Research Progress of Underwater Gas-liquid Separation and Pressurization Technology and Equipment

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Abstract. In recent years, in order to solve the problems of low reservoir pressure, high back pressure at the wellhead, hydrate clogging and high viscosity of oil in the extraction of subsea oil and gas fields, the industry is researching and developing new gas-liquid separation and pressurized transport technologies to improve efficiency, reduce energy consumption and cost, and promote the sustainable development of offshore oil and gas. By analyzing seven advanced foreign underwater projects and three conceptual design cases, we summarize their equipment structures, technical parameters, advantages and challenges, which provide important experience for future technology development. These projects have significantly improved efficiency, reduced energy consumption and enhanced safety by optimizing the separation process and pressurization technology. In the future, with the deepening of deep-sea development, underwater separators will develop in the direction of larger aspect ratios and higher pressure-resistant grades to adapt to extreme environments such as high pressure and low temperature in the deep sea. Therefore, it is necessary to continue to promote technological innovation to meet the strict demands of deep-sea exploitation and provide stronger technical support for offshore oil and gas development.

Keywords: Underwater separation; Underwater pressurized transport; Flow assurance.

1. Introduction

Against the background of global energy structure transformation and the increasing attention to the development of deep-sea oil and gas resources, the underwater production system, as an important equipment for the development of deep-water oil and gas fields, and the enhancement of its technological level not only concerns the safety and stability of energy supply, but also is the key to achieving the optimization of the energy structure and the green and sustainable development. The subsea production system consists of core components such as subsea wellhead, subsea recovery tree, subsea pipeline manifold and subsea control system, which significantly reduces the cost of deepwater oil and gas development, shortens the construction cycle of the project, and demonstrates excellent resistance to natural disasters through the highly integrated operation process, and has become an irreversible development trend in the field of deepwater oil and gas extraction.

In recent years, with the deepening of deep-sea oil and gas exploration and development, the underwater production system has been developing towards a higher degree of integration, intelligence and high efficiency. As the core link connecting deep-sea oil and gas wells and submarine pipelines, the performance optimization and technological innovation of underwater separation and pressurization technology are directly related to the efficiency of the whole underwater production system[1]. Therefore, in-depth study of the latest progress of underwater gas-liquid separation and pressurization technology, analysis of the bottlenecks and challenges faced by the current technology, and outlook of the future development direction and application prospects have far-reaching theoretical and practical significance for promoting the progress of China's deepwater oil and gas extraction technology and enhancing the overall efficiency of the underwater production system.

2. Basic principle of underwater gas-liquid separation and pressurization technology

The key to underwater gas-liquid two-phase separation technology is to utilize the physical differences between the gas-liquid two-phase, including density, inertia and surface tension, etc., and regulate the flow state of gas-liquid mixtures in the separation equipment by means of variable speed, variable direction or vortex formation, prompting the gas-liquid two-phase to produce relative motion, so as to realize effective separation.

The basic methods of underwater gas-liquid separation include gravity separation and centrifugal separation. Gravity separation is based on the difference in density between the liquid and the gas, and the two phases are naturally stratified by standing[2]. This method is suitable for separation scenarios with low flow rates and large particles, and has the advantage of simple operation and low cost. However, in complex gas-liquid mixtures or high flow rates, the efficiency of gravity separation is limited.

The principle of centrifugal separation lies in the use of centrifugal force generated by rotation, combined with sedimentation coefficients or density differences between substances, to rapidly separate the phases of a gas-liquid mixture along different radii. This method is particularly suitable for dealing with complex gas-liquid mixtures containing fine particles, air bubbles or high flow rates and high viscosities, and can be adapted to fluids with different flow rates and viscosities, with wide applicability. However, for very fine particles or bubbles, it may not be possible to completely separate them; in addition, the initial investment cost of the centrifugal separation equipment is relatively high, and regular maintenance and repair are required[3].

3. Status of underwater gas-liquid separation and pressurization technology and equipment

3.1 Marimbá Oilfield VASPS System

In 2001, Petrobras deployed the Vertical Annular Space Separation and Pumping System (VASPS) at the Marimbá field in the Campos Basin, Rio de Janeiro, Brazil, and after completing the subsea installation and initial testing, it did not go into operation until 2004 due to a mechanical failure of the electric submersible pump. Due to the low reservoir pressure in this field, Petrobras deployed the VASPS system one kilometer away from the P-8 platform (operating water depth of 395 m), which enables efficient gas-liquid separation operations, where the gas rises by natural lift and the liquid is pressurized with the help of an electric submersible pump and subsequently transported to the P-8 platform.

The VASPS vertical annular air separation and pumping system consists of a series of key components including a temporary guiding base (TGB), flowbase, top member, separator, and electric submersible pumps (Fig. 1). The system uses a columnar spiral channel cyclone separation technology with a caisson design, which has a diameter of 0.762 meters and a height of 72 meters. The separator consists of three concentric casing: the outer pressure casing, consisting of six sections, with a total length of 72 m, 12 m per section, and a diameter of 0.66 m; the middle layer is a spiral guide vane tube, consisting of six sections, with a diameter of 0.324 m. The outer wall of which is welded with a spiral guide vane, which is in close contact with the inner wall of the pressure casing and forms a spiral channel; and the inner layer is a liquid discharge tube with a diameter of between 0.203 and 0.254 m, which forms a gas ring with the spiral guide vane tube to form a gas annular air channel[4].

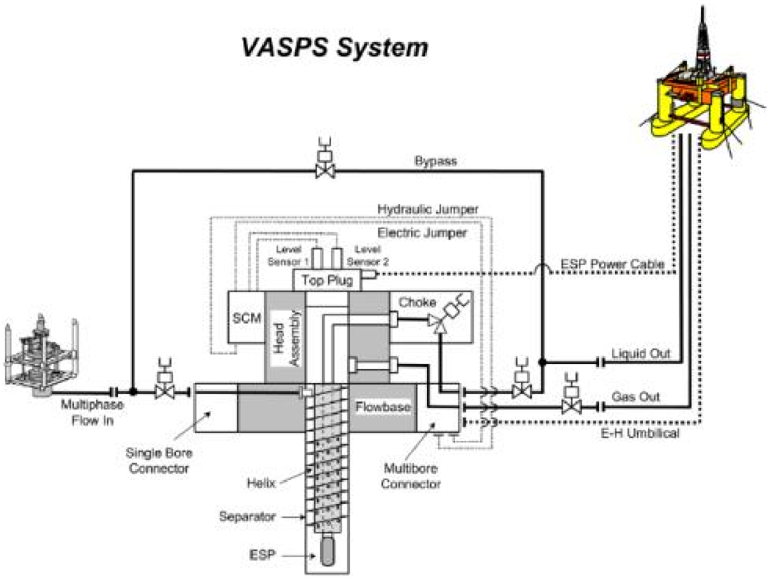

Figure. 1 VASPS separator structure

The VASPS system effectively realizes subsea gas-liquid separation and liquid-phase pressurization to reduce wellhead backpressure, thus increasing the recovery rate of low reservoir pressure fields. The system utilizes mature drilling technology to deploy subsea dummy wells vertically, reducing the difficulty of implementation. The caisson design separator provides ample space to ensure efficient separation and supports single-phase pump pressurization, simplifying the process. In addition, the system is tightly integrated with the wellhead structure, making full use of existing oil recovery technologies and facilitating implementation and dissemination[5].

3.2 Perdido Oilfield Caisson Separation and Pressurization System

Shell initiated the caisson separation and boosting system (SBS) for the Perdido field in the Gulf of Mexico, about 320 km south of Freeport, USA, in 2009, which is the world's first ultra-deepwater field to be developed by applying a deepwater gas-liquid separation and lifting system. To cope with the challenges of low reservoir pressure and wellhead backpressure as high as 13.79 MPa, the field adopted the development strategy of subsea caisson separation and booster system combined with Spar platform. The caisson separation and pressurization system is deployed in the Gulf of Mexico at water depths up to 2450 m. The effective separation of gas and liquids is achieved through a subsea caisson separator. The gas is naturally lifted to the Spar platform through the annular region of the pre-tensioned riser, while the liquid is pressurized by an electric submersible pump and transported to the Spar platform through the inner tube of the pre-tensioned riser[6].

The caisson separation and pressurization system of the Perdido project consists of a caisson embedded in the seabed (Fig. 2), which is fabricated using a seamless steel pipe welding process, with an outer diameter of 0.941 m, an inner diameter of 0.889 m, and a total length reaching 100.584 m. The caisson has been constructed with a pneumatic-hydraulic column and a hydraulic column. The top of the caisson was equipped with a gas-liquid columnar cyclone separation module (GLCC) to achieve efficient gas-liquid separation. An electric submersible pump was installed in the bottom chamber to provide the necessary pressurization[7]. The whole system follows a modular design concept to ensure that each module can be independently transferred to the surface for maintenance and overhaul.

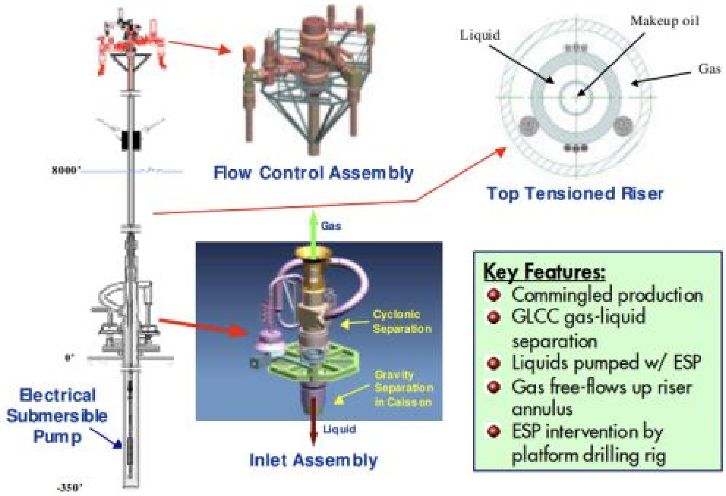

Figure. 2 Structure of Perdido caisson separation and pressurization system

The Perdido system is capable of subsea gas-liquid separation and liquid-phase pressurization, which significantly reduces wellhead backpressure and enhances recovery, effectively expanding the development potential of low-reservoir-pressure oil fields. The caisson separator has a total length of more than 100 meters, can adapt to a wide range of gas-liquid phase apparent flow conditions, and has good adaptability to complex flow changes. The electric submersible pump is completely submerged in the liquid and naturally cools the motor[8]. The diameter and volume of the caisson are precisely calculated to maintain a stable liquid level and guarantee smooth operation of the system. The closed baffles around the electric submersible pump effectively guide the liquid to cool the motor, optimizing the pressure drop and heat transfer performance. The bottom of the caisson adopts a streamlined design to prevent sand deposition, and is equipped with a filtering device to block large debris from entering the electric submersible pump, which further enhances the reliability and durability of the system.

4. Underwater gas-liquid separation and pressurization technology and equipment development trend

In recent years, with the development of marine oil and gas resources to the deep sea and ultra-deep sea field of deep advancement, underwater gas-liquid two-phase separation technology is facing more complex challenges. In this context, large aspect ratio has become an important trend in the design of underwater gas-liquid separators. The large aspect ratio separator not only has excellent separation effect, but also has a larger processing capacity. By optimizing the structural design and material selection of the separator, the separation efficiency and stability can be further improved to effectively cope with the high external pressure conditions in the deep sea environment. Meanwhile, the pressurization technology can conveniently transport the separated gas/liquid phase to the platform, thus facilitating the subsequent oil and gas treatment process. Looking ahead, with the growing demand for deep-sea oil and gas resources development, the combination of large aspect ratio separator and pressurization technology will become an important direction for the development of underwater gas-liquid separation technology.

4.1 Saipem multi-tube separator

In the process of deepwater oilfield development, the implementation of subsea gas-liquid separation and pressurization technology is a key strategy to effectively reduce the back pressure at the wellhead and significantly improve the oil recovery efficiency. Conventional large diameter gravity separators are subjected to tremendous hydrostatic pressure in deepwater environments, resulting in a significant increase in wall thickness, which undoubtedly raises manufacturing costs and prolongs the production cycle. In this regard, Saipem has innovatively designed a multi-pipe large aspect ratio separator (Fig. 3), which significantly reduces the wall thickness compared with the traditional pressure vessel[9], and replaces the traditional pressure vessel by multiple elongated pipes, which not only reduces the cost, simplifies the fabrication process, and shortens the fabrication time, but also realizes the feasibility of on-site assembling, which further broadens the scope of its application in deepwater oilfields.

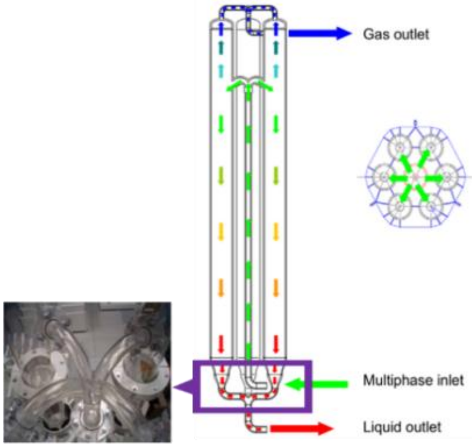

Figure. 3 Structure and separation principle of Saipem multi-tube separator underwater station

The Saipem Multi-Tube Separator achieves a significant reduction in wall thickness by innovatively dividing the traditional single, bulky pressure vessel into smaller vessel units. The separator relies on standardized pipe manufacturing processes and incorporates easy on-site assembly techniques to make it flexible and efficient in practice. The gas-liquid separation mechanism is based on the principle of gravity, and each separation tube is designed to resemble a conventional gravity separator. In order to increase the separation efficiency, a special inlet arrangement has been designed with optional internal components to further optimize the performance. The process flow is as follows: the multiphase fluid enters through the inlet, then travels vertically across the centerline and is evenly distributed among the tubes, which are uniquely equipped to handle blocked flows and to achieve efficient separation of gas and liquid. At the top and bottom of the assembly, the pipes merge to form a single gas and liquid outlet. The gas flows naturally to the surface through one or two flow lines, while the liquid is pressurized by a liquid pump and merges into the single flow line.

The Saipem Multi-Pipe Separator incorporates multiple level sensors to accurately measure the liquid level in each pipe and control the level by adjusting the speed of the liquid pump. The system design ensures that the level is consistent in all pipelines, as the liquid and gas phases share a single outlet. In addition, the distribution and recovery system is symmetrical[10]. Different types of sensor technology (including radar, nuclear and pressure sensors) can be used in the piping to measure the liquid level. The design of the entire separator incorporates an autodrain geometric configuration to prevent sand deposition.

4.2 SEPPUMP Underwater Separator

The design concept of the SEPPUMP underwater separator originated from the Highlander project in the North Sea, and the innovative highlight of the SEPPUMP is that it abandons the traditional vertical electric submersible pump layout and adopts a horizontal configuration, which is directly integrated into the internal part of the segmented plug flow trap. This transformative design makes SEPPUMP not only have the ability of segmented plug trapping, but also has the function of pumping, realizing the efficient separation of gas and liquid phases based on the principle of gravity, which greatly improves the separation efficiency.

The SEPPUMP underwater separator is designed with a pipe diameter of 0.6 meters and a total system length of 24.4 meters to ensure enough space to effectively eliminate the plug flow. The separated liquid is pumped to the outside of the system via a horizontal electric submersible pump of approximately 22 meters in length. To achieve the desired separation, SEPPUMP utilizes a two-layer piping design: a top layer for gas flow and a bottom layer for liquid flow. The cross-branching structure allows the necessary fluid exchange between the two layers (Fig. 4). The total weight of the entire SEPPUMP system is approximately 160 tons[11].

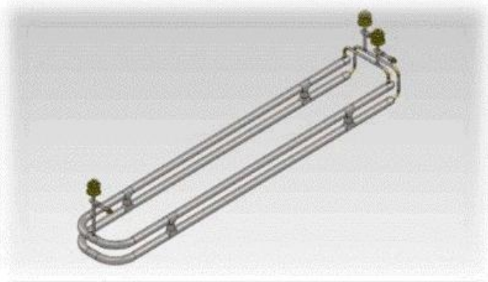

Figure. 4 Basic configuration of SEPPUMP underwater separator

5. Summary

This paper focuses on the latest achievements in underwater gas-liquid separation and pressurization technology, and discusses in detail the challenges, structural features, key parameters and their significant advantages encountered by foreign advanced systems. Through the optimization of the separation process and the enhancement of the conveying efficiency, these advanced systems provide a reliable and efficient solution for the complex and changeable marine environment, which significantly enhances the efficiency and safety of oil and gas extraction.

Going forward, underwater separation engineering will favor design strategies with large aspect ratios to accommodate extreme underwater operating conditions such as high external pressure and high flow rates. Underwater gas-liquid two-phase separation and pressurization technology will focus on accurately matching the separation needs of different underwater environments, and optimizing the selection of separation and pressurization processes to achieve efficient and environmentally friendly material separation and transport. The research in this field will be devoted to developing separation technologies that can adapt to the extreme conditions of high pressure and low temperature in the deep sea, and at the same time, exploring more accurate and efficient separation processes for the physicochemical properties of different components.

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