The Structure Design And The Flow Field Analysis Of The Gas-Liquid Separation Cyclone

Yang Rui\textsuperscript{1,2}, Zhang Lei\textsuperscript{1,2}, Lv Chao \textsuperscript{1,2}, Zhu Baojin \textsuperscript{1,2}

\textsuperscript{1} School of Mechanical Science and Engineering, Northeast Petroleum University, Daqing 163318, Heilongjiang, China;
\textsuperscript{2} Heilongjiang Key Laboratory of Petroleum and Petrochemical Multiphase Treatment and Pollution Prevention, Daqing 163318, Heilongjiang, China

Corresponding author: cinley@nepu.edu.cn

\textbf{ABSTRACT} — This paper introduces the structural characteristics and working principle of the gas-liquid cyclone separation device, and explores the laws of changing of gas volume fraction distribution, velocity field and pressure drop with or without a thimble in the underflow port and under different thimble shapes. The separation efficiency of gas-liquid separator reaches 80\% after adding a thimble. At the same time, indoor experiments fully verified that the pressure loss is greater and the speed increases after changing the shape of the thimble to a truncated cone shape. Truncated cone thimble helps the dense liquid move to the sidewall and the low density gas gathers toward the central axis. And the distribution of internal fluid makes the treatment effect of degassing more superior.

1. \textbf{Introduction}

The gas-liquid cyclone separator is a classification and separation equipment that uses the density difference of the medium and the centrifugal force to separate the heterogeneous phase mixture. The gas-liquid cyclone separator is used to complete liquid clarification, solid-phase particle washing, liquid degassing and sand removal, solid-phase particle classification and systematication and separation of two non-dissolved liquids. Because of its simple structure, high separation efficiency, large processing capacity, low cost, easy installation, convenient operation and so on, gas-liquid cyclone separation technology is widely used in petroleum, chemical, biological and environmental protection industries. And it has broad engineering applications prospects. In recent years, gas-liquid cyclone separation technology has increasingly become a hot technology in the research fields of local and overseas.

2. \textbf{Numerical Simulation}

In order to prevent the separated gas from outflowing from the underflow port, cylindrical and conical thimbles are added at the underflow port, and the other parameter conditions unchanged. The gas-liquid separator with two types of thimble structures at the underflow port and without thimble were compared, analyzed and optimized.

2.1. \textit{Radial section gas volume fraction distribution}

Figure 1(a)-(c) are the cloud diagrams of the gas phase concentration distribution in the overflow section with different thimble types. Comparing the figures, in the study range, it can be seen that the purification rate of the mixed liquid continues to increase at the side wall of the separator after adding the thimble at the underflow port. A relatively stable gas core is basically formed in the axial center area. The volume concentration of the separated gas continues to increase. And the diameter of the gas core also decreases. Near the separator wall, the
concentration of the gas phase suddenly drops. This is because the velocity of the outer swirling area is very large, and the gas phase gradually separates from the liquid phase and moves inward.

![Figure 1. Cloud diagram of gas phase concentration distribution](image)

2.2 Axial section gas volume fraction distribution
The volume fraction of the gas discharged from the overflow port can directly reflect the separation effect of the separator. The percentage of gas volume and space volume is the gas phase volume fraction. According to the gas volume fraction distribution cloud diagram of the axial section in Figure 2, we know, when there is no thimble at the underflow port, there is a large amount of gas on the side wall of the separator. And the gas concentration is very large near the overflow port. At the same time, the gas column is thick in the central axis area. And it extends to the bottom of the separator. After adding the thimble at the underflow port, in the middle and lower part of the thimble of the separator, the gas nucleus concentration is significantly reduced. And the gas volume fraction is approximately 0 at the side wall of the separator. This is because the mixed phase moved downward and collided with the thimble, mixed phase counteracts lifting force of gas core and accelerates the upward migration of the gas core. The gas phase volume concentration near the axis center is close to 80%, and gas phase is quickly discharged from the overflow port. It shows that the degassing and separation efficiency of the cyclone is more obvious after adding the thimble at the underflow port. However, there is little difference between the cylindrical thimble and the conical thimble on the effect of internal gas distribution, and the difference in the gas volume fraction of the overflow port is only about 1%.

![Figure 2. Cloud diagram of the gas volume fraction distribution in axial section](image)

2.3 Pressure distribution
The pressure distribution of the separator in the working state is an important index that determine the separation performance of the gas-liquid separator. If the gas-liquid separation of the cyclone is to be realized, a certain pressure loss and energy loss are inevitably required. Therefore, in order to improve the separation efficiency of the separator, the requirements of the pressure must also be met. The gas volume fraction of initial conditions of the numerical simulation is 60%, and the gas phase can be approximated as a continuous phase. Figure 3 is the pressure distribution cloud diagram of the axial section. It can be seen that the gas dissolved in the liquid moves to the low pressure area and condenses into large bubbles due to the existence of the pressure difference. After adding the thimble, the pressure gradient inside the cyclone increases. Pre-separation has been achieved at the entrance, so the separation efficiency is significantly improved.
2.4. Speed distribution

2.4.1. Tangential speed

Figure 5 shows the tangential velocity distribution curve under different thimble shapes. According to the curve in the figure, it can be obviously seen that the tangential velocity is roughly M-shaped symmetrically distributed. From the side wall of the separator to the axis of the cyclone cavity, the tangential velocity is a trend of increasing firstly and then decreasing. The maximum value appeared near the extension line of the overflow pipe. However the tangential velocity dropped sharply from the overflow pipe to the central axis. Compared the separator with thimble of a truncated cone shape and the separator with thimble of a cylindrical shape, the former’s position of maximum tangential velocity is getting closer to the axis. It indicates that there are no particles separated in the quasi-forced vortex area near the axis. After encountering the conical thimble, it will move to the outer swirling flow to separate again. And a secondary vortex separation appears in the flow field of the separator.
2.4.2. Radial velocity
The radial velocity is the main factor that affects the radial movement of the fluid. The radial velocity distribution curve under different split ratios is shown in Figure 6. The fluid at the inlet is subjected to strong centrifugal force. And the radial velocity increases, forcing the mixed liquid to move toward the axis. The radial velocity drops sharply in the process. It reaches the lowest value at the axis. After the mixed liquid touches the thimble at the bottom, the radial velocity suddenly increases. It makes the denser liquid phase to gradually flow to the side wall. However the less dense gas phase moves upward along the thimble. After the thimble changes from a cylinder to a truncated cone, the radial velocity of the separator increases which helps the denser liquid move to the side wall. While the less dense gas gathers at the central axis, accelerating the separation of the mixed phase.

2.4.3. Axial velocity distribution
The magnitude and direction of the axial velocity determine the direction of the fluid inside the separator. Figure 7 shows the axial velocity distribution curve under different split ratios. According to the curve in the figure, it can be seen intuitively that the axial velocity is w-shaped distribution. Obviously, the axial velocity distribution is symmetric. After the gas-liquid two-phase mixture enters the separator, because of the action of high-speed centrifugal force. An outer swirling area is formed in the separator. And the axial velocity gradually decreases.

However, the mixed liquid encounters the bottom cone thimble when it moves below the separator under the centrifugal action of the strong swirling flow. An air core is formed at the center of the cyclone. Under joint action of the bottom thimble and the central swirling flow, the axial velocity of the gas phase increases suddenly. And the gas phase has a tendency to move towards the overflow port. At the same time, the liquid flows backward to the underflow port of the separator in the central area near the axis. And the axial velocity reaches the maximum near the axis.
3. Conclusion
We numerically simulated the distribution of Internal fluid of the gas-liquid cyclone separator with or without a thimble in the underflow port by Using computational fluid dynamics software. And we explored the law of changing of gas volume fraction distribution, velocity field and pressure drop when the shapes of the thimble are different. We draw the following conclusions through comparative analysis.

After adding the bottom thimble, there are obvious quasi free vortex and quasi forced vortex inside the separator. A relatively stable gas core is basically formed in the axis area. The volume concentration of the separated gas continues to increase. And the purification rate of the mixed liquid at the side wall of the separator continues to increase. The gas concentration near the overflow port increases significantly. And the volume of gas discharged from the overflow port continues to increase. Therefore, increasing the split ratio helps to separate the gas better. The separation efficiency of the gas-liquid separator is as high as over 85%. This shows that the gas-liquid cyclone separator has a superior degassing effect after adding a thimble.

After adding the bottom thimble, the radial pressure gradient inside the separator gradually increases and the pressure in the low pressure zone gradually increases at the axis. And the fluid flows smoothly which is good for the accumulation of gas in the central area, separation from the gas-liquid mixture and discharging from the overflow port.

After adding the bottom thimble, the axial velocity of the axial center area gradually increases upward along the overflow port in the swirl cavity. And the axial velocity near the underflow port gradually decreases downward along the center area. This forces the gas move up and discharge from the overflow port. Both the radial velocity and the tangential velocity gradually increase which helps the gas move toward the overflow port in the radial direction and increases the separation efficiency of the gas.

REFERENCES
[1] Fan Dawei. Theoretical and experimental research of gas-liquid separation hydrocyclone [D]. Daqing Petroleum Institute, 2009.
[2] Jiang Minghu, Zhao Lixin, Li Feng, etc. Cyclone separation technology [M]. Harbin: Harbin Institute of Technology Press, 2000.
[3] Zheng Xiaotao, Gong Cheng, Xu Hongbo, etc. Separation verification of oil-water-gas three-phase cyclone and optimization of gas-liquid chamber structure [J]. Journal of Wuhan University of Technology, 2014, 36 (10): 37-41.
[4] Zhao Lixin, Jiang Minghu, Xu Baorui, et al. Development of a new type high-efficient inner-cone hydrocyclone [J]. Chemical Engineering Research and Design, 2012, 90 (12): 2129-2134.
[5] Cui Hang. Research on separation mechanism and performance of spiral gas-liquid separator [D]. Daqing Petroleum Institute, 2010.
[6] Yu Yang. The effect of the liquid-solid outlet structure of the three-phase cyclone separator on the separation efficiency [D]. Xi’an Shiyou University, 2017.
[7] Xu Baorui, Jiang Minghu, Zhao Lixin. Effect of produced fluid viscosity on the performance of three-phase separation cyclone [J]. Journal of Mechanical Engineering, 2017, 23 (8): 175-182.