Effects of Particle Concentration and Size on the Pulsation Characteristics of Oil

Liu Ge[1] and Chen Bin[1]

[1]North China Institute of Science and Technology

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Abstract

Oil flow with different particles was tested in a square tube using PIV measurement technology. The instantaneous velocity vector data of the flow field were acquired in oil with different particle sizes and concentrations of the particles, and the distributions of the transient speed and average speed and the pulsation intensity of oil along the streamwise and wall-normal directions were analyzed. The results showed that the distribution of the streamwise pulsation intensity of oil changes more gently along the wall-normal direction in the center region and changes more steeply in the near-wall area. With increasing particle concentration, the streamwise pulsation intensity of oil decreases gradually. The distribution of the wall-normal pulsation intensity of oil along the wall-normal direction is roughly "w"-shaped under different particle grain diameters. The amplitude value of the wall-normal pulsation intensity of oil is larger in the center region and near-wall area, and the effect of the particle concentration in oil on the distribution of the wall-normal pulsation intensity of oil is not unidirectional. With increasing particle concentration, the main frequency trend of the oil speed along the streamwise and wall-normal directions decreases, and the streamwise average speed of the oil increases. The change in the wall-normal average speed of oil decreases when the particle concentration is under 3.00 ppm, and the normal velocity of oil increases when the particle concentration is over 3.00 ppm

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Liu Ge[1],Chen Bin[2]

1. School of Environmental Engineering, North China Institute of Science and Technology, Hebei, 065201, China

2. School of Mechanical & Electrical, Hebei Key Laboratory of Safety Monitoring of Mining Equipment,North China Institute of Science and Technology, Hebei, 065201, China

Abstract: The presence of particulate matter in oil has a great impact on the pulsation characteristics of the oil, it is important to understand the effects of particle size and concentration on the pulsation characteristics of oil for safe operation of oil equipment. Oil flow with different particles was tested in a square tube using PIV measurement technology, the instantaneous velocity vector data of the flow field were acquired in oil with different particle sizes and concentrations of the particles, and the distributions of the transient speed and average speed and the pulsation intensity of oil along the streamwise and wall-normal directions were analyzed. The results showed that the distribution of the streamwise pulsation intensity of oil changes more gently along the wall-normal direction in the center region and changes more steeply in the near-wall area. With increasing particle concentration, the streamwise pulsation intensity of oil decreases gradually. The distribution of the wall-normal pulsation intensity of oil along the wall-normal direction is roughly "w"-shaped under different particle grain diameters. The amplitude value of the wall-normal pulsation intensity of oil is larger in the center region and near-wall area, and the effect of the particle concentration in oil on the distribution of the wall-normal pulsation intensity of oil is not unidirectional. With increasing particle concentration, the main frequency trend of the oil speed along the streamwise and wall-normal directions decreases, and the streamwise average speed of the oil increases. The change in the wall-normal average speed of oil decreases when the particle concentration is under 3.00 ppm, and the normal velocity of oil increases when the particle concentration is over 3.00 ppm.

Key words: particle concentration; particle size; pulsation characteristics; PIV measurement;oil flow;

Introduction

Oil will inevitably pulsate during circulating processes of employed oil equipment due to the functional action of the equipment, and this effect will affect the action accuracy of the equipment. A variety of measures are often employed in industry to reduce the effects of such pulsations. However, the pulsation of oil is not only related to the mechanical function but also the characteristics of the oil itself, and the particle size and concentration of particles in oil also play significant roles in the pulsation of oil. The effect of particle size and concentration on the pulsation characteristics of oil belongs to a sparse solid-liquid two-phase flow field, on which domestic and foreign scholars have carried out theoretical simulation and experimental research and obtained many research results(Abiev and Galushko, 2013; Eschmann et al., 2015; Wang et al., 2016; Yuan et al., 2016). These results have a certain reference value to investigate the influence of particle size and concentration in oil with higher viscosity on the pulsation characteristics of the oil.

Papadopoulos et al.(2016) conducted a direct numerical simulation of sinusoidal pulsation turbulence in a straight tube with a low-volume Reynolds number and a high-frequency, indicating the evolution of the average velocity and fluid pulsation over time. Tian et al.(2016) obtained the variation trend of vibration displacement and velocity of a pipeline system by establishing an analysis method of pressure pulsation in the channel and the coupling interaction of tube flow. Yan et al.(2012) studied the interaction between quasiperiodic large-scale vortex structures and flow pulsation in a rectangular channel, and the conclusions indicated that the pulsation of the vortex structure and the flow velocity pulsation could be enhanced by an adjacent velocity interface. Zhao Hui et al.(2016) studied the unsteady flow field in a channel using direct numerical simulation and found that the contributions of the low-frequency vortices to the flow direction and normal pulsation velocity increase with increasing normal height; the pulsation of the spanwise velocity at the near-wall surface exhibited a large pulsation strength in the logarithmic layer and the viscous bottom layer. Ghadi et al.(2016) conducted jet oscillating flow experiments and showed that pulsating flow forms a coherent periodic structure and that the pulsation frequency has a significant influence on the formation, size, and dynamics of a vortex structure. Hsu et al.(2014) measured a jet field using high-speed particle image velocimetry (PIV) and found that with the change in the jet exit velocity, the jet produced vibration within a pulsating period and induced a periodic wavy flow structure in the downstream region. Yang bin et al.(2013) believed that the change in frequency of wind-sand flow was at least greater than 100 Hz, and the effect of atmospheric turbulent pulsation on sediment concentration was related to the sand grain size; the smaller the particle size was, the greater the effect of wind speed fluctuation.

Two-phase flow in pipelines has been studied for the generation and development of flow field pulsation and the interaction of vortex structures in flow fields at home and abroad. Due to the random nature of oil movement and the complexity of its interaction with particles, the understanding of the pulsation characteristics of oil with different particle sizes and concentrations remains in the qualitative or semiquantitative stage. There is little literature that analyzes the pulsation characteristics of oil with higher viscous fluids. Therefore, it is necessary to investigate the pulsation characteristics of oil in the flow direction and for the normal pulsation strength as well as the instantaneous velocity and the average velocity based on the vector field data measured by the PIV of the oil containing particles in pipelines. Additionally, understanding the pulsation movement of oil at different concentrations and particle sizes reveals the interaction between particles and oil and lays a foundation for understanding the physical essence of the formation and development of oil pollution.

1 Experimental apparatus and method

The PIV test apparatus for oils containing different particle sizes and particle concentrations is shown in Fig.

1. 25# transformer oil is used as the test fluid (colorless and transparent for the PIV test). First, the oil is treated by a vacuum filter to obtain an initial oil sample. Then, Cu, Fe and SiO_2 powders with different particle sizes are selected as the particulate matter. According to the ISO4406 standard of oil pollution degree, 0.02 g of Cu, Fe and SiO_2 powder are mixed with 1 L 25# transformer oil and oscillated evenly in an ultrasonic oscillator for 8 h (temperature 30˜60°C). Then, the mixed solution was separated using filter paper having different pore diameters to obtain oil samples having a medium diameter of 5 µm, 15 µm, 25 µm and 50 µm and a concentration of 14.40 ppm. Next, the initial oil sample is added to the oil sample at a certain volume ratio, and ultrasonic vibration is evenly distributed over 8 h (temperature 30˜60°C). Oil samples containing particulates having a gradient concentration of 6.58, 4.57, 3.00, 0.971 and 0.648 ppm of different medium-diameter particles were eventually obtained.

The pipeline containing granular oil is a square tube with a total length of 500 mm and a section of 40×40 mm. The bottom and rear walls of the pipe are made of steel plates, while the front and top walls are made of transparent glass and are detachable for PIV laser incidence and testing.

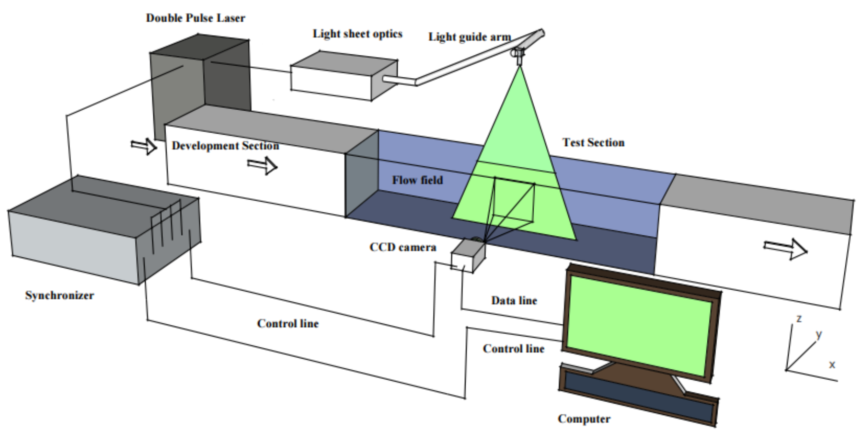

Fig. 1 PIV experimental equipment for oil liquid

The initial velocity of the oil inlet was set to V_0=0.0362 m/s, the corresponding Reynolds number was 138.3, and the oil in the pipeline was in a laminar flow state. Since the temperature did not change much during an experiment, the influence of temperature was not considered. After the oil samples to be tested were thoroughly mixed, they were fed into the test pipeline through a peristaltic pump. After flowing through the pipeline development section, a uniform liquid-solid two-phase suspension flow was formed in the test section and then entered the oil tank through the tail section to form a circulation. The system was run for 30 min before the PIV test to ensure that the oil and particles were evenly mixed during the PIV measurement period.

The PIV equipment used in the experiment was a 2DPIV system from TSI Corporation of the United States. This system consists of a double yttrium aluminum garnet laser (200 mJ, pulse frequency 15 Hz, laser wavelength 532 nm), light guide arm, sheet light source lens (focal length from 30-3000 mm, two sets of cylindrical lenses 15 mm F.L. and -25 mm F.L., and divergence angles 25° and 14° , respectively), a Nikon CCD camera (15 frames per sec, 50 mm / F1.8 lens, 2K×2K pixel resolution) and TSI Insight4G image acquisition, analysis and display software platform. The coordinate frame of the camera is three-dimensional and is automatically controlled by a microcomputer with a movement accuracy of 0.01 mm. The laser light emitted from the laser passes through the light guide arm and the light source lens to form a 1 mm thick sheet light, which is irradiated from the normal direction (z-direction) of the pipe test section. Then, oil image information is obtained by the camera positioned in the direction of the pipe (y-direction). In addition, the synchronization controller (time resolution 0.25 ns) is set to trigger the laser and the camera synchronously.

As the particle size in oil is less than 100 µm, the particles have a good following behavior and uniform distribution of light scattering, so no tracer particles need to be added during the test. The acquired image adopts the algorithms of multigrid iterative mutual correlation and multiadaptive deformation window, and the image query area adopts pipeline horizontal and vertical initial query windows of 72×64 pixels, a final query window of 64×48 pixels and 50% overlap to obtain the original velocity vector and eliminate the impact of the query window boundary. The method of processing the error vector is to use a local average verification method, and this vector is replaced by the mean in the adjacent 5×5 pixel range. The measurement position is 300 mm from the inlet of the pipeline; the measurement area is (flow direction×normal direction) 85.86 mm×22.20 mm, while the center of the area is (flow direction×normal direction) 300 mm×30 mm. In addition, 200 image frames are captured in a test period.

2 Experimental results and analysis

The instantaneous velocity vector field data were averaged over time, and the mean square of the flow velocity and normal pulsation velocity were obtained. The flow pulsation intensity and normal pulsation intensity were as follows:

In the formulas, and indicate the fluctuation intensity of the flow and normal pulsation intensities, respectively; and represent the flow instantaneous velocity and normal instantaneous velocity at a certain position (x.y) at a certain time t, respectively, that are acquired by PIV in the flow field; N is the period of PIV acquisition; and C is the number of acquisitions in the PIV field of view.

2.1 Distribution of flow pulsation intensity along the normal direction

When the particle size in the oil is 5 µm, 15 µm, 25 µm, and 50 µm while the particle concentration is 0.65 ppm, 0.97 ppm, 3.00 ppm, 6.58 ppm and 14.40 ppm, the distribution curves of the flow pulsation intensity along the normal direction are shown in Fig. 2. The horizontal axes of the graphs show the ratio of the flow pulsation intensity to the fluid inlet velocity V_0, and the ordinates represent the normal dimensionless pipe length.

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(a) 5 µm (b) 15 µm

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(c) 25 µm (d) 50 µm

Fig. 2 The distribution of streamwise mean intensity along the normal direction

Fig. 2 (a) shows the distribution of the flow pulsation intensity of the oil along the normal direction with different particle concentrations for a particle size of 5 µm. The figure shows that the flow pulsation intensity of the PIV acquisition oil field is relatively slow to change along the normal distribution in the central region due to the presence of particulate matter, while the change is steep in the near-wall area, and this trend becomes increasingly obvious as the particle concentration increases. On the other hand, when the particle concentration is lower, the flow pulsation intensity of the oil field is larger in the near-wall area and gradually decreases toward the center of the pipe; however, this trend becomes less obvious as the particle concentration increases. On the whole, with increasing particle concentration, the flow pulsation intensity of the oil successively decreases, and if the particle concentration is too large (such as 6.58 ppm and 14.40 ppm), the difference in flow pulsation intensity is smaller. The reason is that the particles in oil in the near-wall area increase the flow velocity of the oil. To maintain mass conservation, the oil flow velocity in the central region decreases. Additionally, coupled with the blocking action of the oil particles, the flow pulsation intensity of the oil is steeply distributed in the near-wall region along the normal direction, while this intensity is relatively gentle in the center area(Ling and Zhong, 1999). In addition, with increasing particle concentration in oil, the effect of near-wall particles on oil flow velocity growth is attenuated due to decreasing viscous shear force, which weakens the tendency of oil flow pulsation intensity growth in the near-wall area. Therefore, as the particle concentration reaches 3.00 ppm or more, the tendency of the flow pulsation intensity distribution along the normal direction becomes slower. This finding also indicates that the flow pulsation of the flow field in the pipeline is greatly affected by the wall surface.

According to the effect of the 15 μm particle size on the flow pulsation intensity of oil shown in Fig. 2 (b), the effect of different particle concentrations on the intensity distribution along the normal direction is basically consistent with that of the 5 μm particle size shown in Fig. 2 (a). The difference is that in the case of low particle concentration, the maximum value of the flow pulsation intensity is larger for the case of the 15 μm particle size. For example, the maximum value of the flow pulsation intensity for the 5 μm particle size under 0.65 ppm particle concentration is 0.233, while the maximum value of the flow pulsation intensity for the 15 μm particle size is 0.236. The reason is that the larger the particle size is, the greater the viscous shearing force of the oil, so the particles in the near-wall region increase the role of oil flow velocity growth.

Fig. 2 (c) shows the effect of different particle concentrations on the flow pulsation intensity of the oil when the particle size is 25 μm. The effect of the 25 μm particle size on the flow pulsation intensity of the oil is similar to the trends in Fig. 2 (a) and (b). However, for the case of the particle size of 25 μm, the flow pulsation intensity is larger in the near-wall region and has a value of 0.256, and then, the 5 μm and 15 μm amplitudes are increased by 9.95% and 8.56%, respectively. In addition, when the particle concentration is 6.58 ppm, the flow pulsation intensity of oil is larger, and this finding indicates that the particle size in the oil has less attenuation effect on the viscous shear force of oil when the particle size is 25 μm. However, the effect of the particles in the near-wall area on the oil growth rate is enhanced when the particle size exceeds 25 μm, as shown in Fig. 2 (d). When the particle size is 50 μm, the amplitude of the flow pulsation intensity under each particle concentration decreases greatly, except for the particle concentration of 0.65 ppm. Moreover, when the particle concentration is 6.58 ppm, the flow pulsation intensity is basically the same as that for 14.40 ppm.

The results in Fig. 2 show that the flow pulsation intensity decreases with increasing particle concentration, and the difference decreases gradually for oil with different particle concentrations.

2.2 Normal pulsation intensity distribution along the normal direction

Fig. 3 shows the distribution curves of the normal pulsation intensity along the normal direction when the particle size is 5 μm, 15 μm, 25 μm, and 50 μm and the particle concentrations are 0.65 ppm, 0.97 ppm, 3.00 ppm, 6.58 ppm, and 14.40 ppm. The horizontal axes in the figures show the ratio of the normal pulsation intensity to the oil inlet velocity V_0, and the ordinates represent the dimensionless length of the pipeline.

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(a) 5 µm (b) 15 µm

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(c) 25 µm (d) 50 µm

Fig. 3 The distribution of the time-averaged pulse velocity along the normal direction

Fig. 3 shows that the distribution of the normal pulsation intensity of oil with different particle sizes along the normal direction is roughly in the shape of a "W". The amplitude of the normal pulsation intensity in the central region and the near-wall region is largely within the field of view tested by PIV; moreover, the particle concentration has a non-unidirectional effect on the distribution of the normal pulsation intensity. The normal pulsation intensity is also affected by the wall of the pipeline, but the distribution of the normal pulsation intensity shows a parabolic shape due to the action of the central mainstream.

Fig. 3 (a) shows the effect of different particle concentrations on the distribution of the normal pulsation intensity when the particle size is 5 µm. The particle concentration (6.58 ppm and 14.40 ppm) is larger and the variation in the normal pulsation intensity of the oil is greater in the near-wall area. In contrast, when the particle concentration (0.65 ppm, 0.97 ppm, and 3.00 ppm) is smaller, the variation range of the normal pulsation intensity in the central region is greater. This finding is because increasing the particle concentration makes the wall surface prone to the rough surface, and this effect enhances the turbulent burst behavior near the wall, thus leading to a significant increase in the normal pulsation intensity near the wall(Li et al., 2012).

Fig. 3 (b) shows the distribution of the normal pulsation intensity of the oil under the diameter of 15 µm particle size along the normal direction. The influence of different particle concentrations is similar to that of 5 µm. Figs. 3 (c) and (d) show that as the particle size increases, the amplitude of the normal pulsation intensity increases slightly, which indicates that the particle size has an influence on the normal pulsation intensity of the oil. Fig. 3 (c) shows that due to a decrease in the viscous shear force of 25 µm particles in the near-wall region, the distribution of the oil normal pulsation intensity for the different particle concentrations increases with increasing particle concentration. However, in the central region, due to the central mainstream, the retardation role of the particles increases, so the normal pulsation intensity decreases as the particle concentration increases.

2.3 Time-frequency curves of transient velocity

To characterize the development of the flow pulsation characteristics over time for oil containing particles, according to the instantaneous velocity vector of the PIV test, a point (0.9, 0.25) near the center of the test field is randomly selected. Time-frequency analysis of the instantaneous flow velocity and normal velocity at different particle concentrations of 0.65 ppm, 0.97 ppm, 3.00 ppm, 6.58 ppm, and 14.40 ppm is shown in Figs. 4-8, respectively. In Figs. 4-8, (a) shows the time curve of the instantaneous flow velocity of the oil, (b) shows the time curve of the instantaneous normal velocity of the oil, (c) presents the spectrum curve of the instantaneous flow velocity of the oil and (d) presents the spectral curve of the instantaneous normal velocity of the oil.

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Fig. 4 The time-frequency variation in the transient velocity of oil when the concentration is 0.65 ppm

Fig. 4 shows the variation in the time-frequency curves of the instantaneous flow velocity and the instantaneous normal velocity when the particle concentration is 0.65 ppm. Fig. 4 (a) presents the change in the instantaneous flow velocity over time. The instantaneous flow velocity fluctuates at approximately 0.2099 under the action of a flow field pulsation base frequency of 0.12 Hz (as shown in Fig. 4 (c)), and the flow velocity appears to have a reflow phenomenon (having a negative velocity) in the first cycle; however, the distribution of the flow velocity tends to be gentle after this cycle. Due to the small particle concentration, the viscous shear force has little effect on the oil, where this force made the pulsation degree increase from -0.4474 to 0.9041, namely, a change of 1.3515. In addition, Fig. 4 (c) shows that the flow velocity pulsation frequency is mainly 0.21 Hz, which is approximately two times the base frequency.

Fig. 4 (b) presents the change in the instantaneous normal velocity with time, and this figure shows that the instantaneous normal velocity at this point fluctuated around 0.0436, indicating that the velocity distribution in the central region is relatively balanced in the normal direction. The change in the amplitude of the normal velocity is relatively flat, from 0.4058 to 0.3965, with a range of 0.8023. Fig. 4 (d) shows that the normal velocity pulsation frequency of the oil mainly includes the base frequencies of 0.12 Hz and 0.21 Hz, which is approximately two times the base frequency.

The time-frequency variations in the instantaneous flow velocity and normal velocity when the particle concentration is 0.97 ppm are shown in Fig. 5. The instantaneous flow velocity changes over time, as shown in Fig. 5 (a), and the instantaneous flow velocity of the point fluctuation is near the value of 0.1683. Under the action of the flow pulsation base frequency of 0.12 Hz (as shown in Fig. 5 (c)), the flow velocity appears to reflow in the first two cycles. Compared with Fig. 4 (a), as the particle concentration increases and the viscous shear force increases, the flow velocity pulsation intensity decreases from -0.3985 to 0.8943; namely, the variation range is 1.2928. In addition, the flow velocity pulsation frequency is 0.18 Hz, which is 1.5 times the base frequency (shown in Fig. 5 (c)).

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Fig. 5 The time-frequency variation in the transient velocity of oil when the concentration is 0.97 ppm

Fig. 5 (b) shows the curve of the change in the instantaneous normal velocity over time. The instantaneous normal velocity of the point fluctuates near the value of 0.0299, which shows that the normal velocity distribution in the central region is balanced with respect to that of Fig. 4 (b). However, the magnitude of the change in the normal velocity is relatively large, ranging from -0.4759 to 0.4649, with a variation of 0.9408. In addition, Fig. 5 (d) shows that the normal velocity pulsation frequency mainly includes the subharmonic frequency of 0.09 Hz and is approximately twice the frequency of 0.21 Hz of the base frequency.

Fig. 6 shows the time-frequency variations in the instantaneous flow velocity and normal velocity when the particle concentration is 3.00 ppm. The instantaneous flow velocity changes over time, as shown in Fig. 6 (a), and the transient flow velocity of the point fluctuates near a value of 0.1635. Under the action of the flow field base pulsation frequency of 0.12 Hz (as shown in Fig. 6 (c)), the flow velocity amplitude in the first period has a large fluctuation phenomenon, and the reflow phenomenon occurs in the third cycle. As the particle concentration increases and the viscous shear force of the oil increases, the flow velocity pulsation degree of the oil shown in Fig. 6(a) relative to that of Fig. 4 (a) and Fig. 5 (a) decreases from -0.1292 to 0.8407, with a variation range of 0.9699. In addition, Fig. 6(c) shows that the flow velocity pulsation frequency is mainly 0.09 Hz, which is a subharmonic frequency of the base frequency.

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Fig. 6 The time-frequency variation in the transient velocity of oil when the concentration is 3.00 ppm

In Fig. 6 (b), the instantaneous normal velocity at this point fluctuates around -0.0387 over time, which indicates that the velocity distribution in the central region has a negative trend in the normal direction relative to that of Fig. 4 (b) and Fig. 5 (b). However, the magnitude of the change in the normal velocity is relatively small, from -0.3491 to 0.3944 with a variation range of 0.7435. Fig. 6 (d) shows that the normal velocity pulsation frequency is 0.06 Hz, which is a subharmonic frequency of the base frequency.

Fig. 7 shows the time-frequency variations in the instantaneous flow velocity and normal velocity when the particle concentration is 6.58 ppm. The instantaneous flow velocity of the point shown in Fig. 7 (a) fluctuates near 0.161 over time. Under the action of the flow field pulsation frequency of 0.12 Hz (as shown in Fig. 7 (c)), the amplitude of the flow velocity in the latter two periods has a large fluctuation phenomenon. As the particle concentration increases and the viscous shear force increases, the flow velocity pulsation degree is reduced from 0.0807 to 0.8113 relative to that of Figs. 4-6 (a), with a variation range of 0.8920. In addition, Fig. 7 (c) shows that the flow velocity pulsation frequency is mainly a subharmonic frequency of 0.03 Hz and a base frequency of 0.12 Hz.

In Fig. 7 (b), the instantaneous normal velocity of the point fluctuates near 0.032 over time, which shows that in the central region, the normal upward velocity distribution has a positive trend relative to the trend of Fig. 4-6 (b). However, the magnitude of the change in the normal velocity is relatively larger from -0.3905 to 0.6698, with a range of 1.0603. In addition, Fig. 7 (d) shows that the normal velocity pulsation frequency is mainly the subharmonic frequency of 0.09 Hz and is approximately twice the frequency of 0.26 Hz of the base frequency.

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Fig. 7 The time-frequency variation in the transient velocity of oil when the concentration is 6.58 ppm

Fig. 8 shows the time-frequency variations in the instantaneous flow velocity and normal velocity when the particle concentration is 14.40 ppm. As shown in Fig. 8 (a), the instantaneous flow velocity at this point fluctuates around 0.166 over time. Under the action of the flow field pulsation frequency of 0.12 Hz (as shown in Fig. 8 (c)), the flow velocity amplitude appears to exhibit large fluctuations in the first two cycles. As the particle concentration increases and the viscous shear force increases, the flow velocity pulsation degree decreases with respect to that of Figs. 4-7 (a), from -0.1459 to 0.6922 with a variation range of 0.8381. In addition, Fig. 8 (c) shows that the flow pulsation frequency is mainly a subharmonic frequency of 0.03 Hz and a base frequency of 0.12 Hz.

As shown in Fig. 8 (b), the instantaneous normal velocity at this point fluctuates around -0.008, which indicates that the normal velocity distribution in the central region is relatively balanced with respect to that of Fig. 4-7 (b). However, the magnitude of the change in the normal velocity is relatively small, ranging from -0.4071 to 0.2982 with a variation range of 0.7053. In addition, Fig. 8 (d) shows that the normal velocity pulsation frequency is mainly the subharmonic frequency of 0.03 Hz and is approximately twice the frequency of 0.26 Hz of the base frequency.

The above results show that with increasing particle concentration in oil, the mean value of the magnitude of the instantaneous flow velocity pulsation is gradually reduced, and the varying amplitude simultaneously decreases. On the other hand, the changes in the mean and variance amplitude of the instantaneous normal velocity pulsation are not obvious due to the influence of the flow field structure.

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Fig. 8 The time-frequency variation in the transient velocity of oil when the concentration is 14.40 ppm

Tab. 1 shows the main frequencies of the instantaneous flow velocity and normal velocity for different particle concentrations. The base frequency of 0.12 Hz is reflected in the frequency domain of the flow velocity. As the particle concentration increases, the main frequency of the flow velocity decreases from twice the base frequency to the subharmonic frequency, which shows an attenuation trend. Similarly, with increasing particle concentration, the main frequency of the normal velocity of oil decreases from the base frequency to the subharmonic frequency, which also shows an attenuation trend.

Table 1 Fluctuation frequency of the transient velocity in the flow field

velocity	concentration	subharmonic	base frequency	second-time frequency	third-time frequency	fourth-ti
flow velocity	0.65	0.06	0.12	0.21	0.41	
	0.97	0.06	0.12	0.18	0.41	
	3.00	0.03	0.12	0.29	0.44	
	6.58	0.03	0.12	0.26	0.35	
	14.40	0.03	0.12	0.26	0.41	
normal velocity	0.65	0.03	0.12	0.29	0.41	0.53
	0.97	0.09		0.21	0.41	0.50
	3.00	0.06	0.18	0.26	0.47	0.56
	6.58	0.09	0.18	0.26	0.41	0.53
	14.40	0.03	0.12	0.26	0.38	0.53

2.4 The speed-frequency curve of average velocity

The instantaneous velocity vectors for different particle concentrations obtained by the PIV test are averaged in the flow direction and the normal direction to obtain the corresponding time-frequency curves of the average flow velocity and normal average velocity of oil in the time of the PIV test, as shown in Fig. 9.

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(a) The time-domain distribution of the flow average velocity (b) The frequency-domain distribution of the flow average velocity

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(c) The time-domain distribution of the normal average velocity (d) The frequency-domain distribution of the normal average velocity

Fig. 9 The time-frequency curves of the mean velocity of oil

Fig. 9 (a) shows the time-domain distribution of the flow average velocity under different particle concentrations; it is obvious that the distribution of the flow average velocity is periodic. In addition, the base frequency of the flow field is 0.12 Hz, as shown in Fig. 9 (b). With increasing particle concentration, the change in the flow average velocity is nonunidirectional, but the overall trend is that the average velocity of the oil gradually increases. The reason is that due to the increase in the particle concentration, the particle inertia increases the average velocity in the near-wall region, so the thickness of the turbulent viscous bottom layer decreases and the flow velocity gradient increases[13], which lead to an increase in the flow pulsation peak value.

The time-domain distribution of the average normal velocity for different particle concentrations is shown in Fig. 9 (c). As the particle concentration increases, the change in the average normal velocity decreases when the particle concentration is below 3.00 ppm, while this change increases when the particle concentration exceeds 3.00 ppm. This result is because when the particle concentration reaches a certain level (3.00 ppm) in the horizontal pipeline, the sedimentation of the particles causes the wall surface to form a rough wall surface, which enhances the release of the oil sudden turbulence behavior in the near-wall region and results in increasing normal average velocity. Fig. 9 (d) shows that the main frequency of the normal average velocity is concentrated in a subharmonic frequency of 0.09 Hz and a base frequency of 0.12 Hz, which is consistent with the main frequency of the transient normal velocity.

3 Conclusions

(1) The distribution of the oil flow pulsation intensity along the normal direction changes slowly in the central region, while the change in the near-wall region is steep, and this trend becomes more obvious with increasing particle concentration. In addition, the flow direction pulsation intensity of oil decreases with increasing particle concentration, and the difference gradually decreases.

(2) The distribution of the normal pulsation strength of oil in the normal direction for different particle sizes is roughly in the shape of a "W". The amplitude of the normal pulsation intensity fluctuates greatly in the central region and near-wall region. In addition, the influence of particle concentration on the distribution of the normal pulsation intensity is nonunidirectional.

(3) With increasing particle concentration, the mean value of the fluctuation amplitude of the instantaneous flow velocity gradually decreases, and the varying amplitude decreases simultaneously. However, the fluctuation amplitude of the instantaneous normal velocity is not obvious. With increasing particle concentration, the main frequencies of the flow direction and normal direction velocities show a decreasing trend.

(4) The distribution periodicity of the average flow velocity of oil is more obvious. As the particle concentration increases, the average flow velocity gradually increases. When the particle concentration is below 3.00 ppm, the average normal velocity decreases with increasing particle concentration, while when the particle concentration exceeds 3.00 ppm, the average normal velocity of the oil shows an increasing trend.

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