

## Research Article

### Research on Dispersed Oil Droplets Breakage and Emulsification in the Dynamic Oil and Water Hydrocyclone

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**Abstract:** Oil and water dynamic hydrocyclone is one type of facilities that separate two phases or multiple phases applied widely in the fields such as food processing, environmental protection, biological pharmacy, petroleum and chemistry. The dispersed oil droplets in the dynamic oil and water hydrocyclone were often broken into small drops by shear force, which decreased the separation efficiency of dynamic oil-water hydrocyclone greatly. To avoid the breakage of the oil droplets, the turbulence field and the velocity field of the dynamic hydrocyclone were studied by the software of Fluent to analyze the main reason that led to breakage of oil droplets. Results indicated that the deformation of oil droplets was caused by the viscous shear force; the breakage of oil droplets was caused by the Reynolds shear stress and the local pressure fluctuations. The main area that the drops were prone to breakup of the dynamic hydrocyclone is that the rotating grating nearby, the wall boundary layer of the drum and center axis of the drum. Finally, the breakage of oil droplets and emulsification of oil and water in the dynamic hydrocyclone were verified by the experiments.

**Keywords:** Droplets breakage, dynamic hydrocyclone, oil and water separation, reynolds shear stress, turbulence intensity

## INTRODUCTION

There were a lot of waste oil-water mixture that were produce in the process of food processing, which was often discharged at the river and the sea. It will kill the fish and pollute the environment greatly. Hydrocyclone is one type of separation devices, which are widely used in the fields such as food processing, environmental protection, biological pharmacy, petroleum and chemistry (Martin, 1986). There are several advantages of the dynamic hydrocyclone comparing with the static hydrocyclone, for instance the larger capacity, a wide range of processing. Hydrocyclone was usually used in marine oil platform, oil refineries and other places to deal with the oily sewage (Yaojun, 1997). In the early 1980s, under the financial support of the commission, the dynamic hydrocyclone was developed by TOTAL CFP and NEYRTEC company (Gay *et al.*, 1987) and in the early 1990s, it was introduce to China, the Daqing petroleum institute (Zunce *et al.*, 2005), logistics engineering university (Panfeng *et al.*, 2005) and other research units have developed a prototype dynamic hydrocyclone separator and carried out related experimental research. A lot of research results have been achieved, such as the characteristics of flow field (Jordan *et al.*, 2006; Udaya Bhaskar *et al.*, 2007), the

structure optimization (Arman and Mehrzad, 2008) were studied and so on. With the deepening of the study, the researchers found the phenomena of deformation, breakage and emulsification, which were caused by the shear stress and turbulence motion and it seriously affected the oil-water separation of dynamic hydrocyclone process (Qicheng and Wenjie, 2011). To study the law of the dispersed phase droplets deformation and rupture in dynamic hydrocyclone, the turbulence field and the velocity field of the dynamic hydro-cyclone were studied by the software of Fluent to analyze the main reason that leaded to breakage of oil droplets, which can effectively prevent the emulsification in the oil and water separation process and improve the efficiency of oil-water separation in dynamic hydrocyclone.

The diagram of total type oil-water dynamic hydrocyclone was shown in Fig. 1. The oil-water mixture to be separated was injected into the dynamic hydrocyclone through the inlet. The swirling flow was caused by the rotating gate and the diversion cone in the drum. There was a centrifugal field in the drum, which was generated by the motor, the drum and the rotating gate. The water phase was thrown to the cyclone wall; the oil phase was gathered to the center of the dynamic hydrocyclone. The water phase were removed through the underflow, oil phase were removed through the

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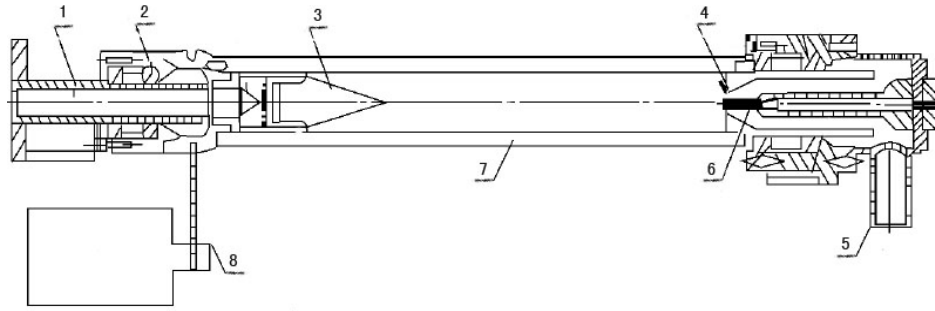


Fig. 1: The sketch of total dynamic liquid-liquid hydrocyclone  
 1: Inlet; 2: Mechanical seal; 3: Rotating grating; 4: Receiving set; 5: Underflow; 6: Overflow; 7: Drum; 8: Motor

overflow at the bottom of the dynamic hydrocyclone. At last, the oil-water mixture was separated by the dynamic hydrocyclone. The vortex formed by the rotation of the drum and the rotary gate is called the "free vortex", it was totally different from the vortex formed by the centrifugal machine, which was called the "forced vortex".

**MODEL SET UP AND SIMULATION**

**Mathematical model:** There have been several turbulence models and multiphase flow models to simulate the dynamic liquid-liquid hydrocyclone. The success of the simulation methodology depends primarily on how best the results are matching with the experimental values and the computational time it requires for obtaining such results. In this study the 3-D swirling, turbulence flow in the dynamic liquid-liquid hydrocyclone were investigated by Reynolds stress model. The approach to multiphase flow simulations is the mixture model for oil-water simulation in the dynamic hydrocyclone. The governing partial differential equations for the conservation of mass, momentum and transport of turbulence kinetic energy and its dissipation were rearranged in a general form, discretized and solved using the control-volume method. The mixture model was expressed by solving the continuity equation, momentum equation, the second phase volume fraction equation and the algebraic expression of relative velocity.

**Continuity equation for the oil-water mixture:**

$$\frac{\partial}{\partial t}(\rho_m) + \frac{\partial}{\partial x_i}(\rho_m u_{m,i}) = 0 \tag{1}$$

where,  
 $u_{m,i}$  = The average speed of the quality:

$$u_{m,i} = \frac{\alpha_o \rho_o u_{o,i} + \alpha_w \rho_w u_{w,i}}{\rho_m} \tag{2}$$

$\rho_m$  = Mixture density of oil-water:

$$\rho_m = \alpha_o \rho_o + \alpha_w \rho_w \tag{3}$$

$\alpha_o, \alpha_w$ : Volume fraction of oil phase and water phase, respectively

**Momentum equation for the oil-water mixture:**

$$\begin{aligned} & \frac{\partial}{\partial t}(\rho_m u_{m,i}) + \frac{\partial}{\partial x_i}(\rho_m u_{m,i} u_{m,j}) \\ &= \frac{\partial}{\partial x_i} \left[ \mu_m \left( \frac{\partial u_{m,i}}{\partial x_j} + \frac{\partial u_{m,j}}{\partial x_i} \right) \right] \\ & - \frac{\partial p}{\partial x_j} + \rho_m g_j + F_j \\ & + \frac{\partial}{\partial x_i} (\alpha_o \rho_o u_{Do,i} u_{Do,j} + \alpha_w \rho_w u_{Dw,i} u_{Dw,j}) \end{aligned} \tag{4}$$

where,  
 $F_j$  = Body force  
 $\mu_m$  = Mixture viscosity of oil and water mixture:

$$\mu_m = \alpha_o \mu_o + \alpha_w \mu_w \tag{5}$$

$u_{Do,i}, u_{Dw,i}$ : Drift velocity of oil phase and water phase respectively:

$$u_{Do,i} = u_{o,i} - u_{m,i} \tag{6}$$

$$u_{Dw,i} = u_{w,i} - u_{m,i} \tag{7}$$

**Slip velocity and drift velocity:** The slip speed refers to the speed difference between dispersed phase and continuous phase in the dynamic liquid-liquid hydrocyclone separation system:

$$v_{wo,i} = u_{o,i} - u_{w,i} \tag{8}$$

Slip velocity can be solve by the type:

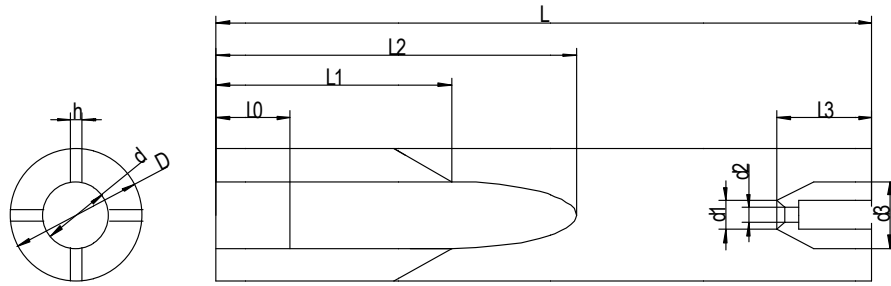


Fig. 2: The liquid-liquid dynamic hydrocyclone geometry

$$v_{wo,i} = \frac{\tau_o (\rho_o - \rho_m)}{f_{drag} \rho_o} \vec{a}_o \quad (9)$$

where,  $\tau_o$  is particle relaxation time:

$$\tau_o = \frac{\rho_o d_o^2}{18 \mu_w}$$

$\vec{a}_o$  = The acceleration of droplets in the dynamic hydrocyclone:

$$\vec{a}_o = \vec{g} - (\vec{v}_m \cdot \nabla) \vec{v}_m - \frac{\partial \vec{v}_m}{\partial t}$$

$d_o$  = Diameter of the dispersed phase droplets  
 $f_{drag}$  = The Drag function (Wang and Yu, 2008):

$$f_{drag} = \begin{cases} 1 + 0.15 Re^{0.875} & Re \leq 1000 \\ 0.018 Re & Re > 1000 \end{cases}$$

The drift velocity is related to slip velocity by the following expression:

$$u_{Do,i} = \frac{a_w \rho_w}{\rho_m} v_{wo,i} \quad (10)$$

where,  $u_{Do,i}$ ,  $u_{wo,i}$ ,  $u_{Dw,i}$ ,  $u_{m,i}$  are the tensor form indicators, the value range of i and j is (1, 2, 3).

**The volume fraction equations of the dispersed oil phase:**

$$\frac{\partial}{\partial t} (\alpha_o \rho_o) + \frac{\partial}{\partial x_i} (\alpha_o \rho_o u_{m,i}) = - \frac{\partial}{\partial x_i} (\alpha_o \rho_o u_{Do,i}) \quad (11)$$

where,  
 $\alpha_o$  = The volume ratio of dispersed phase oil phase  
 $\rho_o$  = The density of the oil phase

**Physical model:** The dynamic hydrocyclone geometry used for simulation and experimental studies is



Fig. 3: Meshing sketch of dynamic liquid-liquid hydrocyclone

presented in Fig. 2. The drum is 60 mm diameter and 800 mm in length, the length of blade is 45 mm, the thickness of blade is 5 mm, the outlet diameter is 20 mm. The structure of the overflow and underflow are simplified, the four-vane structure rotating grid is selected. The physical model is set up by Gambit; the control body model structure is shown in Fig. 3. The control body model structure is set up by the unstructured grid based on tetrahedral cells with T-grid meshing scheme pattern including 250,000 computational cells.

**Boundary and initial conditions:** The 3-D computational model was selected for the study. A simplified physical model was meshed by Gambit software and the mesh was computed in fluent software, the Reynolds stress model and the mixture model were selected. The single reference frame model was selected to simulate the rotation of the flow field. The inlet boundary was defined as velocity inlet boundary and the initial inlet velocity is 0.3 m/s; the inflow pressure is 0.2 Mpa; the overflow and underflow outlet boundary were all handled in accordance with the full development, that is:

$$\frac{\partial v_r}{\partial z} = 0; \frac{\partial v_z}{\partial z} = 0; \frac{\partial v_t}{\partial z} = 0; \frac{\partial k}{\partial z} = 0; \frac{\partial \epsilon}{\partial z} = 0$$

The wall was handled according to the no slip condition; near wall treatment used the wall function method. The backflow direction was specified as normal to the boundary zones and backflow turbulence intensity was assigned a value of 10%. The continuous phase water phase with a density of 998.2 kg/m<sup>3</sup> and the dispersed phase diesel oil with a density of 830 kg/m<sup>3</sup>. And different diameter sizes varying from 10 to 100  $\mu$ m was allowed to enter the dynamic

hydrocyclone. The speed of the drum rotation is 2200 r/min, the diesel contained in the mixture was control at 10%.

**THE FLOW FIELD ANALYSIS**

**Velocity field analysis:** The simulation studies were carried out by RSM turbulence model. The axial, radial and tangential velocity distribution curve were gotten by the simulation. The centrifugal force field necessary for separation inside the dynamic hydrocyclone will be generated by the tangential velocity component of the continuous phase. The rate of the axial velocity and radial velocity is smaller compared to tangential velocity, so to study the shear rate of the velocity field we just consider the tangential velocity. The distribution of tangential velocity at different vertical heights are plotted in Fig. 4.

The viscous shear stress on the oil droplets inside the dynamic hydrocyclone can be expressed like that:

$$\tau = -nC\mu \frac{1}{r^{n+1}}$$

where,

$\mu$  = The viscosity of oil and water mixture

N, C = Constant

Which depends on the location of the oil droplets within the dynamic hydrocyclone, the constant C is proportional to the flow rate and the n of each section is not related with the flow rate. This shows that the viscous shear stress on the oil droplets was increased with the rate of flow and viscosity of oily water. In this case the separation of oil and water is increasingly difficult.

**Turbulence flow field analysis:** Under the same operating conditions, the distribution of turbulence

intensity and turbulence kinetic energy at different vertical heights are plotted in Fig. 5. Turbulence intensity is one of the most important parameters, which reflected the turbulence pulsating size within the cyclone and it is also called turbulence and turbulence density. The distribution of turbulence intensity is like saddle shaped that was found forms the Fig. 5a. The turbulence intensity is small between the drum wall and the center of the drum, in which the flow field is stable and it is suitable for separation process. In the region of the drum wall, the turbulence intensity is high because of the collision between oil and water mixture with the wall, meanwhile, the speed gradient is also very high as Fig. 4. In the separation process other factors will also cause the break-up of droplets, such as the pulse from the pump, unstable rolling of the drum etc. It is easy of oil droplets to break up in the region of the drum wall and the center of the drum.

Turbulence kinetic energy reflects the size of turbulence flow in dynamic hydrocyclone. It was usually characterized by turbulence velocity pulsation. The turbulence velocity pulsation can be computed by combining u, v and w as follows, u, v and w were the axial, radial and tangential velocity:

$$k = \frac{1}{2}(\overline{u^2} + \overline{v^2} + \overline{w^2})$$

The turbulence kinetic energy of fluid in dynamic hydrocyclone was mainly caused by time-averaged flow and it was passed to the oil droplets by the fluid. It can be observed from the Fig. 5b that the time-averaged velocity gradient of turbulence kinetic energy distribution was larger in the region of the drum wall and the internal air column area of the drum, in the same region, the speed of fluid fluctuated drastically when the oil and water mixture flowed through the drum. It presented the anisotropic of the turbulence motion. So the turbulence kinetic energy of the oil droplets is larger, which was passed from the oil-water

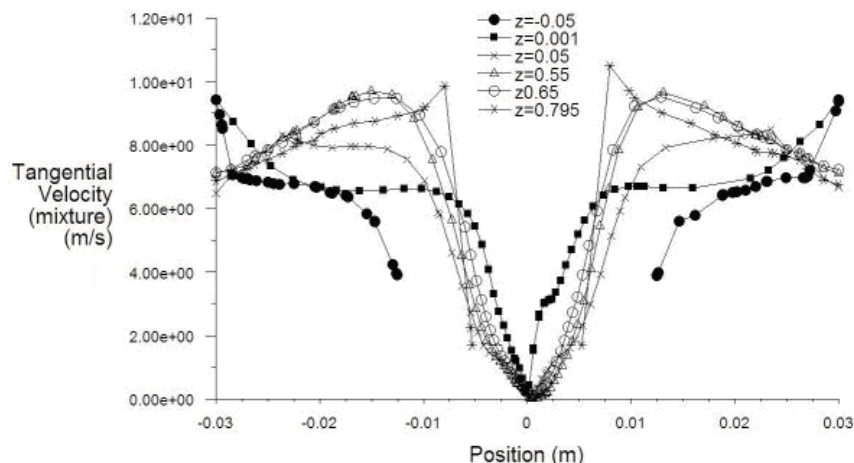
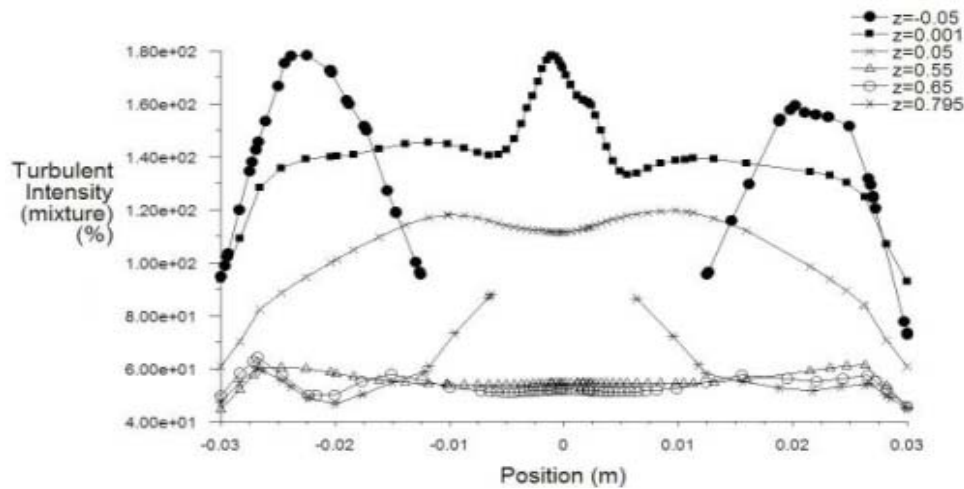
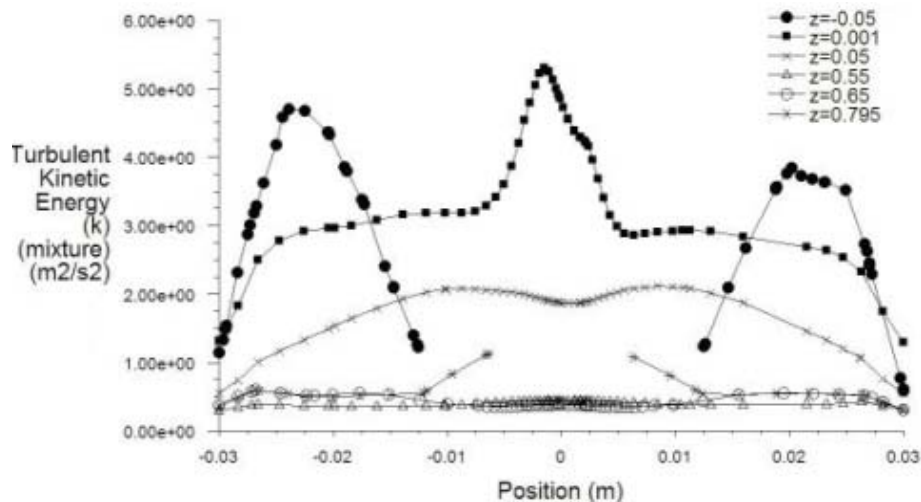


Fig. 4: Distribution of tangential velocity



(a) Turbulence intensity



(b) Turbulence kinetic energy

Fig. 5: Distribution of turbulence intensity and turbulence kinetic energy

mixture. Therefore, in that operating process the oil droplets are easy to deformation and breakage, which will lead to emulsion of oil and water mixture. The turbulence kinetic energy is small between the drum wall and the internal air column area of the drum, in which the flow field is stable and it is suitable for separation process.

#### OIL DROPLETS BROKEN AND OIL-WATER EMULSION

**The force that leads to droplets breakage:** From the simulation analysis of the dynamic hydrocyclone flow field, there are two types of forces, namely the viscous shear stress and Reynolds shear stress.

**Viscous shear force:** According to the above simulation of velocity field of dynamic hydrocyclone,

the oil droplets rupture extremely easily, if oil and water two-phase relative speed is larger; but in the actual operation condition of dynamic hydrocyclone, the two-phase relative velocity of oil and water is small, so the viscous shear force on oil droplets can be ignored. It also can not lead to breakage of oil droplets, but it will result in deformation of oil droplets. The deformation of oil droplets will not bring about the emulsifying process of the oil-water mixture. So to study the emulsifying process of the oil-water mixture, it is more important to study the Reynolds shear stress in the actual operation condition of dynamic hydrocyclone.

**The reynolds shear stress:** The relative velocity between the dispersed phase droplets and the continuous phase fluid is small in the actual operation condition of the dynamic hydrocyclone. The main

reason that leads to the emulsification of oil and water mixture is turbulence, instead of oil droplets deformation by viscous shear force. The Reynolds shear stress on oil droplets in the dynamic hydrocyclone can be used to represent as follows:

$$\tau_{r\theta} = -\rho \overline{u_r' u_\theta'}, \tau_{\theta z} = -\rho \overline{u_\theta' u_z'}, \tau_{rz} = -\rho \overline{u_r' u_z'}$$

**The breakdown location of oil droplets:** According to the numerical simulation analysis of the velocity field and turbulence flow field, the oil droplets were easy to breakdown if the Reynolds shear stress on oil droplets is big. In that case it will lead to emulsification of the oil-water mixture and the separation efficiency of oil-water mixture is very low. The experiment and numerical simulation results show that there are three regions of rotating drum boundary layer, rotating gate nearby and the center of the drum, where the oil droplets is easy to break up. The specific reason is that the high speed of rotating drum will bring about the collision and the friction between the oil-water mixture and the drum wall, so the change of turbulence intensity is significant; the region of rotating gate nearby is located in the inlet of the dynamic hydrocyclone, so when the oil-water mixture is rotating, there will be turbulent flow and circulation flow, which will result in breakage of oil droplets; there is a air column in the region of the center of the drum, where the axial, radial and tangential velocity become to zero suddenly and it will arise very large velocity gradient, also the location of the air column is not fixed, but shaking slightly around the axis, so the turbulence effect is remarkable.

### EXPERIMENTAL VERIFICATION

The experimental setup consisted a slurry tank of 500 L capacity mounted on a stable platform. A screw pump with 3-phase, 7.5 kW motor was connected to the slurry tank at the bottom. Mixture contains diesel oil control in 10%. The pipeline connected to the pump with the inlet opening of a 60 mm diameter dynamic hydrocyclone. The pressure drop inside the dynamic hydrocyclone was maintained at required level with the help of by-pass arrangement actuated through a control valve on the pipeline. The oil concentration was measured with the help of a ultraviolet spectrophotometer; The oil droplets form was measured with the help of a biological microscope (XSP-6CC).

The experimental program was designed to get separation efficiency of the diesel oil and reasons that what bring about the breakage of oil droplets. The dynamic hydrocyclone main body was fixed to the test-rig. Required opening spigot as per the experimental design was fitted to the hydrocyclone bottom. Initially, separation efficiency studies were carried out by pumping oil water mixture into the cyclone at different rate of flow. Later, samples of overflow and underflow products were collected simultaneously for a specific time in different containers. The underflow and

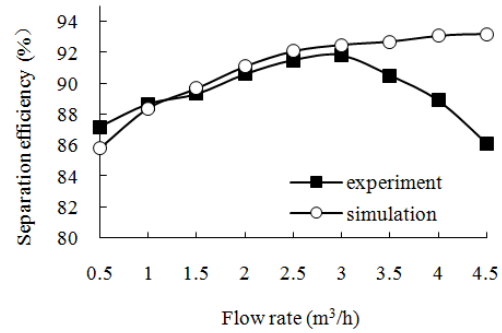


Fig. 6: Efficiency curves of flow rate at 2200 r/min

over flow products collected were tested by the ultraviolet spectrophotometer and biological microscope.

**Separation efficiency experiment:** The results on the separation efficiency of oil obtained during the experimental work at different rate of flow are compared with the simulated values obtained using the mixture model in Fig. 6, which indicates that with the increase of flow rate, the separation efficiency are also increased by the simulated values, which can also be observed from the experimental results. The results obtained with the mixture model are closer to the experimental results when rate of flow was in the interval of 0.5-3 m³/h. The simulated results match with the experimental results with marginal error about 2-5%. In this region the simulated data agrees well with the experimental results with a reasonable accuracy. When rate of flow was in the interval of 3-4.5 m³/h, the separation efficiency of experimental results increased with the increase of flow rate. However, the separation efficiency of simulated results decreases with the increase of flow rate. The reason is that with the increase of the flow rate, the turbulence intensity is enhanced, which will lead to the breakage of oil droplets and produce emulsification of oil-water mixture. But in the numerical simulation, the breakage of oil droplets was not considered, so with the increase of the flow rate, the separation efficiency was still rising.

**Droplet breakage experiment:** According to the analysis of the experiment and numerical simulation, the best working condition for the dynamic hydrocyclone is that the flow rate is 2.5 m³/h and the rotating speed is 2200 r/min. Therefore, in the Droplet breakage experiment, the speed of the drum rotation was qualified at 2200 r/min and the flow rate was changed at 1, 2.5 and 4 m³/h, respectively. In the separation process, the samples were collected from the inlet and the underlet. After the experiment the samples were observed in the biological microscope. Images are magnified 400 times as follows in Fig. 7. Circular droplets is oil droplets, the surrounding is water in Fig. 7.

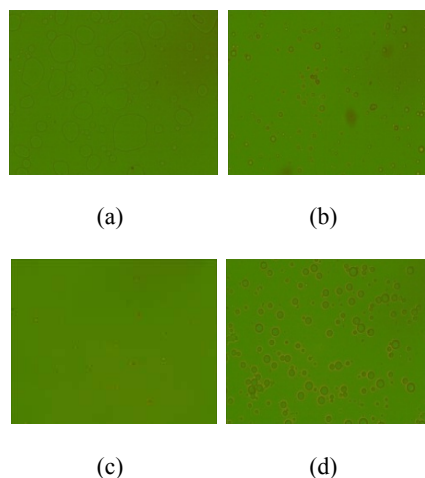


Fig. 7: Observation of oil droplets by biological microscope

Figure 7a is the observation of the sample in the inlet. In the figure, the distribution of oil droplets is more dispersed, the oil droplets diameter sizes is in the interval of 50-150  $\mu\text{m}$ , because of the action of the interfacial tension of oil droplets. Figure 5b and Fig. 5c are observations of the sample in the underlet, which were collected in the working conditions of 1 and 2.5  $\text{m}^3/\text{h}$ , respectively. In the Fig. 5b, the quantities and the particle size of the oil droplets of decreased significantly. The diesel oil was separated effectively and there was no signs of emulsion. In the Fig. 5c, The diesel oil can be separated more effectively than in the working conditions of 1  $\text{m}^3/\text{h}$  and the quantities of oil droplets was less; the particle size of the oil droplets was smaller. It also suggested that the dynamic hydrocyclone was suitable for the separation of oil-water mixture and it can achieve an effective separation in a very wide range of flow rate. In the working conditions of 4  $\text{m}^3/\text{h}$ , the sample from the underlet was observed as shown in Fig. 7d, it can be seen that the particle size of the oil droplets decreased obviously compared with the sample from the inlet, but the quantities of oil droplets increased significantly. There were a large number of tiny droplets in the underlet and the distribution of oil droplets is more uniform. The oil-water mixture is emulsified, which is mainly caused by the breakage of oil droplets. The experiment study has indicated that the numerical simulation adopted can be useful for predicting the performance of dynamic hydrocyclones.

### CONCLUSION

- In the working condition, the flow field of oil-water dynamic hydrocyclone is in turbulence state, the emulsification of oil-water mixture in separation process is mainly caused by the Reynolds shear stress and local pressure fluctuations.
- The main area that the drops were prone to breakup of the dynamic oil droplets is that the rotating

grating nearby, the wall boundary layer of the drum and center axis of the drum.

- There is a critical limit force that control the breakage of oil droplets in the working conditions. When the dynamic hydrocyclone worked below the critical conditions, the oil-water mixture can be separated effectively, in that case the oil droplets deformed slightly; with the increase of the flow rate, the dynamic hydrocyclone worked beyond the critical conditions, the oil droplets broken and the oil-water mixture cannot be separated.

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