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Research Progress in Treatment of Produced Liquids Using Swirl Gas-Liquid Pre-Separation Techniques

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Abstract

This paper provides an overview and analysis of the current research on swirl separators in the field of gas-liquid separation, emphasizing their utility in processes such as pre-degassing of produced liquids. The review encompasses the development, fundamental design, internal flow characteristics, and operational mechanisms of swirl separators. A comparative analysis of different swirl separator designs is also presented, highlighting the limitations of single-structure parameter optimization and static system analysis in capturing the intricacies of actual operational conditions. The study notes that enhancements in separation efficiency have been achieved through modifications to the external structure and internal flow field of swirl separators by researchers globally, thereby potentially increasing industrial productivity. With the expanding application of gas-liquid swirl separation technology, quantitative numerical research on swirl separators and their internal flow fields is deemed essential for engineering applications. The findings of this research are intended to inform the design and application of gas-liquid swirl separators.

Keywords

Produced Liquids; Gas-Liquid Pre-Separation; Swirl Separator; Research Progress.

1. Introduction

Towards the end of the 19th century, the first swirl separator was developed in the United States, initially with a narrow scope of application. However, by the early 20th century, the technology had matured and started to transition towards commercialization. This development sparked interest across numerous industries, leading to the widespread adoption and accelerated advancement of swirl separators. Initially, these separators were primarily utilized for solid-liquid separation in sectors such as food processing, paper manufacturing, and exploration drilling. In the latter half of the 20th century, as solid-liquid separation technology reached a level of maturity, British scientists enhanced the original solid-liquid swirl separator design through experimental methods to effectively address gas-liquid separation needs. This breakthrough resulted in a patent application in 1978 for a gas-liquid separation swirl separator. This patent has had a significant impact on the treatment of oil, gas, and water separation in oilfield produced liquids, and the technology is now extensively used in major oilfields worldwide[1-7].

The advent of the 21st century has been marked by significant strides in swirl separator research, fueled by the rapid progression in multiple scientific disciplines, the invention of a variety of measuring instruments, and the advent of computer-aided calculation software. This progress has enabled researchers to transcend the previous stages of swirl separator research and delve into new areas of investigation. Specifically, the focus has shifted to understanding the intricate relationships between the internal flow fields, particle dynamics, and separation efficiency of swirl separators through advanced observation and simulation techniques. For example, the study conducted by Karimi and colleagues involved a detailed simulation of the entire oil-water separation process in swirl separators, aiming to elucidate the relationship between separation efficiency and various parameters such as flow velocity and vortex structures during separation. Their findings highlighted a close relationship between the separation efficiency of swirl separators for oil-water separation and the tangential and axial velocities, with the formation of specific vortex deformation structures at the top of the swirl separators. In comparison to the broad analysis by Karimi and others, Dharma and others employed observation instruments to dynamically monitor the swirl separators in real-time, systematically observing and analyzing the entire oil-water separation process[8-11]. They investigated the quantitative relationships between the injection velocity of the oil-water mixture, the proportion of oil or water phase, tangential and axial velocities, and separation efficiency, providing a more nuanced understanding of the separation process in swirl separators. In recognition of the fact that real-world operating conditions may extend beyond the separation of two-phase liquids, Yang and associates have meticulously examined the distribution patterns of dispersed phase particles at the feed inlet of swirl separators. This foundational research has led to the development of diverse swirl separator designs, including the CM, PRM, and RRM models. Through sophisticated simulation techniques, they have analyzed the impact of these designs on particle distribution and separation efficiency, resulting in the formulation of targeted separation mechanism models. Similarly, Safikhani and fellow researchers have utilized simulation to investigate the flow patterns and temporal trajectories of dispersed phase particles within swirl separators. Their insights into the velocity distribution across various swirl separator components have significant implications for structural optimization. To this end, as a plethora of swirl separator structures are proposed, the research emphasis remains on optimizing swirl separator design, parameters, and theoretical advancements to bolster separation efficiency[12-19].

2. Mathematical Model of Flow Field of Swirl Separator

2.1 Main Parameters of Gas-liquid Two-phase Flow

(1) Flow rate[20]

The mass flow rate M of the gas-liquid two-phase refers to the sum of the mass flow rates of the gas-liquid two-phase mixture flowing through the cross section of the pipeline per unit time:

$$M = M_g + M_l \tag{1}$$

Where M_g is the mass flow rate of the gas phase and M_l is the mass flow rate of the liquid phase, kg/s.

The gas-liquid mixture volume flow rate Q refers to the sum of the fluid volume flow rate of the gas-liquid two-phase mixture flowing through the cross section in the pipeline per unit time:

$$Q = Q_g + Q_l \tag{2}$$

Where Q_g is the volume flow rate of the gas phase and Q_l is the volume flow rate of the liquid phase, m^3/s.

(2) Flow velocity

In the gas-liquid two-phase pipeline, the circulation areas occupied by the gas-liquid two phases are *Al,* Ag respectively, and the average velocity of the gas phase (also known as the true velocity of the gas phase) v_g refers to the average velocity of the gas phase in its cross section, the unit is m/s:

$$v_g = \frac{Q_g}{A_g} \tag{3}$$

Similarly, the average velocity of the liquid phase v_l, also known as the true velocity of the liquid phase, is in m/s:

$$v_l = \frac{Q_l}{A_l} \tag{4}$$

The gas phase converted velocity j_g refers to the velocity of the gas phase when it flows alone through the cross section of the pipe, and the unit is m/s:

$$j_g = \frac{Q_g}{A} \tag{5}$$

Similarly, the liquid phase conversion velocity j_l, in m/s:

$$j_l = \frac{Q_l}{A} \tag{6}$$

Here, A is the circulation area of the pipeline, $A=A_l+A_g$, and the unit is m^2.
Gas-liquid two-phase mixing speed j_{gl}, m/s:

$$j_{gl} = \frac{Q_l + Q_g}{A} \tag{7}$$

(3) Gas content and liquid content
Section gas hold-up α_g denotes the ratio of gas phase cross-sectional area A_g to cross-sectional area A flowing through the pipeline in unit time:

$$\alpha_g = \frac{A_g}{A} \tag{8}$$

Section liquid hold-up α_l denotes the ratio of the liquid phase cross-sectional area A_l and cross-sectional area A flowing through the pipeline in unit time:

$$\alpha_l = 1 - \alpha_g = \frac{A_l}{A} \tag{9}$$

The volume gas hold-up ζ denotes the ratio of the volume flow rate Q_g of the gas phase flowing through the cross section of the pipeline per unit time to the total volume flow rate Q:

$$\zeta = \frac{Q_g}{Q} \tag{10}$$

Volume effusion holdup $1\text{-}\zeta$, which represents the ratio of the liquid volume flow rate Q_l flowing through the cross section of the pipeline to the total volume flow rate Q per unit time:

$$1 - \zeta = \frac{Q_l}{Q} \tag{11}$$

(4) Viscosity of mixture

For the viscosity calculation of homogeneous gas-liquid two phases, there are mainly the following four kinds:

Dukler' calculation method:

$$\mu_{gl} = \zeta\mu_g + (1 - \zeta)\mu_l \tag{12}$$

McAdams' calculation method:

$$\frac{1}{\mu_{gl}} = \frac{\alpha_g}{\mu_g} + \frac{1 - \alpha_g}{\mu_l} \tag{13}$$

Ciecchеitti' calculation method:

$$\mu_{gl} = \alpha_g\mu_g + (1 - \alpha_g)\mu_l \tag{14}$$

Arrhenius' calculation method:

$$\mu_{gl} = {\mu_l}^{\alpha_l}{\mu_g}^{1-\alpha_l} \tag{15}$$

Where μ_g is the dynamic viscosity of the gas phase, Pa·s; μ_l is the dynamic viscosity of the liquid phase, Pa·s; μ_{gl} is the viscosity of the gas-liquid hybrid, Pa·s.

2.2 Main Models of Gas-liquid Two-phase Flow

The interaction between gas and liquid phases in two-phase flows is complex, and the flow patterns can vary depending on their relative distribution. The existing computational methods for two-phase flows can be broadly categorized into two types. The first involves model simplification, where empirical data from practical engineering applications are analyzed based on experimental observations and outcomes. This approach relies on certain physical assumptions to establish simplified physical models of two-phase flows, resulting in empirical equations and solutions. The second method is the analytical mathematical model, which employs fluid dynamics to formulate differential mathematical equations describing the two-phase flow. However, the complexity of two-phase fluid flow often precludes direct solution of these equations. This paper primarily discusses the model simplification analysis method. When applied to the analysis of flow fields in swirl separators, this method first analyzes the two-phase flows separately, treating the gas and liquid phases as distinct fluids. Subsequently, the two phases are considered as single-phase flows for analysis, which is applicable to various flow patterns within pipes.

(1) Mass equation

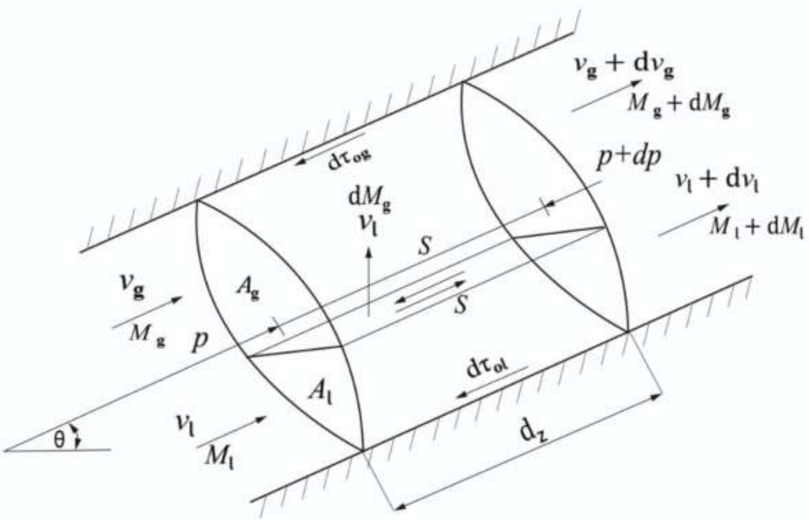

Fig. 1 Model of two-phase flow in micro-element pipe section

The two-phase flow model in a unit length tube is shown in Figure 1, and the continuity equation is listed for each phase:

$$\frac{d(\rho_g \alpha_g A)}{dt} + \frac{d(\rho_g v_g \alpha_g A)}{dz} = \delta \dot{m} \tag{16}$$

$$\frac{d[\rho_l(1-\alpha_g)A]}{dt} + \frac{d[\rho_l v_l(1-\alpha_g)A]}{dz} = -\delta \dot{m} \tag{17}$$

Here, ρ_g is the gas phase density and ρ_l is the liquid phase density in kg/m3. $\delta \dot{m}$ is the momentum exchange rate of gas-liquid two phases.

(2) Momentum equation

The momentum equation of the liquid phase is as follows:

$$\begin{gathered}(1-\alpha_g)\frac{\partial p}{\partial z}+\frac{\tau_{ol}P_{hl}}{A}-\frac{\tau_i P_{hi}}{A}+\rho_l g(1-\alpha_g)\sin\theta \\ +\frac{\partial}{\partial t}[\rho_l(1-\alpha_g)v_l]+\frac{1}{A}\frac{\partial}{\partial t}[\rho_l A(1-\alpha_g)v_l^2]+\frac{\delta\dot{m}}{A}v_i=0\end{gathered} \tag{18}$$

Here, τ_{ol} is the liquid-phase shear stress in Pa. P_{hl} is the perimeter length of the liquid phase control volume in m. v_i is the velocity of the gas-liquid two-phase interface in m/s.

Furthermore, the gas phase momentum equation is given by:

$$\begin{gathered}\alpha_g\frac{\partial p}{\partial z}+\frac{\tau_{og}P_{hg}}{A}+\frac{\tau_i P_{hi}}{A}+\rho_g g\alpha_g\sin\theta \\ +\frac{\partial}{\partial t}[\rho_l\alpha_g v_l]+\frac{1}{A}\frac{\partial}{\partial t}[\rho_g A\alpha_g v_g^2]-\frac{\delta\dot{m}}{A}v_i=0\end{gathered} \tag{19}$$

Here, τ_{og} is the gas-phase shear stress in Pa. P_{hg} is the perimeter length of the gas-phase control volume in m. By adding Equations (18) and (19), the mixed momentum equation of gas-liquid two-phase fluid in stable flow can be written as:

$$-\frac{\partial p}{\partial z}=\frac{\tau_o P_h}{A}+\rho_o g\sin\theta+G^2\frac{\partial}{\partial z}\left[\frac{(1-x)^2}{\rho_l(1-\alpha_g)}+\frac{x^2}{\rho_g\alpha_g}\right] \tag{20}$$

Where, x is the mass hold-up fraction, which is expressed as $x=M_g/M$, and G is the mass flow velocity in kg/(m^2 s).

3. Working Principle and Characteristics of Swirl Separator

3.1 Working Principle of Swirl Separator

Swirl separator operate on the principle of utilizing their distinctive structure to induce swirling motion in a medium that enters with an initial velocity, thereby separating phases of varying densities. The efficacy of this separation process is inherently dependent on the density differences between the phases. Furthermore, the separation efficiency of a swirl separator is also influenced by its structural design and the dimensions of its components. Consequently, the design of a swirl separator involves a critical phase of structural optimization. For different practical applications, the dimensions of the designed swirl separator may need to be adjusted accordingly[5-7].

The conventional swirl separator design, as illustrated in Figure 2, primarily comprises a cylindrical section and a conical section, featuring an inlet for the mixture, as well as separate outlets for overflow and underflow. Across various swirl separator models, the fundamental operating principle remains the same: centrifugal separation driven by the density disparity between non-mixing media. During operation, the denser medium is propelled towards the peripheral wall, while the less dense medium migrates towards the axis. Consequently, media of distinct densities are expelled through the respective outlets of the swirl separator[10, 12-15].

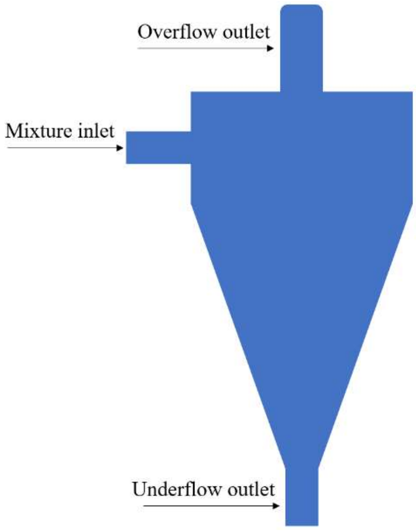

Fig.2 Basic structure diagram of swirl separator

In the operational cycle of a swirl separator, multiphase media are introduced through an inlet, which is aligned tangentially to the cylindrical section's interior wall. The media, propelled by an initial velocity and confined by the structure, initiates a spiral trajectory within this section. During this phase, the lighter gas phase engages in vortex motion, resulting in a radial decrease in internal pressure, reaching a minimum, almost zero, at the central axis. Concurrently, the rotational motion induces varying centrifugal forces on the gas and liquid phases due to their density disparity. The liquid phase, subjected to a greater centrifugal force, migrates towards the wall, whereas the gas phase is directed towards the center. The conical section of the swirl separator is meticulously designed to intensify the swirling effect. As the cone diameter diminishes, the medium experiences augmented centrifugal forces, leading to increased rotational velocities and, consequently, a more potent centrifugal action. This phenomenon accentuates the divergent movement of the gas and liquid phases, with the liquid phase forming an outer swirling motion adjacent to the wall and the gas phase converging at the center axis to create an inner swirling motion, executing an ascending spiral trajectory[16, 17].

In the swirl separator, the way the fluid moves and changes can be split into different types: outer swirl, inner swirl, short circuit flow, circulating flow, a surface where the axial velocity is zero, a surface tracing the max tangential velocity, and an air column. The outer and inner swirls are the main ways the fluid moves around in the swirl separator. They spin the same way, in a spiral, but they move in opposite directions along the axis. The outer swirl, because of the density difference between phases, is usually the heavy stuff and gets pushed out the bottom. The inner swirl is the light stuff and spirals up towards the top outlet. The zero axial velocity envelope is a special surface inside the swirl separator, made up of points where the axial velocity is zero on different sections, shaping a cone that really affects how the flow works. Short-circuit flow and circulating flow are two tricky flow patterns because of the swirl separator's design. Short-circuit flow is when a bit of liquid slides along the wall without separating and sneaks out the top outlet. Circulating flow happens because some of the liquid in the inner swirl can't get out the top and keeps mixing with new stuff coming in, swirling from top to bottom in a loop. The max tangential velocity trajectory surface is a cylindrical surface inside the swirl separator, made up of spots where the fluid is spinning the fastest, dividing the swirl into a forced vortex on the outside and a free vortex on the inside. The air column pops up because the swirl separator's outlet lets air into the low-pressure zone in the middle, and also because some of the gas that was dissolved in the liquid inside the swirl separator comes out[17-20].

3.2 Characteristics of Swirl Separator

The swirl separator is characterized by its multifunctionality and strong adaptability. It features a relatively simple structure. It offers a relatively high level of separation efficiency. Its compact size facilitates installation and reduces transportation costs. It is flexible and convenient to use. It is easy to operate and capable of continuous operation[1-6].

4. Research Status and Disadvantages of Gas-liquid Swirl Separator

4.1 Research Status

The current research on swirl separators, which are pivotal in gas-liquid separation processes, is concentrated on several primary areas[4, 6, 9-12]:

(1) Optimization of swirl separator configuration and operational parameters. The structure, inlet flow rate, and concentration of the dispersed phase significantly impact the efficiency of gas-liquid separation in swirl separators. Selecting appropriate parameters not only achieves the desired separation outcomes but also markedly enhances the separation efficiency of the swirl separators.

(2) Coupling enhancement of swirl separators with other physical fields. In response to increasingly complex production conditions and escalating production demands, the integration of other operational units with centrifugal separation is being explored to intensify gas-liquid separation. This includes the use of coupled pulsed electric fields in conjunction with the swirling centrifugal field, leveraging the pulsed electric field for rapid droplet aggregation and the swirling centrifugal field for efficient removal of droplets and impurity particles, thereby synergistically enhancing the efficiency of gas-liquid separation processes.

(3) Theoretical research on swirl separators. This involves investigating the mechanisms of swirling flow, elucidating separation mechanisms, and employing CFD (Computational Fluid Dynamics) technology for numerical simulation to construct turbulent vortex flow models. This enables quantitative analysis and research on the gas-liquid separation process and prediction of the flow field within the swirl separator. Of particular interest in current research are the optimization of the structural design of the main and inlet parts of the swirl separator and the study of the swirl separator separation mechanism.

4.2 Lack of Research

(1) Swirl separators require stringent operating conditions. These separators are tailored to specific applications, with defined capabilities for handling certain media and flow rates. Deviating from these specifications, either by altering the medium or exceeding the design flow limits, can compromise separation performance. Significant deviations may result in the swirl separator failing to achieve its intended purpose or losing its separation functionality altogether[13, 15-18].

(2) The separation process is highly targeted. Swirl separators are sized based on the particle sizes and separation requirements of the specific application. Consequently, they are effective in separating particles within a particular size range. In gas-liquid separation, the separating property is significantly influenced by the particle size, with smaller particles posing greater challenges. Typically, swirl separators are designed to separate particles within a specific size range, with smaller particles often not being effectively separated. Additionally, the shear forces generated during separation can break droplets, reducing their size and exacerbating emulsification.

(3) Shear effects are inherent. The rotational movement essential for separation in swirl separators also generates shear forces. These forces can break down droplets, reducing particle size and complicating the separation process. Alternatively, it can be understood that the mixed medium entering the swirl separator must be within a certain velocity range. Exceeding this range can result in shear forces that severely impede the separation process, causing a sharp decline in efficiency. Moreover, the shear action introduces numerous smaller particles into the medium, substantially increasing the difficulty of separation.

5. Summary

This paper dives into the history, basic structure, separation mechanism, and working principle of swirl separators. It also looks at where we're at now with using them for gas-liquid separation. It's clear that swirl separators have come a long way, but there's still a lot we don't know. Years of research and real-world use, both at home and abroad, show that these separators have a wide range of applications. But, we're still playing catch-up when it comes to understanding the swirling flow field. We don't have a solid grasp on the internal flow field yet, and there's no clear formula linking flow rate and pressure drop. Plus, we're still struggling to get precise theoretical solutions for the pressure and velocity fields in the guide vanes of axial flow swirl separators. This is definitely an area worth digging into more. Future research needs to focus on beefing up our theoretical understanding of the internal flow field, so we can make these separators even more efficient in the real world.

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