Intelligence and safety: Research progress and trends in multiphase flow separation technology and equipment

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Abstract. At present, with the rapid development of industrial automation and information technology, intelligence has become a key trend to improve the efficiency and safety of industrial equipment. Multiphase flow separation technology is an important link in the energy, chemical, and other industries, and the intelligent upgrade of its equipment and the study of safety technology are of great significance for improving the energy savings, environmental protection level, and production safety of the whole industry. This paper carries out a comprehensive study of domestic and foreign multiphase flow separation technology and equipment, combines the current scientific research background, future research trends, and the structural integrity and safety technology of pressurized equipment, analyzes the current challenges, and puts forward reasonable development suggestions for comprehensively upgrading the intelligence, stability, and reliability of separation equipment.

Keywords: multiphase flow separation technology, intelligence, safety: multiphase flow separation equipment.

1. Introduction

Multiphase flow widely exists in nature and engineering equipment. From the point of view of phase composition, multiphase flow mainly includes gas-liquid, gas-solid, liquid-solid two-phase flow, and gas-liquid-solid three-phase flow. The development of multi-phase flow separation technology has certain guiding significance for the solution of many engineering practical problems, such as petroleum, chemical, electrical, etc. The improvement of this separation technology as well as the optimization and upgrading of the separation equipment have been in a stage of continuous exploration.

At present, with the continuous development of oilfield resources, the separation demand for oil and gas resources is getting higher and higher, and the oilfields in some countries have entered the high water content stage, and the separator is the key equipment for treating the extracted fluids and successfully extracting the oil and gas. How to effectively improve the separation efficiency of the separator is the focus of the research [1]. As the importance of multiphase separation technology represented by oil-water-gas three-phase separation becomes more and more obvious, improving the efficiency of oil-water-gas separation has become an important direction of the current research, among which associated gas separation, drilling fluid treatment, etc. also force hydrocyclone separation equipment to develop from two-phase to three-phase. Secondly, with the exploration of oil fields gradually moving to the deep sea, the implementation of subsea separation and liquid propulsion has also become a common development program for deep-water oil field exploration. In addition, gas-liquid multiphase pumps, as the main gas-liquid phase flow separation equipment, have many challenges in testing technology, accurate numerical model development, and gas-liquid flow control [2]. Improving the intelligence and safety of multiphase flow separation technology and equipment has become an important research trend today.

In the exploration process of multiphase flow separation technology and equipment, it is necessary to continuously improve and enhance its design and performance in order to better adapt to various complex engineering environments. The purpose of this paper is to comprehensively summarize the latest research results of multiphase flow separation technology and equipment in terms of intelligentization and safety technology and to propose possible future development directions with a view to providing references and guidance for researchers and practical applications in related fields.

2. Current status of multiphase flow separation technology

Multiphase flow separation technology is an important part of a variety of industrial production processes, including but not limited to petroleum, chemical, metallurgical, and environmental protection. Its main function is to separate a mixture containing two or more different phases (e.g., solids, liquids, and gases) into a single or more than one phase to be utilized or processed according to differences in physical and chemical properties. Multiphase flow separation technology has a long history. In traditional separation technology, the dominant methods are filtration, gravity sedimentation, sieving, drying, and centrifuge separation. Among them, the settling process and the equipment used are relatively simple, making gravity settling technology occupy a certain position in separation technology. With the development of modem industry and the progress of science and technology, people's requirements for separation theory and technology are getting higher and higher, which prompted the vigorous development of the brand-new modem multiphase flow separation technology. In the past decades, research in the field of multiphase flow separation has continued to progress, especially in the development of intelligent separation models and control systems.

Currently, most of the research on multiphase flow separation techniques focuses on the following areas:

Physical and Chemical Mechanisms of Separation Processes: Past research has focused primarily on understanding and optimizing the underlying physical and chemical mechanisms of one or more separation processes, including matter transfer and heat transfer, in order to improve separation efficiency. For example, in the study of biomolecular liquid-liquid phase separation [3], statistical thermodynamic theories of macromolecular liquid-liquid separation were utilized, including the Flory-Huggins theory, the Overbeek-Vdom correction, the stochastic phase approximation, and field-theoretic simulations, leading to simplified sequential modeling systems for experimental studies [4]. In addition to this, there are studies of ionic competitive adsorption at oil-water interfaces, which provide new insights into the development of efficient strategies to improve the separation efficiency of target ions with similar physicochemical properties by modulating their adsorption behavior at the interface.

Optimization of equipment and methods: Researchers have developed a variety of new separation equipment and methods, including centrifugal, membrane, electron beam, and acoustic wave separation, to meet the needs of specific industrial applications. Taking the development of gravity oil-water separation equipment technology as an example, in order to improve the separation efficiency, at present, the combination of traditional re-election technology and agglomeration separation technology has become a research hotspot, with which the cartridge agglomeration separator [5] as a new type of oil-water separator has also come into being.

Modeling and computational simulation: In order to better understand and predict multiphase flow separation processes, researchers have developed a variety of complex flow models and computational simulation tools. Modern simulation methods such as CFD (computational fluid dynamics) and FLUENT software have been able to simulate complex multiphase flow and separation processes. In the research process of oil-water separator steady flow components, Shu Fangqi et al. [6] used CFD software to carry out numerical simulation and found that the "field" rectifier element installed in the inlet element

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at 0.5 d after the inlet element can achieve a better rectification effect. China University of Petroleum, Li Dongfang et al. [7] implemented the *k-ε* model and multiphase flow mixing model through FLUENT software to numerically simulate the three-dimensional flow field inside the gravity oil-water separator and quantitatively study the size of the remix zone of the gravity oil-water separator.

Intelligent separation control: by using intelligent control technology, such as neural networks and fuzzy logic, intelligent control of oil thinning equipment can be realized, thus further improving the separation efficiency and reducing the energy consumption of separation equipment. For example, a researcher designed an intelligent controller based on neural network nonlinear object recognition and applied it to an atmospheric oil separator. Through experimental tests, it was found that the controller not only solved the problem of regulating the vessel level but also minimized the change in oil flow, weakened interference in the downstream process, and prolonged the service life of several devices [8]. In the cryogenic separation process, for the nonlinear model of the cryogenic separation process, some researchers have proposed an optimal control design method by combining the state-dependent Riccati equation (SDRE) method and the sum-of-squares (SOS) optimization technique so as to maximize the productivity of specific isotopes in the cryogenic separation process equipment [9].

Despite the obvious progress of multiphase flow separation technology in the past decades, it still faces some challenges. How to simulate complex multiphase flow and separation processes more accurately, how to design and optimize new separation equipment and methods, and how to use modern intelligent control means for more efficient separation control are the main research trends in the future. We look forward to developing more effective multiphase flow separation technologies in the future to meet increasingly stringent environmental requirements and growing industrial production needs.

3. Intelligent development of multi-phase flow separation equipment

Multiphase flow separation equipment is widely used industrial equipment that has important applications in many fields such as petroleum, chemical, metallurgy, environmental protection, and so on. With the development of science and technology, the intelligentization of multiphase flow separation equipment has become an important research direction.

Generally speaking, the intelligence of multi-phase flow separation equipment mainly includes two aspects: first, the establishment of an intelligent separation model through accurate simulation of the separation process in order to optimize the separation effect; and second, the realization of intelligent control of the separation equipment in order to improve the operational efficiency and stability of the separation equipment.

In terms of intelligent separation models, through the use of fluid dynamics, thermodynamics, and other theories, it has been able to better simulate the separation process, and to a certain extent, it has realized the optimization of the separation effect. For example, in the research of membrane vibration intelligent mitigation of fouling in the algae separation process, through the establishment of its kinetic model, a comprehensive assessment of its critical vibration frequency, and a better simulation of the separation process, thus improving the efficiency of the vibrating membrane system in the algae separation process [10].In order to describe and predict the continuous separation process of wastewater treatment, some researchers modeled and simulated the process of separating benzoic acid from wastewater by hollow fiber membrane modules using fluid dynamics theory and verified the validity of the model by comparing it with the measured values, which can be used for the design and optimization of membrane benzoic acid removal processes [11]. Meanwhile, some positive results have been achieved by using intelligent algorithms such as neural networks and genetic algorithms to learn and optimize the separation model. In the case of an axial-flow compact separator, for example, a stacked neural network is used to simulate the nonlinear process of performing gas-liquid separation to help operators predict the separation efficiency under changing operating inlet conditions, thus effectively controlling the separator. In addition, for intelligent control of crude oil separation, model-based control and genetic algorithms enable intelligent process control for IIoT (e.g., SCADAPACK 535E and FactoryTalk), which significantly improves the performance of the crude oil separation process [12].

In terms of intelligent control, on the one hand, the precise control and optimal operation of the separation equipment are realized by adopting advanced control strategies such as adaptive control and fuzzy control. Taking chromatographic separation as an example, by introducing an intelligent fuzzy controller similar to an approximate neural network (NN) in the control process, the ideal result of a simulated moving bed (SMB) system [13] is effectively realized. In addition, in the Mixed Separation and Thickening Process (MSTP) of hematite beneficiation, a researcher has adopted a new interval intelligent switching control method to control the underflow slurry density (USD), underflow slurry flow rate (USF), and the rate of change of USF in the target range, which greatly improves the quality of concentrates [14] . On the other hand, through the integration of the Internet of Things (loT) and big data analysis, the remote separation equipment has been realized by using the integration of the Internet of Things and big data analysis. On the other hand, through the integration of the Internet of Things, big data analysis, and other technologies, remote monitoring and fault diagnosis of the separation equipment are realized, which greatly improves the operation efficiency and stability of the separation equipment. Take the cylindrical gas-liquid cyclone (GLCC) as an example. It is sensitive to flow changes that may reduce the separation performance, and the performance of the GLCC can be improved through control. In this regard, a researcher proposed an adaptive feedback linearization controller and implemented the model and controller in Simulink, which ensures the stable separation performance of the GLCC [15]. Secondly, supercritical fluid extraction (SFE) adopts environmentally friendly CO_2 as the extractant as an alternative to conventional separation methods. Safety is the most important factor in supercritical fluid extraction systems. For the extractor vessel, a researcher has developed an SFE system (mechanical and electrical components) by combining the concepts of conventional process control and the Internet of Things (loT) to realize its remote control and supervision [16]. In addition, there are also researchers who have proposed a data-driven diagnostic method based on convolutional neural networks (CNN) for the working condition diagnosis of oil and gas separators that can visualize and analyze the segment plugging flow process, which has higher accuracy and intelligence compared with the traditional threshold-based alarm method [17].

However, the intelligent development of multiphase flow separation equipment still faces many challenges. Firstly, the complexity of the multiphase flow separation process makes it difficult to establish an intelligent separation model; secondly, the current intelligent control strategy cannot fully meet the actual needs of the separation equipment operation; and thirdly, the development and application of intelligent separation equipment still need a lot of research and practice to further verify its effect. In general, the current status of research on the intelligent development of multiphase flow separation equipment is good but still needs further research and improvement.

4. Structural integrity and safety technologies fbr multiphase flow separation equipment

Multiphase flow separation equipment is a key piece of equipment widely used in petroleum, chemical, metallurgy, environmental protection, and other industries, and its structural integrity and safety are directly related to its stable operation and the safety of personnel and the environment in the production process. Therefore, in the process of equipment design, maintenance, and operation, the structural integrity and safety assessment of separation equipment have become important research directions.

In structural integrity research, the main concern is the force, deformation, and fatigue of equipment under complex working conditions. Through finite element analysis, experimental testing, and other methods, the mechanical characteristics, fatigue life, and failure mode of the equipment can be predicted and evaluated. For example, for high-temperature separation equipment, parts and structures will be subjected to creep damage during steady state operation and thermal fatigue damage during frequent switching operation, which is potentially dangerous. A researcher proposes a new high-temperature low-week fatigue creep interaction life prediction model that is not only applicable to the stress control mode but also to the strain control mode and has high prediction accuracy. In addition to this, some researchers have established the quasi-static, temperature- and time-dependent mechanical properties of ZIF-8/Matrimid nanocomposite composite membranes through experiments such as nanoindentation, dynamic mechanical analysis, and large-strain uniaxial tensile measurement of the membranes, investigated their thermomechanical stability and viscoelasticity, and accurately evaluated their mechanical properties [18]. Many practical tools and methods have been developed in this field. For example, using corrosion and stress residual measurements, some researchers have addressed the transportation life of oil and gas pipelines by proposing the use of ultrasonic technology (UT) to monitor residual stress changes that may be induced by corrosion and by evaluating and calibrating the ultrasonic (US) technology on a pipeline model in which a typical localized corrosion damage mechanism exists, greatly reducing the risk of the pipeline during transportation [19]. In addition, equipment usage has been evaluated by NDT methods, and predictive models have been used to predict the remaining service life of equipment and fatigue crack extension. For example, some researchers have utilized acoustic emission (AE) technology for non-destructive testing and health monitoring of equipment and neural networks for crack extension detection and crack depth estimation to ensure safety during equipment operation.

In the area of safety technology research, the main concern is the safety of equipment operation under abnormal operating conditions (e.g., excessive pressure, high or low temperature, change in fluid properties, etc.). In this field, many methods have been developed to reduce equipment safety risks, such as safety valves, overcurrent protection, insulation and fire protection, and other measures. Some researchers have optimized these methods. For example, one researcher has developed an automatic safety valve test system that allows the user to set a variety of test parameters and can automatically open the test channel for the appropriate pressure range according to the operating pressure of the safety valve, automatically performing a complete safety valve test operation. This system can greatly reduce the cost of manual operation of safety valve testing and improve the accuracy of the test [20]. Optimization of the electrical protection circuitry of MV controllers has also been proposed to improve the reliability and safety of pipeline operations, for example, by combining relay protection schemes using high-speed optical sensing and overcurrent detection, or Zonal Selective Interlocking (ZSI) to improve relay protection speed [21]. In addition, the development and implementation of strict operating and maintenance procedures, as well as the training of operator awareness and skills, are also important tools to ensure equipment safety.

However, the current research on structural integrity and safety technology still faces many problems. Firstly, the structural integrity analysis and prediction of equipment are still uncertain under some complex working conditions (e.g., multiple load combinations, material aging, etc.). Secondly, the application of safety technology requires the interplay of preventive and contingency measures, but the boundaries and relationships between them are not clearly defined. Nevertheless, with the development of advanced technologies such as the Internet of Things, big data, and artificial intelligence, as well as breakthroughs in the fields of materials science, failure analysis, and testing technology, it is expected that the structural integrity and safety of multiphase flow separation equipment will be improved.

5. Application of energy-saving and environmental protection technologies in multiphase flow separation equipment

The application of energy-saving and environmental protection technology in multiphase flow separation equipment has received wide attention, and the main contents of the research include improving the separation efficiency of the equipment, reducing energy consumption, and reducing environmental pollution. The traditional multiphase flow separation equipment mainly includes a cyclone separator, sinkhole, flotation machine, air bag, and so on. The advantages of this equipment are its simple structure, convenient operation, and high reliability, but the problems of low separation efficiency and high energy consumption cannot be ignored.

In recent years, the application of energy-saving and environmental protection technologies in multiphase flow separation equipment has achieved some results. For example, some researchers have invented and developed a multi-subordinate equipment central cyclone separator (MSEC) as a new type of cyclone separator, which connects several small cyclones to a tangential cyclone and can improve the collection efficiency while maintaining a low pressure drop. Combining the advantages and disadvantages of the flotation column, some researchers proposed a new type of flotation device: the

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ring inflatable flotation machine. The study shows that the ring inflatable flotation machine has the advantages of low energy consumption, low wear and tear, a high probability of particles and bubbles attaching and colliding, flexible adjustment of the sweeping time and frequency, a wide range of sorting particle sizes, etc. [22]

In addition, researchers are also working to realize more efficient and environmentally friendly multiphase flow separation by introducing new separation principles or new equipment structures. For example, researchers have proposed multiphase flow separation equipment based on microchannel technology, which has a better separation efficiency than traditional equipment and, at the same time, has the advantages of being small, low energy consumption, and environmental protection. Some researchers have developed a new vane-type droplet separator for separation columns based on experimental studies and CFD analysis, which has a higher separation efficiency at the same pressure drop compared with the state-of-the-art standard droplet separator [23]. There are also researchers who developed a new water treatment system, i.e., a mobile magnetic separator system, which consists of three parts, namely, a pre-treatment unit, a rotating membrane separator, and a magnetic separator, which uses long, high-T-c body superconductors (SCs) as permanent magnets. The experimental results show that the system is compact and highly efficient.

In the future, the application of energy-saving and environmental protection technology in multiphase flow separation equipment is promising. With the development of science and technology, people's requirements for the separation efficiency, energy consumption, and environmental protection of equipment will be further improved. Therefore, in-depth research on the application of energy-saving and environmental protection technologies in multiphase flow separation equipment can not only promote the progress of related technologies but also play an important role in energy saving, emission reduction, and environmental protection.

6. Conclusion

In this paper, the following work has been accomplished with respect to the development of multiphase flow separation techniques and equipment and their application in various fields:

(1)An overview of the current state of the art in multiphase flow separation technology is presented, mainly in the areas of physicochemical mechanisms of the separation process, optimization of equipment and methods, modeling and computational simulation, and intelligent separation control.

(2)The intelligent development of multiphase flow separation equipment and the structural integrity and safety technology of multiphase flow separation equipment are analyzed. From the establishment of intelligent separation models and intelligent control to structural integrity, safety technology research, and detection technology, the intelligentization and safety of multiphase flow separation equipment are shown in all aspects.

(3)The application of energy-saving and environmental protection technologies in multiphase flow separation equipment is discussed, and future development trends and challenges are proposed in light of the current research background.

The continuous development of multiphase flow separation technology and the innovation of multiphase flow separation equipment have not only promoted the development of traditional industries such as petroleum and chemical industry but also proposed innovative new and efficient technical support and solutions for the development of medical care, scientific research, and other related aspects. The research in this paper can be well combined with the current scientific research background and future research trends, and it has high practical and academic value.

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