Journal of Research in Science and Engineering (JRSE)
ISSN: 1656-1996 Volume-7, Issue-6, June 2025
DOI: 10.53469/jrse.2025.07(06).04

Research and Application Progress of Downhole Gas-Liquid Separation Technology

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Abstract: ***With the continuous advancement of oil and gas field development, the problem of water production in gas wells has become increasingly prominent, severely affecting natural gas production efficiency and economic benefits. As an effective solution, downhole gas-liquid separation technology can achieve gas-liquid separation in the wellbore, reinjecting water-rich fluids into the formation and lifting gas-rich fluids to the surface. This reduces lifting and treatment costs, minimizes environmental pollution, and improves recovery efficiency. This paper elaborates on the research and application progress of downhole gas-liquid separation technology, including its technical principles, main equipment, application cases, and future development trends, aiming to provide references for the further development and promotion of this technology.***

Keywords: Downhole gas-liquid separation, Swirl separator, Spiral separator, Reinjection technology, Development trend**.**

1. Introduction

During gas well production, formation water often flows into the wellbottom. When gas well production is high, the gas-liquid velocity at the wellbottom is large, and the fluid volume is relatively low, water is carried to the surface by the gas flow; otherwise, fluid accumulation occurs in the wellbore. The presence of accumulated fluid increases backpressure on the gas reservoir, restricting gas well productivity, and in severe cases, may even kill the gas reservoir and shut down the well. Currently, traditional drainage and gas production methods for gas wells mainly fall into three categories: gas dynamics methods, mechanical methods, and physicochemical methods. These methods share the common feature of producing downhole fluid to the surface, separating gas and liquid on the surface, and reinjecting the separated fluid into the formation via a pressure pump after accumulation through a pipeline. However, this traditional process suffers from numerous issues, such as numerous surface equipment, high investment, and environmental pollution.

Downhole gas-liquid separation and reinjection technology emerged to address these challenges. This technology uses a gas-liquid separation device in the well to separate natural gas produced from the formation, lifting gas-rich fluids (with low water content) to the surface while directly reinjecting water-rich fluids (with low gas content) into the injection formation. This technology offers significant advantages, including reduced lifting and treatment costs, extended gas field production period, increased production life and recovery efficiency, reduced environmental pollution, simplified surface separation, and improved investment efficiency, thus attracting extensive attention and in-depth research.

2. Principles of Downhole Gas-Liquid Separation Technology

2.1 Swirl Separation Principle

Swirl separation is a highly efficient multiphase flow separation technology. The working principle of a downhole gas-liquid swirl separator is the same as that of surface separators, primarily utilizing centrifugal force for gas-liquid separation. When gas-liquid mixture flows into the swirl separator, it forms a high-speed rotating helical flow field inside the separator. Due to the density difference between gas and liquid, the denser liquid is thrown to the outer wall of the separator by centrifugal force, flowing downward along the wall and converging, eventually discharging from the bottom outlet of the separator; the less dense gas forms an internal swirl in the central area of the separator, flowing upward and exiting from the top outlet, achieving gas-liquid separation.

Swirl separation technology exhibits high separation efficiency in handling gas-water mixtures with high gas-liquid ratios or high flow velocities. For example, in some high-yield gas wells with large gas-liquid mixture flow rates and high velocities, traditional gravity separation technology struggles to meet separation requirements, while swirl separators can quickly and effectively separate gas and liquid using strong centrifugal force. Its separation efficiency is influenced by multiple factors, such as separator structural parameters (e.g., cone angle, diameter ratio, inlet type), operating parameters (e.g., gas-liquid mixture flow velocity, pressure, temperature), and properties of the gas-liquid mixture (e.g., viscosity, surface tension). Optimizing these parameters can further enhance the separation performance of swirl separators.

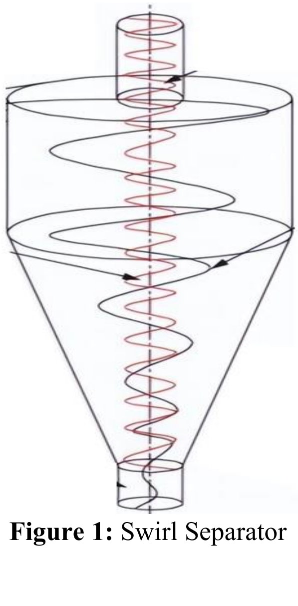

Figure 1: Swirl Separator

2.2 Spiral Separation Principle

The technical principle of spiral gas-liquid separators for gas-liquid separation mainly includes collision coalescence, centrifugal separation, and gravitational settling. Inside a downhole spiral gas-liquid separator, as the gas-liquid mixture flows through the spiral blades, it moves along a spiral path. During this process, water droplets collide and coalesce into larger droplets. Meanwhile, due to the centrifugal force generated by the spiral motion, large water droplets are separated from the gas phase under the combined action of centrifugal and gravitational forces. The separated water accumulates along the inner wall of the casing to form a water flow, which then flows downward along the casing wall into a container formed by the annulus between the flow tube string and the casing, accumulating as an annular water column. At the bottom of the annular water column, water is sucked into a screw pump, pressurized by the pump, and injected into the tubing. As the pressure of the water column in the tubing gradually increases, when it exceeds the pressure of the lower injection formation, water is reinjected into the formation through the central channel of the tubing string (reinjection pipe channel). The separated natural gas, on the other hand, continues to rise to the surface through the annulus, is produced from the casing valve, and enters the gas transmission pipeline network.

Spiral separators have a relatively simple structure and small volume, making them suitable for downhole environments with limited space. They can achieve relatively stable gas-liquid separation within a certain range of gas-liquid ratios and flow rates. Their separation efficiency is also closely related to structural parameters of the spiral blades (e.g., spiral angle, pitch, number of blades), gas-liquid mixture flow velocity, and gas-liquid properties. Reasonable design of spiral blade parameters can enhance collision coalescence and centrifugal separation effects, thereby improving overall separation efficiency.

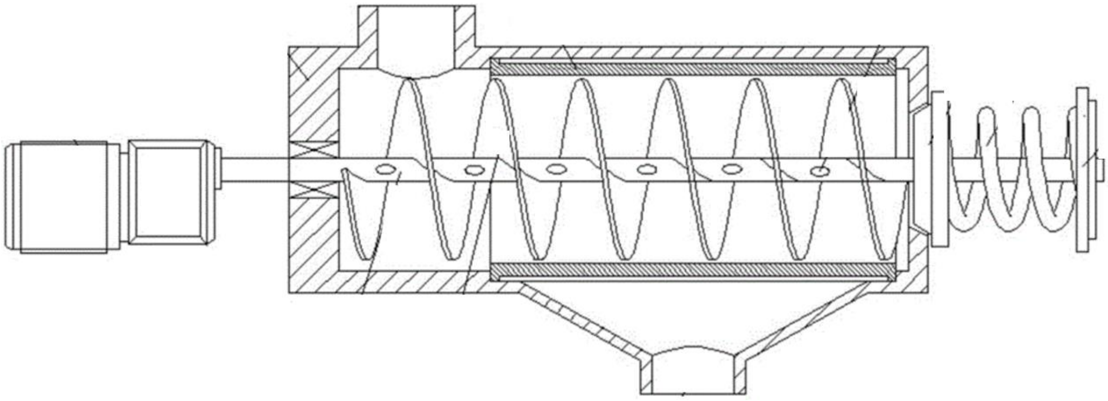

Figure 2: Spiral Separation Principle

2.3 Gravity Separation Principle

Gravity separation is one of the most fundamental methods for downhole gas-water separation in gas wells, relying on the significant density difference between gas and liquid. Under the action of gravity, the denser liquid gains a downward velocity component due to gravitational force while flowing with the gas, while the gas, with lower density, is less affected by gravity and maintains its original flow direction. This velocity difference causes gradual separation of gas and water during flow: liquid settles downward under gravity, adhering to the pipeline or separator wall, gathering, and discharging through a specific outlet; gas continues to flow upward, achieving preliminary gas-water separation.

Gravity separation performs well in gas wells with relatively low water production, high gas-liquid ratios, and low flow velocities. For example, in some low-yield gas wells with stable and relatively low gas flow velocities, liquid has sufficient time to separate from gas under gravity. In such cases, gravity separation equipment can effectively separate gas and water with simple structure and low operation-maintenance costs. However, when gas well water production increases, gas-liquid ratio decreases, or flow velocity becomes too high, the limitations of gravity separation become evident. At high gas-liquid flow velocities, the residence time of liquid in the pipeline is too short for gravity to cause sufficient settlement and separation, leading to a significant decline in separation efficiency. Additionally, gravity separation is sensitive to fluctuations in gas-water mixture flow rate; unstable flow rates can disrupt the normal flow pattern in the separator, further reducing separation performance.

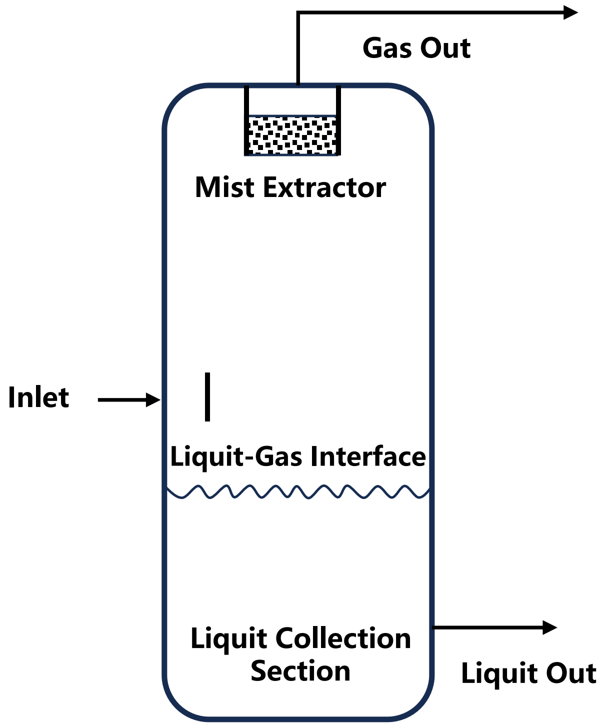

Figure 3: Gravity Separation Principle

Journal of Research in Science and Engineering (JRSE)
ISSN: 1656-1996 Volume-7, Issue-6, June 2025

2.4 Inertial Separation Principle

Inertial separation utilizes the inertia difference between gas and liquid in gas-water mixtures to achieve separation. When gas-water mixtures flow through specific devices, such as sharp bends, baffles, or specially designed separation elements that suddenly change flow direction, gas and liquid respond differently to the direction change due to their inertia differences. Liquid, with higher mass and inertia, tends to maintain its original motion direction when encountering a flow direction change, thus separating from the gas. Specifically, when gas-water mixtures impact a baffle, gas quickly changes direction to flow around the baffle, while liquid impacts the baffle due to inertia, adheres to its surface, and then collects downward under gravity to discharge through an outlet; when passing through a bend, liquid is thrown to the outer side of the bend due to inertia, while gas flows to the inner side, achieving gas-liquid separation.

Inertial separation is suitable for scenarios with moderate separation efficiency requirements but needing preliminary separation or pretreatment of gas-water mixtures. It can be used in conjunction with other separation technologies (e.g., gravity separation, swirl separation) to improve overall separation performance. The separation efficiency of inertial separation devices depends on factors such as the flow velocity of the gas-water mixture, the angle and mode of flow direction change, and the structural design of the device. Rational design of the shape, size, and arrangement of separation elements can fully leverage the inertia difference between gas and liquid to enhance inertial separation efficiency.

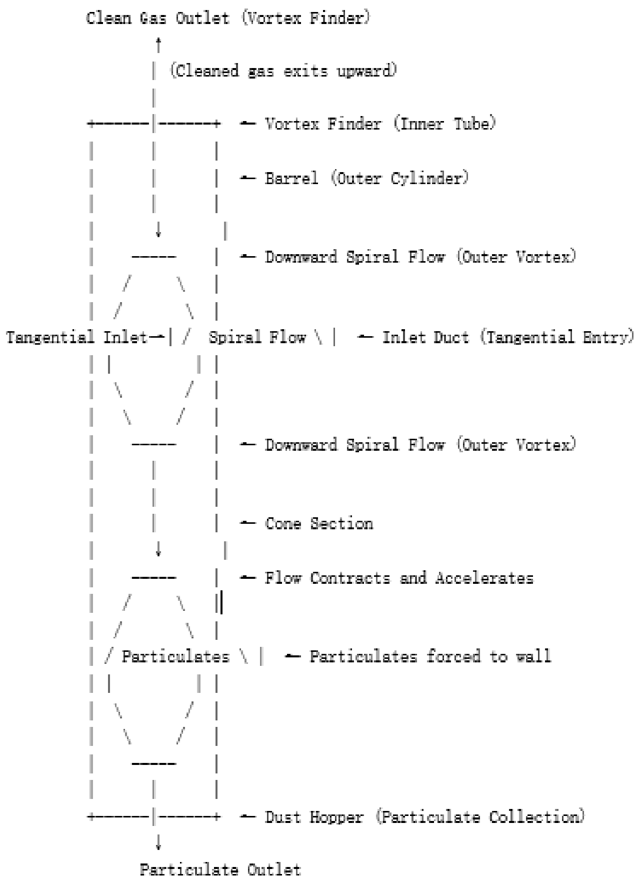

Figure 4: Inertial Separation Principle

3. Main Equipment for Downhole Gas-Liquid Separation

3.1 Downhole Gas-Liquid Swirl Separator

A downhole gas-liquid swirl separator typically consists of an inlet section, swirl section, separation section, and outlet section. The inlet section is designed to enable uniform and high-velocity entry of the gas-liquid mixture into the swirl section, with common inlet types including tangential and axial inlets. A tangential inlet allows the gas-liquid mixture to rapidly form a rotating flow field upon entering the swirl section, enhancing centrifugal separation; an axial inlet features a simpler structure, suitable for downhole environments with space constraints. The swirl section is the core part of the separator, usually equipped with helical blades or special flow-guiding structures to induce stable helical motion in the gas-liquid mixture. The separation section utilizes centrifugal force to separate gas and liquid: liquid is thrown to the separator's outer wall and flows downward, while gas moves upward in the central area. The outlet section has separate gas and liquid outlets to discharge the separated phases.

To improve swirl separator performance, researchers have continuously optimized its structure. For example, adjusting the cone angle to modify centrifugal force distribution affects gas-liquid separation efficiency. Studies show that within a certain range, increasing the cone angle can improve separation efficiency, but excessive cone angles may increase pressure drop and energy consumption. Additionally, structural parameters such as diameter ratio (e.g., inlet diameter to separator body diameter) and helical blade parameters (e.g., helix angle, pitch) significantly impact separation performance. Through experimental research and numerical simulation, the relationship model between these parameters and separation efficiency/pressure drop has been established, providing a theoretical basis for optimal design.

In material selection, downhole swirl separators are typically made of high-strength, corrosion-resistant materials due to the complex downhole environment (high pressure, high temperature, corrosion). For example, stainless steel is used to resist corrosion by downhole fluids; in particularly corrosive environments, special steel alloys containing nickel, molybdenum, etc., or anti-corrosion coatings on the separator inner wall may be employed to enhance equipment service life and reliability.

3.2 Downhole Spiral Gas-Liquid Separator

A downhole spiral gas-liquid separator mainly comprises helical blades, a central tube, an outer cylinder, and connecting components. Helical blades are spirally arranged around the central tube, with the outer cylinder surrounding the blades to form the flow channel for the gas-liquid mixture. The mixture enters the separator from one end and flows along the helical path formed by the blades, achieving gas-liquid separation during movement. The central tube guides the separated gas to flow upward, while the outer cylinder protects the helical blades and collects separated liquid. Connecting components firmly assemble the separator parts to ensure integrity and stability under complex downhole conditions.

The structural parameters of helical blades are critical to the separator's performance. The helix angle determines the helical trajectory and centrifugal force of the gas-liquid mixture in the separator; appropriately increasing the helix angle generally enhances centrifugal separation, but an excessively large angle may increase flow resistance and reduce processing capacity. The pitch affects the residence time and separation efficiency of the mixture in the separator; rational pitch design ensures sufficient time for collision coalescence and separation. The number of blades also influences separation performance: more blades increase gas-liquid collision opportunities but also raise flow resistance, requiring comprehensive trade-offs during design.

Compared with swirl separators, spiral gas-liquid separators feature simpler structures and lower manufacturing/maintenance costs. With no complex moving parts, they exhibit higher reliability in harsh downhole environments. However, their separation efficiency may be relatively lower than swirl separators under high gas-liquid ratio or high flow velocity conditions. Therefore, in practical applications, the type and parameters of spiral separators must be rationally selected based on specific gas well production conditions and requirements to achieve optimal separation results.

3.3 Other Separation Equipment

Besides swirl and spiral separators, other types of downhole gas-liquid separation equipment are applied in specific scenarios. For example, gravity settling separators, which utilize gravity for gas-liquid separation, have simple structures, typically consisting of a large-diameter container. When gas-liquid mixture enters the container, flow velocity decreases, allowing liquid to settle to the bottom under gravity while gas discharges from the top. These separators are suitable for high gas-liquid ratio, low liquid content, and low separation efficiency requirements, such as low-pressure, low-yield gas wells.

Inertial separators are common auxiliary separation devices that use special baffles, bends, or other structures to separate gas and liquid via inertia differences. They can serve as pretreatment equipment, used in conjunction with main separation devices to remove larger liquid droplets from the gas-liquid mixture before entering the main separator, reducing the burden on subsequent equipment and improving overall separation system performance.

Furthermore, with technological advancements, new separation equipment is emerging. For instance, compound separators integrating multiple separation principles (e.g., swirl, gravity, inertial separation) into a single device leverage the advantages of various technologies to improve separation efficiency and adapt to more complex downhole conditions. Additionally, separation equipment using special materials or physical effects, such as membrane separation devices, which utilize special semi-permeable membranes for selective gas-liquid separation, currently face technical challenges in downhole applications, such as membrane corrosion resistance, anti-fouling capability, and compatibility with downhole environments, requiring further research and improvement.

4. Application Cases of Downhole Gas-Liquid Separation Technology

4.1 Overseas Application Cases

In 1991, Canada's C-FER (the Centre for Engineering Research Inc.) first proposed the concept of "downhole gas-liquid separation" and initiated feasibility studies to explore unconventional methods for reducing gas well lifting and water treatment costs by minimizing water production. In July 1994, the first ESPAQWANOT system underwent field testing, with the separator operating satisfactorily and a significant reduction in surface water production. Field test results showed drastic changes in gas volume, water volume, and gas-liquid ratio, demonstrating the system's advantages, though substantial improvements in equipment design and structure were still needed for further optimization.

The United States widely applies downhole gas-liquid separation technology in shale gas extraction. For example, in the Eagle Ford shale area, some gas wells use advanced downhole gas-liquid separation equipment with remarkable results. One gas well employs a high-efficiency swirl separator integrated with an intelligent control system, which automatically adjusts separator operating parameters based on real-time production data. After application, the separation efficiency exceeds 98%, maintenance cycles are extended by 6–8 months compared to traditional processes, and daily single-well production increases by 20%. This not only boosts natural gas output but also significantly reduces equipment maintenance costs and improves gas well economic benefits.

In offshore gas fields in the North Sea, downhole gas-liquid separation technology and a complete produced water reinjection system have been adopted to address water production issues in gas wells. By separating gas and liquid downhole and reinjecting the separated water into the formation, this approach effectively reduces corrosion risks to pipelines caused by liquid carryover, extending pipeline and compressor service life. Meanwhile, the reduction in surface water treatment equipment and processes decreases space occupation and operational costs on offshore platforms, enhancing overall gas field production efficiency and economic benefits.

4.2 Domestic Application Cases

Sinopec Shengli Oilfield has gained rich experience in applying downhole gas-liquid separation technology. For watered-out gas wells, Shengli Oilfield uses self-developed downhole gas-water separation and reinjection devices combining spiral swirl separators with screw pumps or electric submersible pumps. After application in a watered-out gas well, gas production significantly increased, and recovery efficiency rose by 15%–20%. The device achieves efficient gas-liquid separation through spiral swirl separators, with screw pumps or electric submersible pumps pressurizing and reinjecting separated water into the formation. During practical application, the separation device and reinjection system were optimized according to the gas well's specific geological conditions and production parameters to ensure stable and efficient operation.

Shenyang Oilfield has also conducted research and applications of downhole gas-liquid separation and produced water reinjection technology. Through structural optimization design, parameter optimization, and indoor prototype testing of gas-liquid separators, the technology has been improved with screw pumps and separators as core components. Field implementation shows that this technology enables efficient downhole gas-liquid separation and water reinjection, reducing lifting and treatment costs while extending gas well production life. Additionally, using screw pumps as power equipment saves over 40% energy per day compared to sucker rod pump drainage and gas production, offering significant economic and environmental benefits.

In the Sulige Gas Field, due to its large area, numerous gas wells, and prominent water production issues in some wells, downhole gas-liquid separation technology was introduced to achieve efficient and sustainable development. Various downhole gas-liquid separation devices (e.g., swirl separators, spiral separators) were tested and applied in different types of gas wells, with separation processes and reinjection schemes optimized based on the gas field's geological characteristics and production needs. Practical verification shows that downhole gas-liquid separation technology effectively mitigates fluid accumulation in gas wells, improves gas production stability and recovery efficiency, and reduces pressure on surface gathering systems and sewage treatment costs, providing strong technical support for large-scale efficient development of the Sulige Gas Field.

5. Development Trends of Downhole Gas-Liquid Separation Technology

5.1 Intelligent Development

With the continuous advancement of sensor technology, automation control, and IoT (Internet of Things), downhole gas-liquid separation systems will develop toward intelligence. Future intelligent downhole gas-liquid separation systems will real-time monitor gas well production data (e.g., flow rate, pressure, temperature, water cut) and automatically adjust separation equipment parameters (e.g., swirl separator inlet velocity, spiral separator rotational speed, if adjustable) via built-in intelligent control systems and advanced algorithms to achieve optimal separation efficiency. Meanwhile, intelligent systems will monitor equipment operation status in real time, perform fault diagnosis, identify potential issues promptly, and take corresponding measures, enhancing equipment reliability and stability while reducing manual intervention and maintenance costs.

For example, using IoT technology to connect downhole gas-liquid separation equipment with surface monitoring centers enables remote monitoring and operation. Staff can remotely adjust equipment parameters and control operations through the monitoring system, gaining real-time insights into downhole equipment status. When faults occur, the system automatically alarms and provides fault causes and solution suggestions via data analysis, significantly improving gas well production management efficiency and intelligence levels.

5.2 Research and Development of High-Efficiency Energy-Saving Technologies

To enhance downhole gas-liquid separation efficiency and reduce energy consumption, the development of new high-efficiency and energy-saving technologies will continue in the future. In terms of optimizing the structure of separation equipment, more in-depth experimental research and numerical simulation analysis will be conducted to further optimize the structural parameters of swirl separators, spiral separators, and other equipment. For example, improving blade shapes and optimizing diameter ratios can enhance separation efficiency while reducing flow resistance and energy consumption within the equipment. Additionally, new separation principles and technologies will be explored, such as the application of adsorption separation technology and membrane separation technology in downhole gas-liquid separation by using new types of adsorbents or separation membranes. Adsorption separation technology can selectively separate gas and liquid through special adsorbents, while membrane separation technology can achieve separation by utilizing the selective permeability of membranes to gas and liquid. Although these technologies currently face challenges in downhole applications, such as the corrosion resistance of membranes, anti-fouling properties, and compatibility with downhole environments, continuous research and innovation are expected to overcome these obstacles and promote their practical application.

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