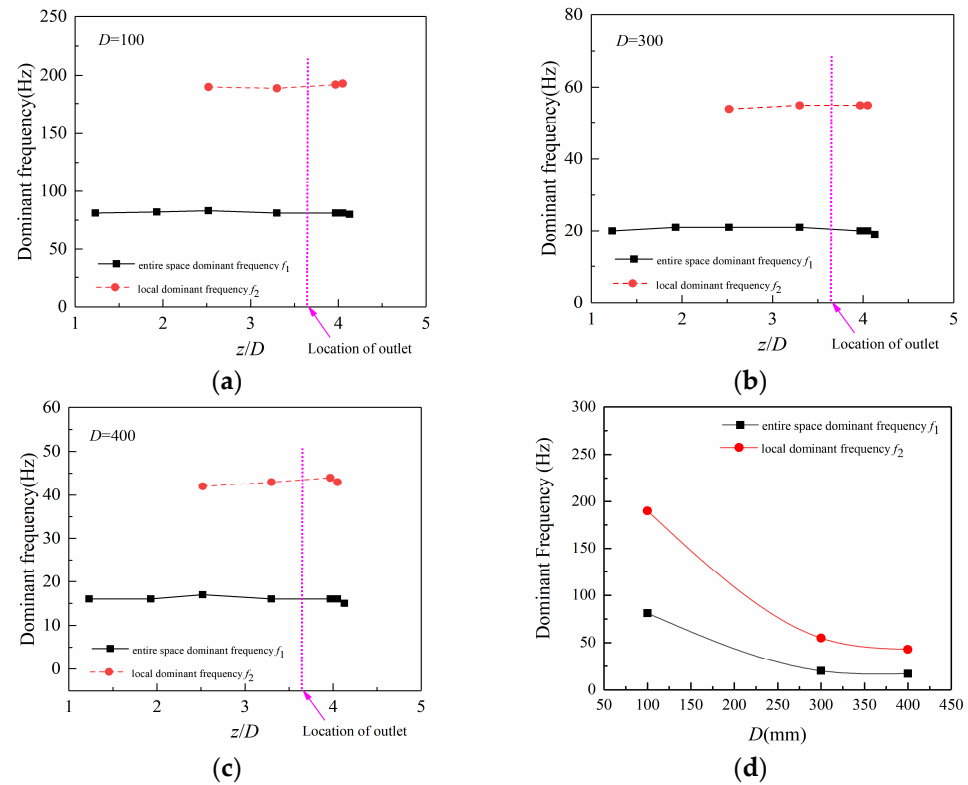


Figure 7. Variation in dominant frequency f_1 and f_2 with the cyclone cylinder diameter. (a) $D = 100$ mm; (b) $D = 300$ mm; (c) $D = 400$ mm; (d) Variation in f_1 and f_2 with D .

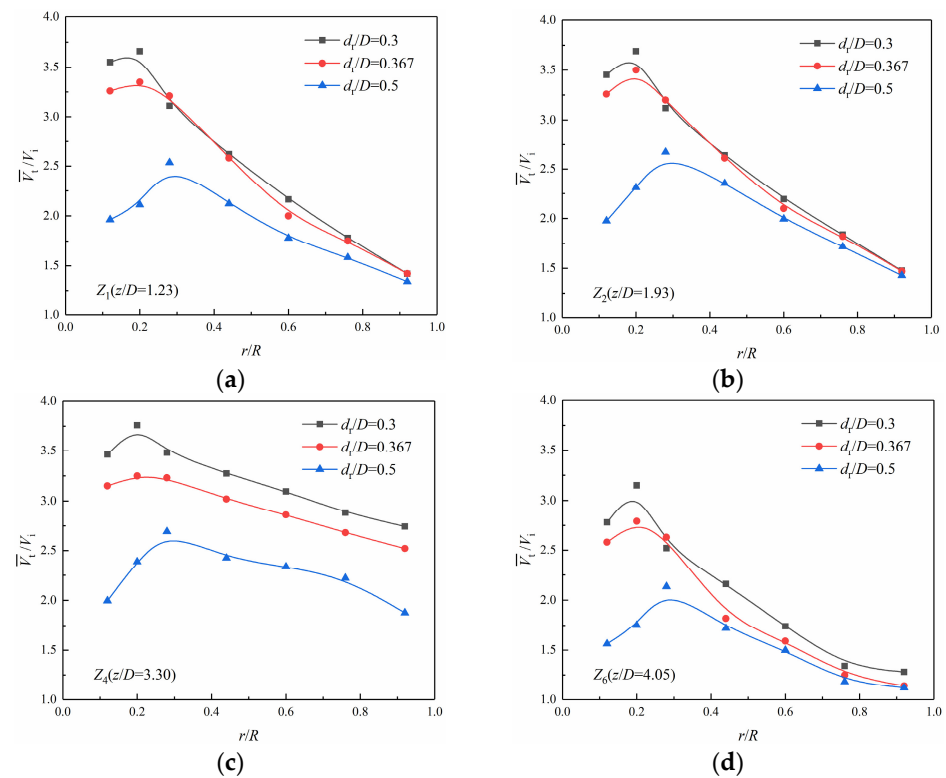


Figure 8. Time-mean tangential velocity profiles in cyclones with different vortex finder diameters. (a) $z/D = 1.23$; (b) $z/D = 1.93$; (c) $z/D = 3.30$; (d) $z/D = 4.05$.

Figure 9 shows the instantaneous tangential velocity profiles at two measurement sections of the cylinder Z_1 ($z/D = 1.23$) and lower cone Z_4 ($z/D = 3.30$) in cyclones with different vortex finder diameters. In contrast to Figure 4b,e, the instantaneous tangential velocity fluctuations and periodic behavior in cyclones with different vortex finder diameters had similar rules; that is, the instantaneous tangential velocity showed low-frequency fluctuations superimposed onto the high-frequency turbulence pulsation. The fluctuations were small near the wall but increased as the measurement point moved toward the geometric center, and the quasi-periodic behavior near the central region was more obvious.

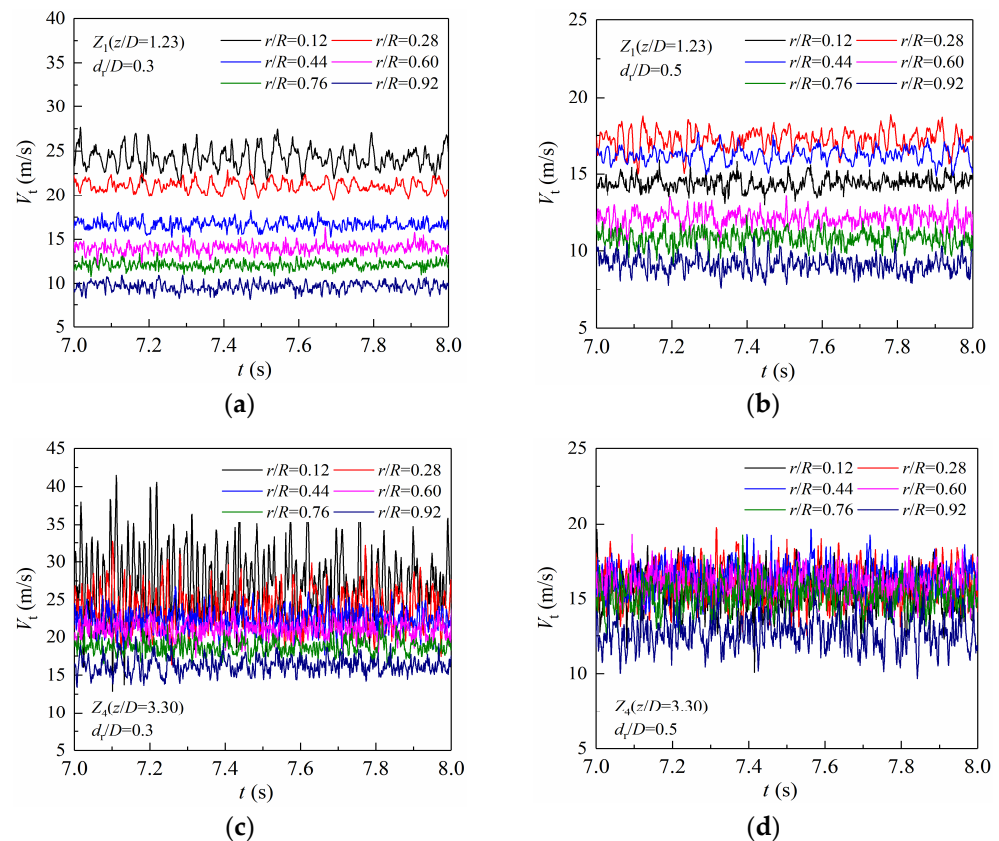


Figure 9. Instantaneous tangential velocity profiles in cyclones with different vortex finder diameters. (a) $d_f/D = 0.3$, $z/D = 1.23$; (b) $d_f/D = 0.5$, $z/D = 1.23$; (c) $d_f/D = 0.3$, $z/D = 3.30$; (d) $d_f/D = 0.5$, $z/D = 3.30$.

3.2.2. Fluctuation Intensity

Figure 10 shows the S_d distributions in cyclones with different vortex finder diameters. In contrast to Figure 5b, the S_d variation in the instantaneous tangential velocity of the cyclones with different vortex finder diameters had consistent distribution rules in the axial and radial directions. However, the S_d decreased as the vortex finder diameter increased. The increased vortex finder diameter reduced not only the time-mean tangential velocities and rotation intensity but also the gas swirling flow turbulent intensity in cyclones. In addition, the increased vortex finder diameter reduced the gas intake of the hopper, weakened the impact of the hopper backflow, and weakened the tangential velocity fluctuations.

3.2.3. Frequency Domain Characteristics

Similarly, FFT analyses were performed on the instantaneous tangential velocities in cyclones with different vortex finder diameters. Figure 11a–c show the dominant frequencies of the instantaneous tangential velocities in different experimental cyclones, and Figure 11d shows the variation in the dominant frequency f_1 and f_2 with the cyclone vortex finder diameter. The entire space dominant frequency f_1 was approximately 23 Hz, 20 Hz,

and 17 Hz, and the local dominant frequency f_2 was approximately 64 Hz, 56 Hz, and 49 Hz, respectively, in cyclones with different vortex finder diameters. When the vortex finder diameter increased, i.e., with increasing d_r/D , both the f_1 and f_2 decreased. This indicated that the increased vortex finder diameter not only weakened the fluctuation intensity of the tangential velocity but also reduced the dominant frequency of quasi-periodic fluctuations, which was not revealed by the Strouhal number described in previous studies.

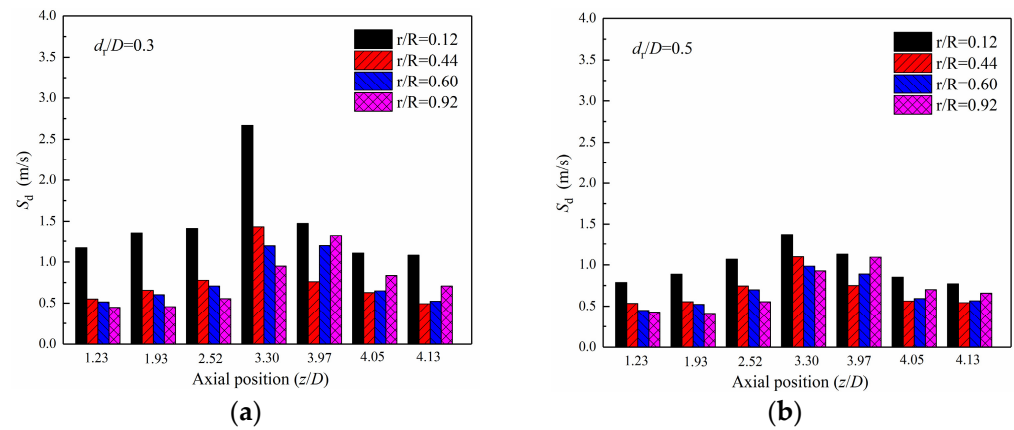


Figure 10. S_d of tangential velocity fluctuation in cyclones with different vortex finder diameters. (a) $d_r/D = 0.3$; (b) $d_r/D = 0.5$.

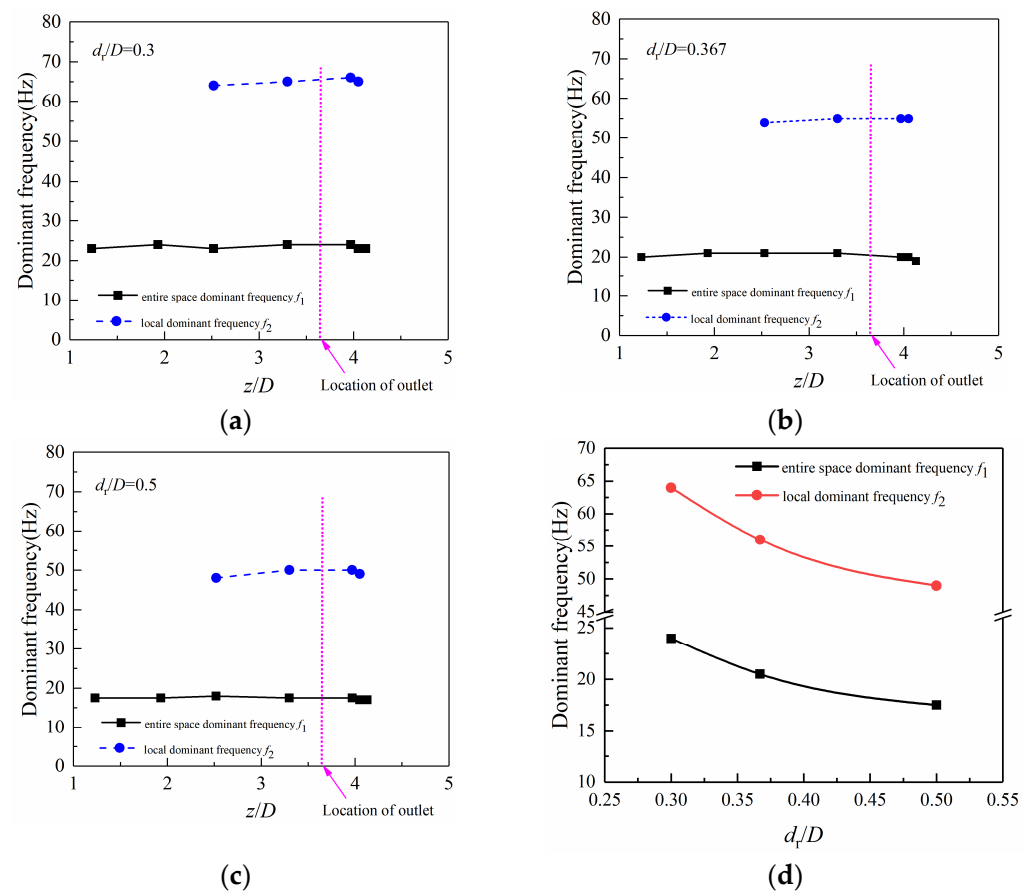


Figure 11. Variation in dominant frequency f_1 and f_2 with the cyclone vortex finder diameter. (a) $d_r/D = 0.3$; (b) $d_r/D = 0.367$; (c) $d_r/D = 0.5$; (d) Variation in f_1 and f_2 with d_r/D .

3.2.4. Improved Frequency Calculation Model

If following the Strouhal number, $St = \frac{fD}{V_i}$, the dominant frequency of the velocity fluctuations should be consistent under the conditions of a consistent cyclone diameter and an inlet velocity. However, Figure 11 shows that different vortex finder diameters played an important role in the fluctuation frequency in the cyclone. Taking the entire space dominant frequency f_1 as an example, the St calculated by the experimentally obtained frequency was 1.05, 0.88, and 0.75, which indicated that the St model was obviously not appropriate. This is mainly because the above model did not consider the influence of the vortex finder diameter and was incomplete. Therefore, the above model was modified to Formula (2) to calculate the dominant frequency, $St' = 0.53$, which agreed with the experimental measurements to an extent.

$$St' = \frac{f\sqrt{Dd_r}}{V_i} \quad (2)$$

4. Conclusions

This study investigated the flow field characteristics, especially the dynamic characteristics, of cyclones with different cylinder and vortex finder diameters. An HWA system was employed to measure the instantaneous tangential velocities, and the properties of the time and frequency domain were analyzed based on the experimental measurements. The effects of diameter parameters on the gas flow field characteristics in cyclones were discussed, and the dominant frequency calculation model for cyclones was improved. The main conclusions were as follows:

1. Distribution patterns of the time-mean tangential velocity in cyclones with different cylinder and vortex finder diameters were in accordance with the Rankine vortex structure. The maximum tangential velocity increased slightly when the cylinder diameter was increased. However, the maximum tangential velocity decreased significantly when d_r/D was increased, and the interface between the rigid vortex and the quasi-free vortex gradually increased;
2. The instantaneous tangential velocities in cyclones with different cylinder and vortex finder diameters showed that the form of tangential velocity fluctuations was low-frequency fluctuations superimposed on high-frequency turbulence pulsation. The tangential velocity fluctuation intensity characterized by the standard deviation (S_d) increased when the cylinder diameter was increased and when the vortex finder diameter was decreased at the same dimensionless axial section;
3. The phenomenon of the two dominant frequencies appeared in cyclones with different cylinder diameters and vortex finder diameters. The diameter parameters of the cyclone (the cylinder diameter and the vortex finder diameter) affect the frequency domain characteristics of instantaneous tangential velocities. The increases in cyclone cylinder diameter and vortex finder diameter led to both the two dominant frequencies being decreased but not showing strict linearity;
4. The dominant frequency in the cyclone is caused by the swing of the swirling flow. The relationship between the swing frequency of the swirling flow in the cyclone and the inlet velocity, the cylinder diameter, and the vortex finder diameter was established by the instantaneous tangential velocity frequency domain; the frequency calculation model was improved.

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Data Availability Statement: Data are contained within the article.

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

Abbreviations

a	Rectangular inlet height (mm)
b	Rectangular inlet width (mm)
D	Cylinder diameter (mm)
d_r	Vortex finder diameter (mm)
f_1	Entire space dominant frequency (Hz)
f_2	Local dominant frequency (Hz)
f	Dominant frequency (Hz)
R	Radius of cross section (mm)
r	Radial coordinate (mm)
S_d	Standard deviation (m/s)
St	Strouhal number
V_i	Inlet velocity (m/s)
V_t	Tangential velocity (m/s)
$\overline{V_t}$	Time-mean tangential velocity (m/s)
V_{ti}	Instantaneous tangential velocity (m/s)
x, y, z	Coordinates (mm)

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