Numerical simulation on gas–liquid separation characteristics in a GLCC-horizontal combined separator

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Abstract
Currently, computational fluid dynamics has become the primary method for analyzing the fluid flow state inside the machine. Herein, the Ansys Fluent software is used to design a more effective oil-field device, namely, a gas–liquid cylindrical cyclone (GLCC)-horizontal combined separator. The characteristics of gas–liquid mixed flow, fluid turbulence intensity, and phase volume fraction distribution are analyzed, and the factors affecting the gas–liquid separation efficiency are evaluated under various working conditions. The results show that low gas–liquid separation efficiencies are obtained at inlet liquid ratios (liquid proportion in fluid) of both 30% and 70% in GLCC. After the fluid enters the separator, the maximum level of turbulence in the collision area increases from 2.458 to 3.033 m²/s² as the inlet liquid ratio is increased from 30% to 70%, with the generation of oil–water and gas–liquid stratification at the back. Furthermore, the maximum gas holdup in the liquid outlet increases from 7% to 12% to 25% as the liquid ratio is increased from 30% to 50% to 70%. With throttling at a liquid ratio of 70%, the maximum gas holdup is again close to 14%.

1 | INTRODUCTION
Computational fluid dynamics (CFD) is an important tool for analyzing the complex flow state in separators, and for the improvement of devices. At the present time, CO₂-enhanced oil recovery technology is widely used in many oil-field projects. However, the produced fluid contains much CO₂, so it is critical to improve the gas–liquid separation process in the separator at the first station. In this respect, the flow characteristics of the CO₂-containing oil–water fluid mixture in the separator are complicated by the solubility of CO₂ in the liquid phase. After the fluid enters the separator, the stability is poor, and it is difficult to optimize the gas–liquid separation under various working conditions by the simple arrangement of the internal components of the separator. Therefore, a new gas–liquid separation device for gas-containing crude oil is required.

Due to no separation components inside the gas–liquid cylindrical cyclone (GLCC), the flow state and separator’s structure mainly influence the performance. Katare et al. found that the increase of flowing velocity at the inlet of GLCC can increase separation efficiency, but it raises the pressure drop. Therefore, it is...
not recommended to increase velocity to increase efficiency. To decrease the cylinder’s diameter can be used in design to improve efficiency.

Wang et al. clarified the fluid flow mechanism by analyzing the velocity field, pressure field, and streamline inside the oil–gas separator. Putra et al. compared the CFD simulated results with the flow characteristics in the swirl separator under experimental conditions. The results indicated that the CFD simulation could correctly represent the gas–liquid-phase distribution inside the separator, whereas the simulated bubble decay process was quite different from the experimental results. Zhang et al., from experimental results, found that produced fluid entering the separator generates much foam because of the decreased pressure, which leads to low separation efficiency. With more pressure drops, the foam volume and defoaming rate also increase. Movafaghian et al. compared different flow rates of gas–liquid two-phase fluid under different inlet sizes, fluid viscosity, and inlet pressures. The experimental results and the simulation showed that more foam is generated when the gas superficial velocity is low.

Luo et al. analyzed the separation characteristics of the swirl separator with various expansion ratios and inclination angles. The results indicated that increasing the expansion diameter ratio and the inclination angle of the inlet section is beneficial for eliminating the slug. In the cylinder, increasing the expansion diameter ratio can significantly reduce the liquid holdup in the gas, but it also causes a slight increase in the gas content in the liquid space. Moreover, increasing the inclination angle will intensify the gas–liquid mixing and increase the gas content in the liquid. Ho et al. compared the separation efficiency of gas–liquid entering GLCC, and the results showed that the best inlet angle was 27°, with two symmetrical square inlets, which leads to the highest separation efficiency. Gao et al. proposed a new Q criterion in cyclone separators with various inlet structures, and the results indicated that the isovortex surface is distorted and does not distribute around the central axis. With the development of flow, the equivalent diameter of isovortex surface decreases gradually. The spiral inlet structure can improve the flow instability at the inlet of GLCC and eliminate some foam caused by the highly turbulent fluid.

Laleh et al. summarized the literature about the design and CFD simulation of the gravity separator. They proposed the separator design standard based on the CFD simulation results and supplied an effective evaluation method. Yu et al. used the CFD simulation software to compare the fluid flow state after entering the gravity separator under various inlet conditions, and demonstrated that the low-hole-box inlet increases the stability of the fluid flow state after entering the separator. Ghaffarkhah et al. used the deformable parts model to calculate the particle kinetic energy in the gas-phase region in separators with various structures. The results indicated a measurable increase in the droplet distribution in the gas-phase region when the kinetic energy of the fluid was high, thus leading to more oil droplets at the gas outlet, and decreasing the oil-water separation efficiency.

However, the latest research has mainly focused on controlling the size and structure of the separator, with the lack of CFD research on combination devices of GLCC and horizontal devices, and few studies have focused on the change in gas–liquid separation efficiency under various inlet and outlet conditions, even though this may be necessary. Hence, the present study aims to provide a reference for the control of inlet and outlet throttling of the separator to improve gas–liquid separation efficiency.

## 2 | METHODOLOGY

### 2.1 CFD simulation

The CFD-based finite element software, Ansys Fluent, was used. For high accuracy, the multiphase flow volume of fluid (VOF) model, pressure-correction solver, and transient calculation were used. Furthermore, the VOF model is beneficial to study the CO₂’s volume fraction, especially when there are bubbles in the liquid-collecting area, and the realizable $k−ε$ equation was selected as the turbulence model because the results match the actual turbulence characteristics.

The default pressure value was set to 101,325 Pa. The acceleration of gravity (~9.81 m/s²) was set in the Y-direction. The related material properties were tested by experiment and are listed in Table 1.

### 2.2 Geometric model

The structure of the new GLCC-horizontal separator is shown in Figure 1, along with the physical dimensions of the experimental device.

| Component | Density (kg/m³) | Viscosity (kg/(m s)) |
|-----------|----------------|---------------------|
| Water     | 998.2          | 0.001003            |
| Oil       | 830            | 0.00332             |
| CO₂       | 1.7878         | $1.37 \times 10^{-5}$ |
(a) The inclined inlet of the GLCC provides the gas–liquid two-phase flow stratification under the conditions of the medium-high gas–liquid ratio, thereby playing the role of preseparation. The optimum inclination angle of the inlet pipe is in the range of $25^\circ$–$30^\circ$. Therefore, the GLCC inlet adopts a snail-type, $27^\circ$ tangential inlet.

(b) The gas-phase outlet at the top of the GLCC is the straight tube type with an insertion depth of 5 cm.

(c) The liquid-phase outlet at the bottom of the GLCC is the straight tube type with an insertion depth of 8 cm.

(d) The horizontal separator is provided with a straight liquid outlet at its bottom right, with an insertion depth of 2.5 cm.

(e) A straight tubular gas outlet is arranged at the top right end of the horizontal separator, with an insertion depth of 2.5 cm, and this is joined with part (b). Furthermore, these two parts share one outlet.

### 2.3 Boundary condition setting

The boundary setting was similar to that used in a previous experiment. The entire CFD simulation process was divided into three stages, namely, the preoperation stage (stage 1), the static stage (stage 2), and the continuous operation stage (stage 3). In stage 1, the liquid is collected until the height reaches $1/3$ of the horizontal separator, and the system pressure was controlled at 0.2 MPa so that only the inlet of the separator and the outlet of the gas phase were open, and the outlet of liquid-phase was closed. In stage 2, the aim was to complete the two-phase gas–liquid separation for the subsequent continuous operation stage. Hence, only the gas-phase outlet was opened, and the inlet and liquid-phase outlets were kept closed. In stage 3, the inlet and outlet of the separator were all open, and the liquid level of the separator remained constant. The boundary conditions at each position during the three stages are summarized in Table 2.

Since the separator needed to be filled with the separated gas in advance, it was assumed to be initially filled with pure CO$_2$, and the internal pressure was 0.2 MPa. The CO$_2$ and oil input parameters are listed in Table 3. Due to the possibility of reflux in stages 1 and 2, the reflux component of the gas-phase outlet was considered pure CO$_2$, and the reflux component of the liquid-phase outlet was a 1:4 oil-water mixture by volume. Finally, the wall boundary conditions were set to no slip and standard roughness.

For the validity of calculation results, the calculation time was constrained to be longer than the residence time of the fluid in the separator to stabilize the flow state.

### 2.4 Grid-independence test

The VOF model and realizable $k–\varepsilon$ have been widely confirmed by experimental data. In the present study, tetrahedral grids were used for every simulation, and the results of the grid-independence test are compared with the experimental value in Figure 2. The testing device has been demonstrated in a previously published paper. The mixture consists of 30% CO$_2$, 14% oil phase, and 56% water, with a flow rate of 2.4 m/s. Position 1 is at the inlet section of the separator; Position 2 is at the lower part of the GLCC cylinder; Position 3 is at the 1/3 height of the interior space of the horizontal separator. The results indicate that simulations using 2.04 and 3.23 million grids are always in a 5% error band, which can be considered accurate. Therefore, the above-mentioned models were used with 2.04 million grids to simulate the separation for less computation time.
In this section, the separation effect is evaluated by comparing the effects of various working conditions on the flow field and phase volume fraction, as detailed in the Methodology section.

3.1 | Flow characteristics of the two-phase gas–liquid fluid

The streamline patterns obtained after the fluid enters the separator under various conditions are presented in Figure 3. These patterns reflect the velocity direction of the fluid at various times. Here, clearly distinct degrees of spiral motion are produced after the fluid enters the GLCC under each of the four working conditions. The gas moves upward and flows out of the gas outlet. When the inlet liquid ratio reaches 70%, the upward flow of the gas is less regular. With more gas in the fluid, the gas in the upper area of the GLCC cylinder flows to the gas-phase outlet in a stable spiral flow. The lower area of the GLCC cylinder is dominated by the downward spiral movement of the liquid. When the inlet liquid ratio is only 30%, the liquid still flows downward in a spiral movement, but its continuity is poor. Since the main factor affecting the GLCC separation efficiency is the centrifugal movement of the internal fluid, too low or too high the liquid ratio is not conducive to the gas–liquid separation in GLCC.

After preseparation, the fluid flows out of the cylinder and into the horizontal separator, where distinct flow characteristics are observed in the three internal regions labeled A, B, and C in Figure 3. Thus, in region A, the velocity direction of the fluid changes after collision with the surface of the liquid-collecting zone. Each droplet rises to a certain height and then falls back towards the liquid space so that strong reflux occurs in the gas-phase space below the GLCC. As the liquid ratio decreases, the degree of fluid reflux at this location decreases, thereby indicating a decrease in the degree of mixing between the gas and liquid phases.

In region B, the gas entering the horizontal separator flows uniformly towards the gas outlet after multiple collisions with the wall. As the liquid ratio decreases, the gas flow state in the upper region tends to be stable, but an excessively low liquid ratio also makes it difficult for liquid droplets in the gas-phase space to fall into the liquid phase. After closing the liquid-phase outlet (Figure 3D), the complexity of the streamline increases, but the streamline density in the liquid-phase area decreases, and there is almost no streamline rising from the bottom to the gas space at the end of the separator. This indicates that throttling of the liquid-phase outlet will increase the degree of gas mixing, but reduce the gas content in the liquid.

In region C, fluid enters the horizontal separator, and the streamline in liquid space has obvious reflux and produces a low-pressure region. The collision between droplets causes the highest mixing degree here. With increasing liquid ratio from 30% to 70%, the streamlines in the collision region (the interface between A and C) become more complex, and the distribution of streamlines in liquid space becomes more even. In contrast, when the liquid ratio is low, such as 30%, there are two highly intensive streamline regions in the liquid-collecting zone, which shows the separation degree of oil and water is high.
The calculation results show that when the liquid ratio at the inlet is low, the collision between particles at the intersection of two gas outlets is intense, which helps reduce the number of droplets carried in the gas at the separator outlet. Moreover, when the inlet liquid ratio is high, the gas outlet velocity of the horizontal separator is higher than that of the GLCC gas outlet, which will lead to the gas-reflux phenomenon in the GLCC gas outlet pipeline. This, in turn, affects the separation efficiency and regular operation of the equipment.

In conclusion, liquid ratios of 30% and 70% are not conducive to GLCC gas–liquid separation. Complex streamlines inside the horizontal separator lead to high degrees of mixing between phases and have a negative effect on the horizontal separator. By contrast, the amount of interphase mixing can be decreased, and the gas–liquid separation efficiency increased, by using a liquid ratio of 50% and throttling the liquid outlet.

### 3.2 Distribution of turbulence kinetic energy

As an important measurement of turbulence intensity at various locations, the turbulent kinetic energy distributions of the fluid entering the separator under various conditions are presented in Figure 4. When the liquid ratio is low, such as 30%, the turbulence intensity of the fluid in the upper region of GLCC is low, this is because the gas flow law in the region is stable. With the increase in the liquid ratio, the upward gas movement regularity becomes worse, and the fluid turbulence intensity in this region increases slightly. The turbulence intensity of the lower region of the GLCC is less affected by the change of the liquid ratio, and as the liquid ratio decreases, the fluid turbulence intensity in this region decreases slightly, which indicates that GLCC is beneficial to reducing the fluid
turbulence intensity after entering the separator under high liquid ratio, such as 70%.

After the fluid flows down into the horizontal separator, it collides with the collected liquid and the velocity direction changes. Therefore, the fluid at this position has a high level of turbulence, and its instability is not conducive to efficient separation. With the increase in the liquid ratio from 30% to 70%, the maximum turbulence intensity in this region increases from 2.458 to 3.033 m²/s², which indicates that the stability of the fluid in this region is poor. If the liquid outlet of the horizontal separator is closed, the area of high turbulence intensity is reduced, but the maximum fluid turbulence intensity near the collision position is increased to 3.784 m²/s². In addition, the fluid has a high level of turbulence at the pipeline junctions. As the liquid ratio increases, the level of turbulence of the fluid at the gas-phase-pipeline junction decreases. After closing the liquid outlet of the horizontal separator, the fluid flow state at the junction of the liquid outlet pipeline is stable, thereby demonstrating that throttling the liquid outlet can decrease the level of turbulence of the fluid.

In brief, increasing the liquid ratio will increase the level of turbulence at the collision area in the liquid-collecting zone, where the fluid collides with the liquid after entering the horizontal separator. In addition, throttling the liquid outlet will increase the maximum level of fluid turbulence in this region, generating more foam.

### 3.3 | Phase volume fraction

#### 3.3.1 | The volume fraction of CO₂

The volume fractions of CO₂ under various working conditions are shown in Figure 5. Here, the fluid flow pattern in the inlet pipe is seen to change from slug flow to stratified flow as the gas ratio at the inlet is increased from 30% to 70%. When the liquid ratio is 30%
the continuity and stability of the fluid flow in the low part of the GLCC cylinder are poor. As the liquid ratio is increased to 50% and 70%, however, the liquid phase in this area flows into the horizontal separator with a more continuous spiral motion (Figure 5B,C). Under all four working conditions, the liquid phase region below the bottom outlet of the GLCC has a high gas content, and the high liquid ratio at the inlet means the liquid in this region also has a high gas content. When the liquid outlet of the horizontal separator is closed, however, the gas distribution in the liquid collecting zone becomes more uniform, and the gas content in this region at the end of the separator is decreased (Figure 5D).

3.3.2 | The volume fraction of oil

The volume fractions of oil under various working conditions are shown in Figure 6. When the fluid enters the liquid-phase space of the horizontal separator from the GLCC, the degree of mixing of the three-phase CO₂-oil-water fluid below the inlet is high, and rapid separation of the oil–water and gas–liquid phases occurs along the direction of the separator outlet. The pressure gradient at two positions is seen to be higher in the liquid-phase space in the horizontal separator. The high-pressure gradient interface at the upper position represents the gas–liquid interface, and that at the lower position represents the oil–water interface. After entering the liquid-collecting area, along the fluid flow direction, the gas–liquid interface rises slightly and tends to level off, while the oil–water interface initially falls, then rises, and finally levels off. The lower the liquid ratio, the smaller the region of high turbulence fluid, and the earlier the generation of the oil–water and gas–liquid stratification (Figure 6A). Closing the liquid outlet also leads to the location of the oil–water and gas–liquid stratification towards the front, and the mixing degree of the fluid in the liquid-phase region below the GLCC

(Figure 5A)}
becomes lower (Figure 6D). In addition, part of the low gradient region remains above the gas–liquid interface, and the height of this region, along the fluid flow direction initially, rises and then falls. The high region generally represents that the component transmission rate between the gas and liquid is low.

Therefore, decreasing the liquid ratio at the inlet can decrease the gas content in the liquid-collecting zone, and increase the degree of oil–water and gas–liquid separation. Additionally, throttling the liquid outlet can decrease the gas content in the liquid near the liquid outlet, and increase the oil–water and gas–liquid separation efficiency.

3.4 Separation efficiency

The new separator exhibits a high gas–liquid separation efficiency under all four working conditions because the gas-phase outlet contains almost no droplets. In detail, the separation efficiency is evaluated according to the maximum gas content (maximum bubble diameter) in the liquid outlet. The results in Figure 7 indicate that the gas holdup in the liquid outlet increases from 7% to 25% as the liquid ratio is increased from 30% to 70%. The higher liquid ratio at the separator inlet leads to a larger maximum bubble diameter at the liquid-phase outlet and, hence, a lower separation efficiency. There are two underlying reasons for this phenomenon. First, the 70% liquid ratio of the mixed fluid produces more turbulent kinetic energy after entering the horizontal separator, thereby strengthening the ability of the fluid to produce bubbles after entering the separator. Second, the stability of the liquid level inside the separator when the liquid ratio is 70% requires the liquid–phase outlet to be widely opened, thereby shortening the residence time of the fluid in the separator and, thus, decreasing the separation efficiency. In addition, closing the liquid outlet under 70% liquid ratio conditions significantly decreases the maximum bubble diameter at the liquid outlet, resulting in only 14% gas holdup in the liquid. This is because throttling the liquid outlet increases the residence time of the fluid, thereby significantly improving the gas–liquid separation efficiency. Therefore, the methods for
improving the gas–liquid separation efficiency include: (1) reducing the liquid ratio at the inlet, and (2) throttling the liquid outlet to prolong the residence time of the fluid.

4 | CONCLUSIONS

Herein, the design of a device combining a GLCC and horizontal separator was performed via CFD, and its performance was analyzed under oil-field operating conditions. The following conclusions were drawn by calculating and analyzing the effects of various inlet liquid ratios and outlet throttling upon the flow field and separation efficiency:

(1) Inlet liquid ratios of 30% or 70% are not conducive to GLCC gas–liquid separation. When the liquid phase ratio is 70%, the liquid holdup is increased at the gas outlet on the top, and, when the liquid-phase ratio is 30%, the gas content in the liquid at the bottom outlet is increased. Furthermore, the installation of a diversion plate at the junction of the horizontal separator gas-phase outlet pipeline and the GLCC gas-phase outlet pipeline is beneficial to the regular operation of the separator under a 70% liquid ratio.

(2) Setting GLCC before the horizontal separator can effectively reduce the turbulence strength when the fluid enters the separator. After the fluid enters the horizontal separator from GLCC, the collision with the liquid-collecting area will produce foam, which is not conducive to gas–liquid separation. Reducing the liquid ratio at the inlet reduces the maximum turbulence intensity in the region, and the positions of oil–water stratification and gas–liquid stratification are at the front. Extending the retention time of the fluid in the horizontal separator through the liquid-phase outlet valve also improves the separation efficiency.

(3) Under different inlet conditions, the separator always keeps good gas–liquid separation efficiency, and the gas-phase outlet contained almost no droplets. When the inlet liquid ratio is 30%, the maximum gas holdup of the liquid outlet is only 7%. When the liquid-phase ratio is 70%, the maximum gas holdup of the liquid outlet reaches 25%. At this time, it can be reduced to 14% through the liquid-phase outlet throttling.

AUTHOR CONTRIBUTIONS

Hongtao Ma: Conceptualization, methodology, modeling, simulation, experiment, formal analysis, writing original draft, and writing review and editing. Shuhao Zhang: Conceptualization, modeling, simulation, formal analysis, visualization, writing original draft, and writing review and editing. Yuxing Li: Conceptualization, supervision, and funding.

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