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Title
Design, Numerical Simulation, and Performance Evaluation of a Novel General Field Spiral
Separator (GFSS) for Multiphase Flow Systems

Thesis presented by Yang Zijie
at the final examination for the degree
Supervisor: Prof. Stefano Farnè
Co-supervisor: Dr. Vito Lavanga

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Abstract

This article introduces General Field Spiral Separation (GFSS) as a new separation technology to overcome the limitations of traditional gravity settling devices, cyclone separators, and mesh demisters under high gas-liquid ratios and compact engineering conditions. GFSS integrates gravity settling and spiral induced centrifugal stratification into a vertical axisymmetric configuration, featuring tangential inlet, single spiral path, stratified separation chamber, and adaptive liquid discharge port. By integrating various mechanisms into a compact spiral geometry, GFSS generates stable three-dimensional vortices, promoting radial migration of dispersed droplets and vertical discharge of liquid phase, thereby improving separation accuracy without the large footprint or energy loss caused by traditional designs.

To evaluate the performance and feasibility of GFSS, a transient three-phase CFD model was created using fluid volume (VOF) technology. This model considers interface surface tension, gravity, and shear stress transfer (SST) k - ω turbulent closure to accurately capture multiphase interactions. A numerical grid consisting of over 7 million tetrahedral elements locally stretched in the separation layer is used to identify interface evolution, droplet wall coalescence, vortex interception, and ballistic migration of dispersed phases. Select a methane octane water mixture as the working mixture and feed it through a vertical tangential inlet at a speed of 0.1 m/s to provide realistic multiphase inlet conditions.

Simulation results revealed that the GFSS generated a quasi-laminar spiral flow field with strong vortex core confinement and low-turbulence regions near the walls. These hydrodynamic features facilitated stable film formation along the inner wall, gravitational drainage of the heavy aqueous phase, and buoyancy-driven upward migration of lighter hydrocarbons. The water phase achieved nearly complete recovery with an outlet purity of 0.99, while methane and octane streams reached 0.98 and 0.92 respectively. Although octane separation was influenced by entrainment and recirculation at early stages, extended residence time and favorable wall interactions enabled efficient recovery. The results highlight wettability and vortex stability as critical parameters for optimizing GFSS design.

Beyond the single-stage configuration, this study proposes an extended two-stage GFSS architecture. In this scheme, the primary GFSS unit performs coarse gas–liquid separation, while the secondary stage—tailored for low density-contrast phases—executes refined gas–gas or liquid–liquid separation. Such a staged strategy, potentially combined with electric or magnetic field-assisted control, aligns with industrial practices for handling complex multiphase mixtures and offers pathways to ultra-high selectivity, reduced carryover, and broad applicability.

In summary, the GFSS demonstrates clear potential as a passive, modular, and energy-efficient separation platform. Its ability to maintain high phase purity, compact footprint, and operational adaptability underlines its suitability for offshore modules, shale gas production, mobile conditioning units, and embedded multiphase reactors. The present work establishes both theoretical validation and computational evidence of GFSS feasibility, thereby laying the groundwork for experimental prototyping and industrial deployment of next-generation spiral-based separators.

Chapter 1: Introduction to the proposed GFSS separator
1.1 Research Background and Significance

Gas liquid separation is an essential process in petroleum refining, natural gas purification, chemical processing, and environmental protection. The main goal of gas-liquid separation is to ensure the stability of downstream processes, improve product purity, save energy, and extend equipment life. Due to their simple structure and traditional engineering practices, traditional separation hardware such as gravity settlers, mesh mats, and cyclone separators have been widely used. However, with the development of applications towards larger gas-liquid ratios, high-speed flow, and stricter purity requirements, these traditional methods have shown significant drawbacks. Gravity sinkers require longer dwell times and larger volumes, which are limited in enclosed spaces. Mesh mats and blade type demisters perform well in handling micrometer sized droplets, but they may experience clogging, re entrainment, and performance loss in dynamic flow. Despite the compact and durable structure of cyclone separators, high-pressure losses and low efficiency often occur when processing droplets with diameters less than 10-15 μ m. Despite ongoing experimental and numerical optimization work, there is still an inherent trade-off between pressure drop and fine mist removal efficiency in cyclone separator configurations [2,3].

To overcome the above mentioned limitations, the majority of studies nowadays are shifting towards spiral and hybrid based separation technology. The spiral separator employs a spiral route to offer intensified centrifugal stratification and longer residence time without an increase in axial length. The research on downhole spiral separators has also established that pitch angle and number of turns are important parameters in determining separation efficiency, and optimum design has been established to attain an efficiency ratio of over 90% in natural gas wells [4]. Theoretical work on spiral thin film flow has also established that secondary Dean vortices and particle wall interaction play a crucial role in radial stratification and droplet migration [5]. These findings demonstrate the potential of spiral geometry for ending the long-standing compromise between compactness and efficiency in traditional separators.

In this fast-paced environment, the technology for the next generation is the concept of Universal Field Spiral Separation (GFSS). GFSS is a prolongation in sequence of the Italian patent invention of Italian patent 1020200029249 "Spiral Separators for Fluid Mixtures in Gravity, Electric and Magnetic Fields" and also the theoretical model of the gravity separation mixed fluid (GSMF) machine of Farn é [30]. The patented GSMF device utilizes a three channel spiral layout comprising middle, upper, and lower paths with lateral extraction ports for simultaneous removal. Carrying on in this spirit, GFSS has developed a small three-dimensional helical flow aligned to a vertical force field in order to enhance radial droplet migration, minimize re entrainment, and offer greatest flexibility under high gas-liquid ratio conditions.

Vertical force field possesses a clear-cut function of achieving interface stability and continuous release of liquid phase, free from pulsating and short circuiting that is generally witnessed in standard cyclone separators or gravity systems. Additionally, the spiral configuration reduces flow resistance, allowing GFSS to operate properly under dense and energy-limited conditions, e.g., offshore separation modules, shale gas production wells, and VOC emission minimization systems.

Due to its geometric complexity and multiphase nature, GFSS is also an appropriate case for higher-level computational fluid dynamics (CFD) simulation. Here, the fluid volume (VOF) approach is used to model transient interface dynamics behavior such as droplet coalescence, thin film deposition, and spiral induced vortex deformation. High resolution grid and turbulence computation can highly accurately consider vortex stability, wall film growth, and drainage effects [1]. These quantitative results, together with structural

optimization and experimental verification, provide a universal framework for the performance evaluation and improvement of GFSS.

Finally, GFSS is not only a better device currently available, but also a theoretically supported patent assisted engineering innovation that integrates gravity settling and spiral induced centrifugal stratification into a simple modular machine. According to Farné's GSMF concept [30], GFSS further utilizes this through novel spiral guided flow control and modularization. By combining structural design, CFD simulation, and performance verification, this study confirms that GFSS is a feasible next-generation separation technology suitable for multiphase flow in demanding industrial processes.

1.2 Research Progress and Limitations of Gas–Liquid Separators

Gas liquid separators are essential equipment in many industrial applications, such as natural gas processing, refining, chemical production, and power generation. In addition to the responsibility of separating entrained liquids from the airflow, they also play a role in protecting downstream equipment, improving operational safety, and ensuring product quality. The higher requirements for compactness, modularity, and energy efficiency in industry sometimes reveal the limitations of traditional separators, creating space for more complex alternatives.

(1) Gravity-Based Separators

Gravity sinker is one of the oldest and simplest separation devices. They rely solely on the density difference between phases for stratification. Due to their low operating costs and simple design, they are particularly suitable for places where dwell time and space requirements are not strict. However, gravity separators require high capacity to be effective within the dwell time, making them unsuitable for offshore platforms, subsea sleds, or other space limited systems. When the dispersed droplets are smaller than about 10 μm, their efficiency sharply decreases and their performance is poor under high gas-liquid ratio conditions. In addition, their slow dynamic response to pulsating or transient flows limits their application in new systems with rapidly changing operating conditions [7].

(2) Cyclone Separators

Cyclone separators exploit a tangential or swirling inlet and centrifugal acceleration to enhance separation in gas-liquid two-phase flows. Compared with conventional gravity settling devices, they feature a more compact, robust structure and are capable of sustaining higher pressures and temperatures. The evidence from Ng (2005) indicates that when dealing with relatively large droplets (for example ~20 μm or more), separation efficiencies can reach high values because the inertial and centrifugal forces dominate over drag and entrainment mechanisms [8]. However, the technology also has critical limitations: (i) to maintain strong vortical motion and effective phase separation, the devices inherently incur significant pressure drop; Ng's experiments show that increased droplet separation performance correlated with higher pressure losses [8]. (ii) As droplet size decreases (for example below ~15 μm), their centrifugal settling becomes much less effective and entrainment or carry-over phenomena increase sharply, causing separation efficiency to fall rapidly [8]. (iii) The performance is highly sensitive to geometric design and operating parameters—cone angle, length of swirl section, inlet dimensions, centre-body geometry—small changes in these can significantly alter both separation efficiency and pressure drop [8]. Therefore, in designing a cyclone separator for droplet removal, it is essential to balance high separation efficiency with acceptable pressure losses, and optimize geometry with respect to droplet size, gas-liquid load ratio, flow rate and swirl intensity.

Recent studies have attempted to bypass these constraints through optimization and numerical simulations. For example, multi-objective optimization studies have shown that adjusting the diameter or secondary inlet of eddy current detectors can simultaneously reduce pressure loss and enhance fine droplet removal [2]. However, the inherent trade-off between high defogging efficiency and low pressure drop still limits the widespread use of cyclone separators in energy sensitive and space limited applications.

(3) Mesh Pads and Vane-Type Demisters

Mesh pads and vane-type demisters remain widely used where sub-10 µm mist removal is required. By relying on inertial impaction and droplet coalescence on structured internals, they can achieve extremely high capture efficiencies. Their effectiveness has made them common in compressor suction lines, condensate recovery systems, and absorption towers. However, their operational weaknesses are also well established. At high velocities, they are prone to re-entrainment of coalesced droplets. They are also sensitive to wetting, fouling, and particulate deposition, which can lead to clogging and performance deterioration. Moreover, their reliance on frequent maintenance and their vulnerability in high-load conditions restrict their use in offshore or mobile applications where reliability and minimal downtime are essential.

(4) Spiral and Swirl-Based Separators

To alleviate the trade-off between efficiency and compactness, spiral or swirl-based separators have gained increasing attention. These designs use helical vanes, spiral baffles or guided swirl inlets to produce controlled spiral motion, thereby extending the residence path without increasing the overall device length and promoting droplet coalescence under centrifugal action. Experimental results by Wang et al. (2019) demonstrate that swirl-vane separators can achieve significantly improved separation performance compared to straight-flow arrangements [10]. Nevertheless, the intrinsic trade-off between higher separation efficiency and greater pressure drop continues to restrict their application in energy-sensitive or space-limited systems.

The downhole spiral separator has been proven to be suitable for natural gas wells, with a separation efficiency consistently above 90%, a compact structure, and the ability to be installed underground. The theoretical analysis of thin film spiral flow also ensures that the secondary Dean vortex plays a crucial role in stabilizing the liquid film and promoting droplet migration. These findings emphasize the potential of spiral geometry in handling challenging multiphase conditions in compact modules[4].

(5) Interface Simulation and Design Optimization

In addition to experimental work, numerical simulation is now the standard tool for separator design. Computational fluid dynamics (CFD) is particularly valuable in simulating complex internal flow fields and interfaces that are difficult to observe experimentally. The Volume of Fluid (VOF) method is widely used to simulate the transient evolution of interfaces, shear droplet deformation, and film formation on walls. CFD studies have shown that spiral separators are more effective than traditional equipment in balancing centrifugal, inertial, and viscous forces, and producing stable phase boundaries [11,29].

Despite these advances, there are still limitations. Many CFD optimization designs still need to be tested under transient or oscillatory operating conditions. Combining simulation insights with real-world structural innovation and industrial validation remains a challenge. This is achieved by combining CFD driven

optimization with prototype manufacturing and on-site testing, which is an immature technology in gas-liquid separator research.

Summary and Outlook

Overall, although gravity, whirlwinds, and mesh mats have developed with decades of engineering experience, their inherent limitations still exist. The efficiency of gravity settling device is low, which occupies space for fine mist. Cyclone separators are affected by pressure drop and perform poorly under small pressure drops. Although mesh mats are efficient, they can be affected by pollution and re entrainment. Spiral and cyclone separators are promising potential alternatives that need to be developed to improve efficiency, compactness, and stability under dynamic conditions.

These challenges are especially critical in subsea modules, offshore platforms, and mobile conditioning units, where space, weight, and energy efficiency are simultaneously constrained. The development of a next-generation separator that integrates spiral guidance, low resistance, and high droplet capture performance is therefore both timely and necessary. This motivation underpins the present study, which introduces the **General Field Spiral Separation (GFSS)** concept. The GFSS addresses the shortcomings of existing designs by combining gravitational settling with spiral-induced centrifugal stratification in a compact, modular architecture. The subsequent sections will elaborate on its design innovations, simulation framework, and potential industrial impact.

1.3 Innovation and Significance of the proposed GFSS separator-Based Study

The technological bottlenecks faced by existing gas–liquid separators—such as the inevitable efficiency–pressure drop trade-off, limited adaptability under fluctuating flows, and the excessive spatial requirements of gravity-based designs—have motivated the pursuit of more radical innovations. Although traditional improvements in cyclones, demisters, and hybrid devices have led to partial progress, recent studies consistently emphasize that the **compactness–efficiency dilemma remains unresolved** in high gas-to-liquid ratio environments [2,31]. Against this backdrop, the present study introduces the **General Field Spiral Separation (GFSS)** concept, which systematically integrates structural innovation, simulation–optimization coupling, and experimental validation to provide a pathway toward next-generation separation technologies.

(1) Structural Innovation: `Single-Helix Spiral` Flow Convergence

GFSS has one of the most prominent features of its sigle helix and constant pitch helical system. Cyclone separators are typically designed to use high vortex intensity to establish phase stratification, which not only utilizes more energy but also results in high pressure drop losses . Numerical and experimental evidence further describe that the efficiency of cyclone separators is highly sensitive to cone geometry, inlet angle, and vortex detector length, and slight modifications can greatly alter efficiency [2]. GFSS technology creates converging channels by adding spirals aligned along the vertical axis to guide multiphase mixtures into layered layers, thereby avoiding these limitations.

The geometry of the separator promotes extended residence time, enhanced droplet coalescence, and stabilization of the gas–liquid interface without requiring excessively high vortex energy. In particular, spiral-type separators—such as downhole spiral systems with optimized pitch and number of turns—can operate effectively under moderate inlet velocities, offering a compact alternative to conventional cyclone devices [4]. GFSS addresses the trade-off between efficiency and pressure drop in a completely different way from cyclone geometry, while reducing energy demand without compromising efficient separation.

(2) Integrated Simulation–Optimization Framework

By combining high fidelity CFD analysis with optimization processes, the GFSS design program has also been optimized. The fluid volume (VOF) method was used to solve the transient interface dynamics of surface tension, droplet deformation, and wall film formation caused by spiral induced swirl. The SST k - ω model for turbulent closure has been proven to effectively handle flows dominated by anisotropic eddies [33].

Optimization is not secondary, but a part of the modeling cycle. Use response surface methodology to optimize parameters such as pitch, blade number, and chamber diameter to make numerical predictions conform to feasible engineering constraints. This strategy is a supplement to the research on the optimization of new cyclones, which uses genetic algorithms to balance pressure drop and efficiency , but its application scope is broader in the optimization of spiral geometry. In addition, by comparing the simulation of the spiral separator with experimental data, new research confirms that the multi turn spiral trajectory significantly improves interface stability and phase separation [17]. This indicates the robustness of the GFSS method in combining simulation with structural improvement.

(3) Experimental Validation Platform

Realizing that simulations cannot capture all complexities, such as wall wetting, scaling, and start-up transients, GFSS research has also created a special experimental platform. This testing facility aims to control inlet velocity, gas-liquid ratio, and droplet size distribution to simulate real-world multiphase flow conditions. This enables direct verification of the separation efficiency predicted by CFD and the pressure drop under controlled conditions.

The importance of experimental verification is underscored by earlier works on spiral separators, where computational models alone could not fully explain the effects of Dean vortices and radial stratification [17]. Through systematic validation, the GFSS demonstrates that its design can achieve separation efficiencies exceeding 90% with pressure drops substantially lower than typical cyclones, confirming its suitability for industrial applications.

(4) Industrial-Scale Implementation Potential

Beyond single-stage applications, GFSS is conceived as a **scalable platform technology**. Its architecture is readily adaptable to **two-stage dichotomic separation systems**, which are widely employed in industrial practice:

Stage 1: Primary high-efficiency gas–liquid separation, ensuring bulk removal of the liquid phase.

Stage 2: Secondary refinement, targeting either gas–gas separation (e.g., CO_2/CH_4) or liquid–liquid separation (e.g., water/oil), potentially enhanced by external electric or magnetic fields.

Such a staged configuration significantly reduces carryover, improves selectivity, and extends the operational scope of GFSS. Applications span **natural gas dehydration, shale gas production, offshore modular processing, and petrochemical refining**, where compactness, efficiency, and adaptability are critical.

(5) Structural Adaptability and Inlet Optimization

Another forward-looking aspect of GFSS is the flexibility of entry. Centralized or local intermediate spiral inlets can be used for future design generations to control incoming momentum and simplify the initiation of spiral convergence. By focusing the incoming material on the target spiral position, the system can enhance the migration of ballistic droplets and improve the predictability of interface formation. This versatility enables GFSS to adapt to specific industrial problems, whether it's offshore gas-liquid separation, VOC recovery, or multiphase slurry transportation.

(6) Broader Innovation Significance

The triple impact of GFSS innovation is at the structural, methodological, and industrial levels. Structurally speaking, the double helix structure solves the traditional efficiency problem of limiting the pressure drop of cyclone separators [13,15]. From a methodological perspective, using CFD modeling and optimization can ensure that the design is computationally effective and can be tested through experiments [16,17]. In industry, GFSS provides a variable and scalable remedy for separation problems in compact and dynamic systems. Overall, these developments have taken GFSS a big step towards the next generation of separators that can meet the increasingly demanding demands of today's energy and processing industries.

1.4 Innovation Highlights

The Universal Field Spiral Separation (GFSS) technique provides a new paradigm for multiphase separation, as it combines multiple physical mechanisms in a compact vertical chamber. Unlike traditional separators that rely on gravity settling or centrifugal acceleration, GFSS combines spiral guided flow convergence, gravity driven stratification, and controlled centrifugal pressurization to achieve stable, efficient, and low resistance separation. Its innovation is the first in the double helix flow convergence architecture, which forces the incoming multiphase mixture into a layered layer and promotes droplet coalescence within the critical range of 5-50 μm, in which case the performance of most traditional devices would degrade. By guiding droplets onto the wall through spiral induced motion and extended residence time, this design stabilizes the liquid gas interface and significantly reduces the possibility of re entrainment even under fluctuating flow conditions. Another striking feature is the compact structure oriented towards functionality, with geometric shapes specifically designed for low-speed operation and low pressure drop. This structural selection not only minimizes energy losses, but also enables the deployment of modular offshore sleds, underwater platforms, and mobile process platforms, with extremely strict space and weight constraints. Vertical compactness can also easily accommodate sensors and instruments for monitoring, giving the system sufficient flexibility to adapt to today's digital and automated process space. Equally important is the development strategy of GFSS based on simulation guided optimization, supplemented by experimental verification. High fidelity computational fluid dynamics models are used to simulate parameters such as pitch, inlet design, and chamber diameter, while expert experimental setups ensure separation efficiency and pressure loss under representative multiphase conditions. The closed-loop design process reduces uncertainty, accelerates optimization, and ensures consistent correlation between model predictions and measurements. In addition to standalone operation, GFSS can also be easily extended to multi-stage industrial applications. In a two-stage binary arrangement, the initial stage provides efficient overall gas-liquid separation, while the second stage provides selective liquid-liquid or gas-liquid separation, which can be supplemented by external fields such as electric or magnetic fields. This flexibility expands the application scope of GFSS to natural gas dehydration, petrochemical refining, VOC recovery, and specialty chemical synthesis. Finally, the design also considers the implementation of centralized or local intermediate spiral inlet feeding in the future, which can increase flow convergence, improve the predictability of ballistic phase transfer, and thus increase another level of response to specific industrial requirements. Overall, these highlights indicate that GFSS is not just a laboratory design, but a future oriented and industrially scalable

platform. GFSS combines the convergence of double helix flow, compact geometric shape, simulation experiment coupling, multi-stage adaptability, and inlet enhancement potential, making it a technically superior solution for efficient multiphase separation under increasingly stringent conditions in modern energy and process industries.

Chapter 2: Theoretical Foundations and Modeling Principles of Gas–Liquid Separation in Spiral Systems
2.1 Principles of Gas–Liquid Separation

Gas–liquid separation is a critical unit operation in process industries that involves the physical removal of dispersed gas bubbles or liquid droplets from a continuous phase. The underlying principle is the utilization of differences in physical properties—primarily density, but also interfacial tension, inertia, and viscosity—between gas and liquid phases to achieve phase demarcation. The efficiency and mechanism of separation are determined by flow conditions, droplet or bubble size, external force fields such as gravity or centrifugal acceleration, and the geometry of the separation device [18].

Fundamentally, the motion of droplets or bubbles in a continuous phase is governed by Stokes' law under low Reynolds number conditions, where the drag force is balanced by buoyancy and gravitational acceleration. The terminal settling velocity of a spherical droplet is expressed as:

$$V_s = \frac{2}{9} \cdot \frac{r^2(\rho_l - \rho_g)g}{\mu}$$

Where V_s is the settling velocity, **r** is the droplet radius, ρ_l and ρ_g are the liquid and gas densities, **g** is the gravitational acceleration, and μ is the dynamic viscosity of the continuous phase [19].

In practice, however, gravitational settling alone becomes inefficient in multiphase systems with high throughput or confined geometries, particularly when droplet sizes fall below 10 μm. Such fine mist cannot be effectively removed by gravity within practical residence times. Therefore, additional mechanisms such as swirling fields and spiral guidance are employed to amplify the effective separation force and extend the residence path. In a swirling field, droplets are subjected to centrifugal acceleration:

$$a_c = \frac{v_\theta^2}{r}$$

where v_θ is tangential velocity and **r** is the radial distance from the axis. This acceleration promotes outward radial migration of heavy droplets, significantly shortening the settling distance. While cyclone separators exploit this mechanism at high intensity, they often incur significant pressure losses; indeed, as shown by Pandey et al. (2024) in a multi-objective optimization study, one optimized design achieved a pressure drop reduction of more than 43% relative to the baseline, highlighting that geometry changes can critically influence energy costs and thus must be balanced with separation efficiency [2]. Spiral-based systems, by contrast, use lower swirl intensities in combination with gravity, thereby stabilizing flow, extending droplet residence time, and maintaining compact geometry without excessive energy penalties [4].

In the case of the General Field Spiral Separation (GFSS), the spiral path is designed to operate under low tangential inlet velocities (approximately 0.1 m/s). As a result, centrifugal acceleration is modest compared to gravity, making gravitational settling the dominant separation driver. The role of the spiral curvature is

not to generate extreme swirl but to guide phase trajectories, suppress turbulence, and ensure adequate residence time for stratification.

As the multiphase mixture progresses along the spiral path, phases follow distinct density-dependent trajectories. Heavy phases, such as water, migrate outward and downward, adhering to the wall and draining through the liquid outlet. Medium-density phases, such as hydrocarbons, display slower radial migration and remain suspended in transitional bands. Light phases, such as methane, are buoyed upward and concentrated near the central axis, eventually exiting through the gas outlet. This behavior reflects a combined balance of gravitational, inertial, and drag forces that can be represented in cylindrical coordinates as:

$$F_{\text{net}} = F_g + F_c - F_d$$

where Fg is the gravitational component perpendicular to the flow path, Fc is the centrifugal force, Fd the drag resistance, and r the radial position of the droplet. Such a formulation captures the essential balance that governs phase migration and stratification in spiral-guided systems.

Experimental and computational studies on spiral separators have shown that effective ballistic stratification is still feasible at low speeds if the flow path is long enough. The GFSS design ensures that heavier phases are pumped into the wall membrane within a few cycles, while lighter phases are recovered for a long time in the core, resulting in sharp vertical stratification with minimal remixing. This is consistent with the observation results of spiral gas-liquid separators, which have been found to have stable stratified flow fields and better phase purity than traditional cyclone separators [4].

A significant characteristic of spiral separators is the formation of a radial stratification zone, wherein particles or droplets of intermediate density are driven outward or downward via combined gravitational and centripetal/secondary flows, leading to the establishment of a relatively stable interface region. Ding et al. (2024) demonstrated in their thin-film spiral-channel analysis that steady states may be described by distinct radial bands of concentration, and that changes in spiral geometry (e.g., channel width, radius) significantly influence the formation and thickness of this interface region [6]. The aggregation in the middle layer also improves stability, reduces entrainment, and optimizes overall separation efficiency.

In addition, the deformation of droplets, adhesion and separation due to wall shear all have a significant impact on the performance of the separator. In high gas fraction multiphase flow, the interface needs to be stabilized in a way that prevents re entrainment. Spiral guidance is used to suppress turbulent instability, maintain wall membrane continuity, and stabilize phase distribution. Through the synergistic effect of gravity settling, centrifugal enhancement, and spiral induced residence time extension, GFSS is an effective but passive separation process in small volumes.

In summary, the principles of gas–liquid separation in spiral systems combine classical droplet mechanics with modern design strategies. Gravity remains the dominant force, centrifugal effects assist radial migration, and spiral geometries provide compactness and flow stability. These mechanisms collectively ensure efficient phase demarcation even under space-constrained and energy-sensitive conditions, laying the theoretical foundation for the CFD modeling and optimization presented in the next section.
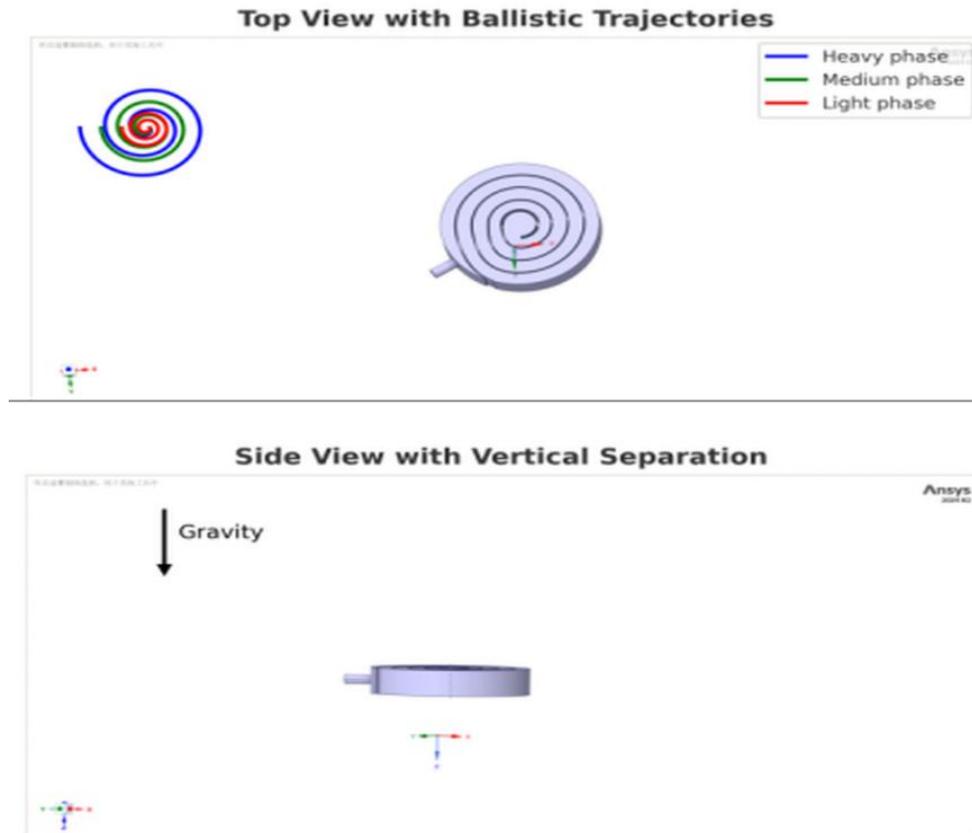
Top View with Ballistic Trajectories

Heavy phase
Medium phase
Light phase

Side View with Vertical Separation

Gravity

Figure2.1

2.2 Fundamentals of Multiphase Flow and Interface Evolution

Multiphase flows are characterized by the simultaneous presence of two or more immiscible phases, such as gas–liquid, liquid–liquid, or gas–solid systems. In gas–liquid separation processes, the interaction between the dispersed and continuous phases produces complex flow structures involving interfacial deformation, droplet coalescence, breakup, and detachment. A sound understanding of the physical principles underlying these phenomena is essential for accurate numerical modeling and the design of efficient separators .

Flow Patterns in Multiphase Systems

Multiphase flow is usually divided based on flow structure and phase distribution. The gas-liquid flow in a vertical channel may exist in the form of bubbly flow, slug flow, turbulent flow, annular flow, or misty flow. The state of interest is a function of gas-liquid volume ratio and phase velocity. Various systems exhibit different interface behaviors and pressure loss trends. For example, a bubble flow is composed of a single spherical bubble with a relatively low interface area, while an annular flow is composed of dispersed liquid droplets mainly composed of liquid film, which are carried in the gas core. These institutional changes are particularly important in compact separators, where slight changes in geometry or operating conditions can trigger flow pattern switching, thereby altering separation efficiency [19].

Dynamics of Phase Interfaces

A unique feature of multiphase systems is the dynamic nature of phase interfaces. There is a continuous interaction between surface tension, inertia, and viscous shear forces at the interface. The formation of this

interface determines the mechanism of deformation, coalescence, or rupture of droplets, bubbles, and films. The main physical phenomena are:

Agglomeration: The collision and merging of two or more droplets to form a large droplet with the minimum total interfacial energy. Agglomeration is influenced by local velocity gradients, interfacial tension, and phase compatibility. Slight shear in the spiral separator can cause agglomeration in the intermediate zone, thereby improving settling efficiency.

Crushing: The fragmentation and deformation of large droplets under inertia or high shear stress. Crushing usually occurs in high swirl or high turbulence regions, where it counteracts agglomeration and reduces overall separation efficiency.

Wettability and wall adhesion: Film formation, retention, and drainage are controlled by fluid wall interactions. A stable wall membrane is beneficial for liquid removal, while poor wettability may promote droplet separation and entrainment.

Re entrainment: Tiny droplets detached from the film may be re entrained by the continuous phase, especially in unstable or turbulent regions, resulting in efficiency loss. It is very important to minimize re entrainment in order to maintain high purity.

Modeling Interface Evolution

To describe these behaviors, computational fluid dynamics (CFD) employs interfacial tracking techniques. Among them, the **Volume of Fluid (VOF) method** is widely used for immiscible multiphase systems with distinct interfaces [18]. VOF introduces a volume fraction transport equation that allows direct simulation of interface deformation, stretching, and breakup without requiring explicit reconstruction. Surface tension forces are incorporated using models such as the **Continuum Surface Force (CSF)** approach, which converts curvature-driven capillary forces into body forces within the momentum equations.

The governing equations for multiphase flow therefore extend the incompressible Navier–Stokes framework with additional phase fraction conservation equations, interfacial stress terms, and surface tension modeling. This enables accurate resolution of interface topology, droplet migration, and wall-film dynamics. However, achieving mesh independence and minimizing numerical diffusion remain challenges in simulating thin films and small droplets, especially under swirling conditions [18].

Implications for Spiral Gas–Liquid Separation

In the context of spiral separators such as GFSS, interfacial dynamics are further complicated by swirling flow fields, centrifugal stratification, and secondary recirculation. The helical pathway not only extends the residence time but also stabilizes intermediate stratified layers, where coalescence reduces fine mist carryover. Studies on spiral separators confirm that properly tuned pitch and curvature reduce turbulence dissipation and promote robust interface formation [6,17]. In particular, the balance between gravitational drainage and curvature-induced secondary flows determines whether a stable intermediate band can be maintained without significant re-entrainment.
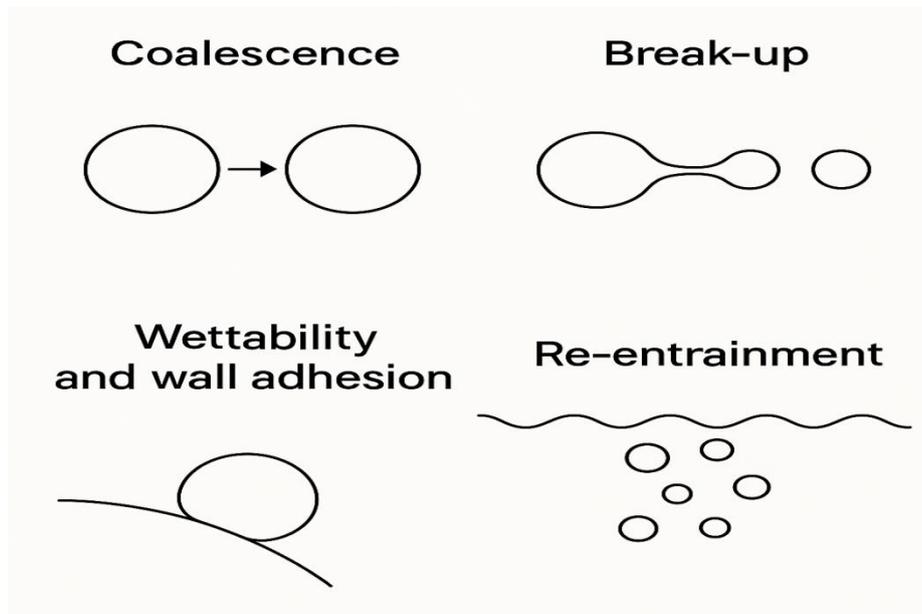
Figure2.2

Coalescence: This process occurs when two or more droplets combine into a larger droplet, reducing the overall surface energy. It is influenced by factors like velocity gradients, phase compatibility, and interfacial tension.

Break-up: This happens when a larger droplet deforms and splits into smaller droplets due to turbulent shear or inertial forces. It is important in regions with high rotation or compressibility.

Wettability and Wall Adhesion: The interactions between the fluid interface and the wall surface can lead to phase retention, film formation, or the creation of recirculation zones, impacting the efficiency of separation processes.

Re-entrainment: Detached small droplets can be re-captured by the continuous phase, particularly in conditions of high turbulence or instability, resulting in a loss of efficiency.

To describe these behaviors, computational fluid dynamics (CFD) models use interfacial tracking methods. The Volume of Fluid (VOF) method is particularly effective for immiscible multiphase systems with clear interfaces. It allows for the direct simulation of interface changes, such as deformation, stretching, and break-up, without needing explicit reconstruction of the interface.

The governing equations for multiphase flow, like the Navier-Stokes equations, are enhanced with a volume fraction transport equation to track the phase interface. Surface tension effects are modeled using methods like the Continuum Surface Force (CSF) model, which transforms curvature-driven forces into body forces within the momentum equation.

In the context of spiral gas–liquid (or multiphase) separators like the proposed GFSS separator, these interfacial dynamics are further complicated by swirling flow fields, centrifugal stratification, and secondary recirculations. Understanding the fundamentals of multiphase behavior at both macro and micro scales is crucial for capturing the true separation dynamics and guiding structural improvements through simulation.

Gas–liquid separation, as a fundamental unit operation in process control, is widely applied across various industrial domains, including petrochemical engineering, natural gas purification, fine chemicals, environmental engineering, pharmaceutical manufacturing, and metallurgy. Its primary objective is to efficiently decouple the gas and liquid phases, ensuring the stability of downstream processing units, the purity of final products, and the operational safety of equipment. As emphasized by Slettebø [5], with the increasing industrial demand for high efficiency, compact equipment, and low energy consumption, traditional separation devices are gradually revealing limitations such as poor adaptability, low separation precision, and high energy consumption. These challenges have spurred researchers to explore innovations in both separation principles and structural design.

Currently, mainstream gas–liquid (or multiphase) separation methods include gravity settling, gravitationally guided ballistic separation, cyclone separation, membrane filtration, coalescence separation, electrostatic separation, and high-gravity intensified techniques. Each method offers unique advantages and limitations in terms of applicable droplet sizes, operational complexity, and cost-effectiveness. Often, a hybrid design that combines multiple methods is required to meet the demands of complex industrial environments.
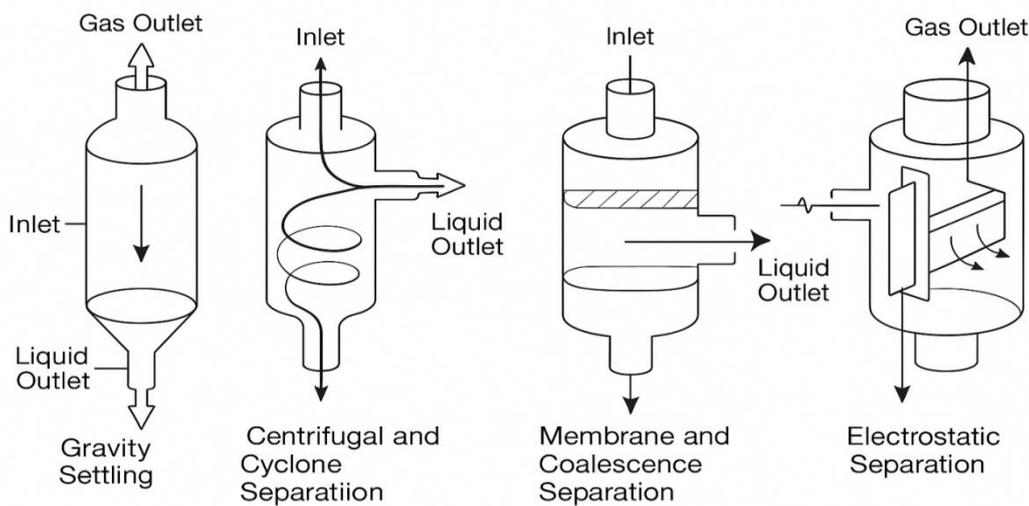
Figure2.3

Gravity Settling

As one of the oldest and most straightforward separation techniques, gravity settling relies on density differences between dispersed liquid droplets and the continuous gas phase, allowing droplets to migrate downward under gravitational acceleration. This method is reliable for large droplets and low-velocity flow conditions, but its applicability is limited under modern process requirements. It has been observed that gravity settlers remain effective primarily for droplets larger than 30 μm, whereas their efficiency decreases dramatically for fine mist (droplets smaller than 10 μm) or at high gas velocities. Furthermore, due to the need for long residence times, gravity settlers require large installation spaces, making them unsuitable for constrained environments such as downhole systems or compact modular skids.

Centrifugal and Cyclone Separation Technologies

Centrifugal and cyclone separators enhance phase separation by generating strong rotational flow fields, where droplets are subjected to both centrifugal acceleration and gravitational forces. These devices are widely employed in natural-gas dehydration, catalytic cracking and condensate oil separation. Multi-objective optimization studies on cyclone geometry have shown that high separation efficiency (especially for droplets in the tens of micrometers range) can be achieved, but typically at the cost of increased pressure drop. Conversely, recent work on down-hole spiral gas–liquid separators demonstrates compact structural alternatives with efficiencies above 90% and lower energy penalties [2,4]. Recent optimization studies suggest that even with improved geometries, the fundamental trade-off between efficiency and pressure loss persists [2,22].

Membrane and Coalescence Separation

Membrane separation has gained increasing attention in high-value applications such as pharmaceuticals and fine chemicals, owing to its capability to filter dispersed phases with high precision. By tailoring pore sizes, membranes can selectively allow components to pass, achieving sharp phase boundaries. Nevertheless, membrane fouling, high-pressure requirements, and sensitivity to flow disturbances severely restrict long-term performance under high liquid loads. Similarly, coalescence-based separation relies on engineered internals or fibrous materials to promote droplet merging. This mechanism is effective in oil mist and condensate treatment, where enlarged droplets can be subsequently removed by gravity or mild centrifugal forces. However, coalescers are highly sensitive to unstable flow regimes and particulate contamination, leading to rapid degradation of efficiency.

Electrostatic Separation and Emerging Hybrid-Field Techniques

Electrostatic separation applies external electric fields to polarize and charge droplets, inducing migration toward collection electrodes. This technique offers advantages for removing submicron droplets and is often used in environmental remediation and fine-particle pollution control. Its effectiveness, however, depends strongly on droplet conductivity. Electrode configurations must be carefully designed to prevent short-circuiting caused by liquid accumulation, and unstable energy consumption further limits industrial use.

To address the limitations of conventional designs, emerging structural enhancements and hybrid-field systems have been proposed. For instance, variable-pitch cyclones have been reported to enhance radial droplet migration and significantly improve efficiency. Similarly, inline compact separators that combine gravity, centrifugal, and shear-driven mechanisms have been developed to reduce device size while improving robustness. Hybrid flotation–cyclone systems have also demonstrated potential in wastewater treatment, providing expanded applicability of gas–liquid separation in challenging environments.

Trends Toward Multi-Field Coupling and Intelligent Separation

A significant trend in recent years has been the integration of **multi-field coupling** (e.g., gravitational, centrifugal, and electrostatic effects) with advanced computational tools. The combination of CFD simulations with machine learning algorithms is pushing gas–liquid separators toward "intelligent separation systems." In these frameworks, structural parameters are continuously optimized based on feedback from real-time data. The incorporation of multiscale interfacial tension models and transient perturbation dynamics into numerical simulations provides more accurate predictions of droplet behavior, enabling multi-objective optimization and adaptive control. Such approaches lay the groundwork for next-generation

separators like GFSS, which integrate **structural innovation, simulation-guided optimization, and adaptive operation** into a unified design [18,23].

In summary, current gas–liquid separation technologies continue to show limitations in terms of operational flexibility, structural complexity, and separation precision. Under multiphase and high-load conditions, single-mechanism devices are often insufficient. The future of separation technology lies in the **integrated construction of systems featuring "multi-field synergy + structural innovation + intelligent control."** Such developments are expected to deliver compact, efficient, and stable separation performance even under the most demanding industrial conditions, including high pressures, high flow rates, and elevated liquid loadings.

2.3 Computational Fluid Dynamics (CFD) Principles and Model Framework

Computational Fluid Dynamics (CFD) has become one of the most powerful simulation based tools in modern engineering. By numerically solving the control fluid flow equation, CFD provides insightful and non-invasive understanding of fluid behavior in complex geometries - a particularly interesting advantage when examining multiphase flow in tight separation devices such as General Field Spiral Separators (GFSS). Its ability to handle transient, three-dimensional, and nonlinear interactions makes it a key tool for achieving optimal design and operational performance of separators under representative industrial conditions.

The cornerstone of any CFD technique is the numerical solution of mass, momentum, and, if necessary, energy conservation equations. These equations are discretized within the computational domain, typically using the finite volume method (FVM) to transform partial differential equations into algebraic equations suitable for numerical computation [19]. The accuracy and stability of such simulations largely depend on grid resolution, time discretization, and the physical model chosen for simulating turbulence and multiphase interactions [1].

One of the serious modeling challenges in multiphase separation is the coexistence of immiscible fluids and flow interfaces. To address this challenge, several special techniques have been developed, including fluid volume (VOF) models, Euler Euler methods, and mixture models. Each has its advantages based on the flow state and the level of required interface details.

VOF is particularly suitable for sharp and immiscible interface problems such as gas-liquid or liquid-liquid flow. This model implicitly reconstructs the interface by solving the transport equation for the volume fraction of each phase, and can capture the effects of deformation, agglomeration, and film formation on the wall. For GFSS, gravity settling and spiral guided stratification are the main mechanisms, and VOF technology provides an effective method to visualize and analyze the interface between phases at a reasonable computational cost [18].

However, the Euler model represents each stage as a complete, interpenetrating continuum with its own conservation equations. This helps in closed multiphase flows, such as fluidized beds, where the transfer of momentum, heat, and mass between phases is crucial. However, its computational requirements are high, and the closed model of drag, lift, and turbulence phase coupling makes things complicated.

A hybrid model is a compromise model that assumes complete interpenetration of phases and a single momentum equation with an additional term representing sliding velocity. Although not very precise in the detailed interface representation, it can handle situations such as diluted suspension or slurry flow, where tight interface reconstruction is not very important.

The precise resolution of turbulence is another important building block for CFD simulations. In a spiral separator, wall boundary shear layers and internal flow of vortices are typical. The SST k - ω model is widely used in the Reynolds averaged Navier Stokes (RANS) closure, which has the advantages of the k - ϵ model in the free flow region and the k − ω formulation in the near wall region . It improves the accuracy of the recirculation and reverse pressure gradient regions, which are typically encountered in spiral separation channels.

In addition to turbulence, surface tension is another fundamental characteristic of multiphase delamination separation. The curvature of the fluid interface generates local forces that control droplet coalescence, thin film separation, and capillary mediated transport. In CFD, this is typically modeled by the Continuum Surface Force (CSF) model, which transfers surface tension as a volumetric force within the interface element. This model achieves numerical stability while reproducing real interface dynamics.

From a numerical perspective, the effectiveness of CFD solutions depends not only on physical modeling, but also on numerical schemes. A sufficiently high resolution scheme is needed to prevent numerical diffusion near the interface, and pressure velocity coupling algorithms such as SIMPLE and PISO are still the standard for implementing mass conservation . For problems involving transient phenomena and phase interface generation, film rupture, or ballistic droplet repositioning, the time step must be small enough to follow rapid changes without causing instability.

In the present study, CFD serves not only as a visualization tool but also as a design and optimization instrument. By simulating the internal hydrodynamics of the GFSS separator under varying inlet conditions, phase ratios, and material properties, the separation performance can be quantitatively evaluated prior to fabrication. This reduces experimental costs, highlights structural weaknesses, and provides guidance for operational strategies. As demonstrated in later sections, CFD analysis allows detailed tracking of velocity distributions, droplet migration paths, and outlet concentrations, thereby establishing the theoretical and computational foundation for assessing and improving the GFSS separation mechanism.

2.4 Principles and Applicability of the Volume of Fluid (VOF) Model

The Volume of Fluid (VOF) model is a widely used numerical method for simulating immiscible multiphase flows, which requires tracking the interfaces between phases. It has special applications in the presence of sharp gas-liquid interfaces, free surface flow, and the movement of droplets or bubbles under external forces such as gravity or centrifugal acceleration. These characteristics make the VOF model particularly important for spiral separation systems, such as the GFSS separator proposed here, where dynamically formed layered interfaces appear within narrow geometric shapes.

(1) Core Principles of the VOF Model

The VOF approach is formulated within the Eulerian framework, in which all phases share a common set of conservation equations for momentum and, when needed, energy. The distinguishing feature of each phase is represented by its volume fraction α, a scalar quantity defining the proportion of a given phase in each computational cell. The transport of α is governed by a volume-fraction conservation equation:

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot (\alpha \mathbf{u}) = 0$$

where **u** denotes the velocity field. This formulation ensures that the interface evolves consistently with the underlying flow. Local fluid properties such as density **ρ** and viscosity **μ** are calculated as volume-fraction-weighted averages of the constituent phases:

$$\rho = \alpha\rho_l + (1 - \alpha)\rho_g$$
$$\mu = \alpha\mu_l + (1 - \alpha)\mu_g$$

where subscripts l and g indicate liquid and gas phases.

Interfacial effects, particularly surface tension, are incorporated using the **Continuum Surface Force (CSF)** method. The CSF approach introduces a volumetric force term into the momentum equations, derived from the local curvature of the interface. This allows the model to capture surface tension-driven phenomena such as droplet coalescence, capillary waves, and film detachment [23].

(2) Advantages and Limitations

The VOF model provides various advantages that explain why it is widely used:

It can capture complex interface topologies without the need for explicit surface reconstruction.

It ensures global conservation of mass for deformation or coalescence boundaries.

It is suitable for transient and swirling flows with substantial topological changes, such as droplet fragmentation or coalescence.

For two-phase problems with significant differences in properties between immiscible phases, it is computationally efficient.

But there are also limitations. The VOF model is not very accurate for simulating dispersed phase systems with a large number of well distributed small bubbles or droplets in flow. In this case, Euler Euler or Lagrange models can provide more statistical explanations for the transfer of momentum and mass between phases [19].

(3) Applicability to the GFSS Separator

The GFSS separator processes swirling gas-liquid flows with strong gravity centrifugal coupling, time-dependent interface deformation, droplet entrainment, and radial stratification. All of these processes are within the capabilities of the VOF model. Specifically, VOF is highly suitable for:

Simulate radial and axial layered separation along a spiral channel;

Capture the formation, development, and separation of liquid films on curved walls;

Solve the problems of ballistic droplet migration and interface dynamics under secondary spiral induction cycle.

By using the VOF method, GFSS separators can be studied within the framework of phase boundary stability, pressure drop, and overall separation efficiency. This model provides an acceptable compromise between computational feasibility and physical reality for evaluating structural modifications and operational

conditions prior to physical prototyping. Therefore, VOF is the foundation for numerical optimization and theoretical research of new separators [18].

2.5 Applications of Spiral and Gravity–Centrifugal Separation Technologies Across Multiple Fields

Spiral and gravity–centrifugal separation devices, leveraging the synergy of swirling flow, gravitational–centrifugal field coupling, and gravity-induced stratification, have developed considerably beyond their initial use in petrochemical and mechanical processing. Owing to their compactness, high precision in separation, and applicability for handling complex multiphase conditions, these devices—like the proposed General Field Spiral Separation (GFSS)—are quickly emerging as holistic solutions across industrial, biomedical, environmental, and consumer applications.

Oil, Gas, and Chemical Industries.

In oil and gas production and refining heavy industries, spiral centrifugal separators are used widely for stratified liquid–liquid and gas–liquid separation. Spiral centrifugal separators remove efficiently water, oil droplets, and entrained gas bubbles from multiphase streams in offshore platforms, subsea wellhead modules, and natural gas dehydration systems. Spiral centrifugal separators are especially well adapted for space-limited areas where conventional equipment cannot be mounted due to their low-pressure drop and compact design. Spiral separators find significant applications in chemical production, crystallization, recovery of polymers, treatment of multiphase reactor effluent, and in separation of immiscible liquids, in which they facilitate selective extraction of a phase under dynamic operation without compromising system stability.

Environmental Engineering and Water Treatment.

Spiral gravity separators find increasing usage in environmental protection and wastewater treatment, in which they facilitate the removal of suspended solids, oils, and immiscible organic pollutants. In oily wastewater treatment, spiral compact units are able to perform multiphase stratified separation without chemical dosing or membrane utilization, reducing running costs and preventing secondary pollution. In sludge dewatering and membrane system pre-treatment, the equipment can reduce solid loading, prolong membrane life, and improve downstream reliability. Cyclone- and spiral-type droplet separators find extensive applications in air pollution control for aerosol and moisture removal prior to the discharge of gases for the purposes of attaining standards of emissions and ensuring stable long-term performance in power plants and incinerators.

Food and Beverage Processing.

Gravity-assisted separation technology has also found application in the food sector to control emulsified and multiphase food systems. Spiral separators are specialty applied in vegetable oil refining to achieve soapstock and water separation from oil and minimization of emulsification loss. Centrifugal spiral equipment is applied in the dairy processing sector for cream separation, milk fat standardization, and whey clarification. Spiral centrifugal equipment is applied in foods and beverages like juices and plant beverages to remove suspended solids and fine pulp, thereby improving product stability, quality, and sensory attributes. Compared to traditional filtration systems, spiral separators have lower possibilities of fouling and are better for shear-sensitive or foaming-tendency fluids.

Biomedical and Pharmaceutical Applications.

Spiral separators in miniaturized sizes used in biomedical and pharmaceutical applications enable non-invasive, label-free cell or plasma separation. For instance, spiral microfluidic devices are capable of separating plasma from whole blood without the need for conventional centrifugation, thus facilitating point-of-care diagnostics in resource-limited settings. In bioprocessing, spiral-type devices facilitate continuous cell separation from microbial broths, recovery of microbial cells, and concentration of protein-enriched fractions. The gentle hydrodynamics and continuous flow characteristics of their operation enhance sterility and purity of the product, which is particularly favorable to pharmaceutical and biotech manufacturing lines.

Microfluidics and Lab-on-a-Chip Technologies.

At the microscale, spiral geometries find pivotal applications in lab-on-a-chip systems for diagnostics, cellular biology, and drug screening. Dean vortices generated in spiral microchannels allow size- and density-based separation without the need for labels or centrifugation. This is particularly important in rare-cell detection, e.g., extracting circulating tumor cells (CTCs) or fetal cells from mother blood. Spiral microfluidic devices thus provide a highly accurate yet miniaturized substitute for large laboratory apparatus, placing them firmly in place in modern biomedical research.

Energy and Battery Material Processing.

In energy applications, i.e., battery manufacturing, spiral and gravity-centrifugal separators are largely used to classify active material suspensions, separate focused particle phases, and clean impurities from electrolytes. Controlled flow spiral flow fields are utilized to realize homogeneous mixing of the slurry, avoid particle agglomeration, and enhance electrode material quality. These developments are pivotal for the performance and lifespan of new generation energy storage devices such as lithium-ion batteries.

From oil pipelines to biomedical microdevices, general Field Spiral Separatorhave emerged as a multi-applied class of technologies that possess the ability to achieve highly efficient multiphase stratified separation across a wide range of physical scales and application settings. The ability to combine compactness, energy efficiency, and flexibility has seen them find applications in oil and gas engineering, wastewater treatment, food processing, and biomedical research. With growing incorporation of smart sensors, real-time monitoring, and microfluidic platforms, their applications are being progressively driven under the Industry 4.0 and precision medicine paradigms. With relentless research advancements in flow control, material compatibility, and modularization in multi-stages, devices such as the GFSS are poised to drive the future of separation technologies in various domains [30].

Chapter 3: Structural Design, Flow Mechanism, and Simulation Framework of the proposed GFSS separator

3.1 Basic Structure of the proposed GFSS separator Device

General Field Spiral Separation (GFSS) is an advanced gas-liquid or multiphase separation system designed to integrate the advantages of gravity-assisted inertial separation, gravity settling, and flow driven interface control. Its design is based on a patented concept, featuring compactness, modularity, and multifunctionality, capable of handling complex flow conditions. As shown in Figure 3.1, the GFSS separator is a cylindrical axisymmetric body containing multiple vertically stacked functional modules. These modules work together to achieve efficient separation with minimal pressure drop and liquid carryover.

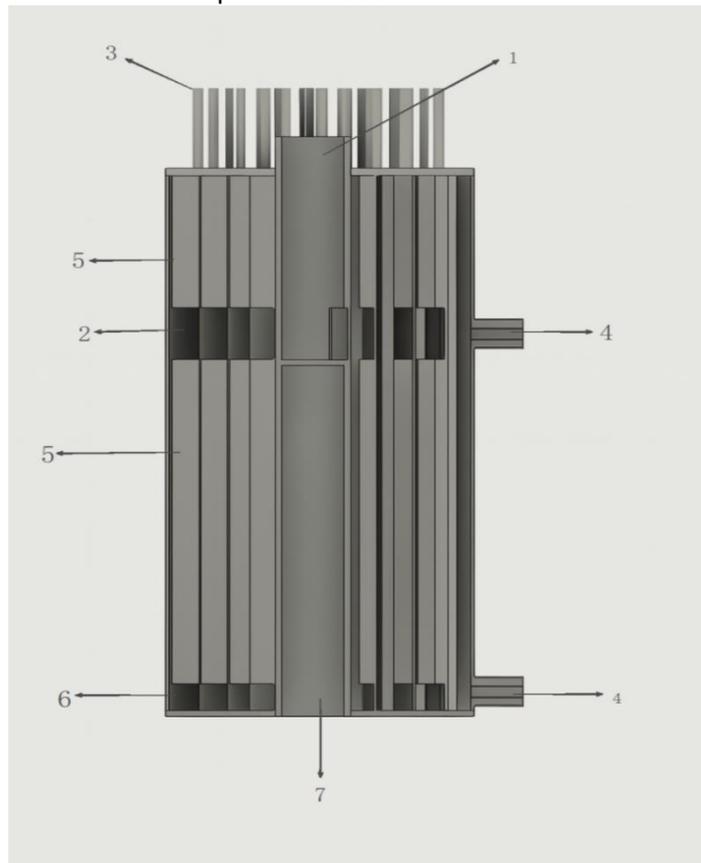The main structural components of the GFSS separator include:

Figure3.1

(1) Central Inlet Pipe – Vertical Inlet

The gas-liquid (or multiphase) mixture is fed into the separator through a vertical inlet located at the top center. The design purpose of the entrance is to redirect the axial inflow towards tangential spiral guidance, so that the inflow momentum matches the initial turn of the spiral separation path. Through this configuration, the generation of axial turbulence is minimized, and the establishment of a highly ordered vortex field is very rapid, which is a condition before gravity guided trajectory separation begins.

(2) Single-Helix Spiral Spiral Guide Vanes – Primary Separation Core

The center of the GFSS separator is a continuous spiral guide vane installed vertically along the centerline of the separation chamber. The blades have a constant pitch spiral path from the inlet area to the lower part, forming a well-defined channel that guides the path of incoming multiphase flow.

Compared to the geometry of cyclone separators that primarily rely on high rotational speeds, GFSS spirals are mainly used for guiding, converging, and stabilizing flow. When gas-liquid (or multiphase) flow enters the chamber

tangentially, it is swept by the spiral surface and turns into a controlled spiral path. This motion combines axial and tangential velocity components to maintain orderly flow and prevent uncontrolled radial dispersion.
When the mixture is discharged downwards in the spiral:

Droplets with increasing density migrate to the chamber wall.
When these droplets hit the wall, they merge into a complete liquid film.
Gravity drives this film to the bottom outlet, ensuring uninterrupted discharge of liquid.

The fusion of geometry provides two significant benefits:

Increasing dwell time - The spiral extends the flow path, allowing gravity settling and surface tension effects to play a more effective role.

Stable phase interface - controlled helical motion suppresses large-scale turbulence and recirculation, limits droplet re entrainment, and maintains a sharp separation interface.

Through this single helix structure, GFSS can effectively capture and classify droplets in the size range of 5-50 μm even at relatively low inlet velocities. The compact vertical configuration also allows for simple scaling and integration into multi-stage separators, making it suitable for industrial applications that require high separation accuracy and versatility.

(3) Perforated Gas Outlet Module – Top Outlet

Strategically place a perforated cover plate with micropores at the top of the separator as the gas phase outlet.
Optimize module exports through CFD calculations to achieve the following goals:
Uniform distribution of surface flow at the outlet
Prevent local back pressure accumulation
Minimizing droplet entrainment during gas release process

This outlet geometry stabilizes the exhaust airflow and improves the efficiency of multiphase stratified separation even under fluctuating flow conditions.

(4) Liquid Discharge System – Mid and Bottom Drainage with Anti-Backflow Control

The liquid phase collection chamber is located in the middle and lower regions of the device, where falling droplets accumulate and are discharged through a unique outlet channel. Liquid sealing mechanisms, such as U-shaped seals or fluid gates, are used to prevent gas leakage upwards but ensure continuous drainage. In addition, adjustable valves or liquid level sensors should be placed at the outlet to control the retention height of the liquid, thereby accurately controlling the interface separation and preventing secondary re entrainment caused by liquid vibration.

(5) Outer Shell with Longitudinal Flow-Stabilizing Ribs

In order to increase mechanical strength and ensure uniform flow, longitudinal ribs are reinforced on the outer cylindrical shell. These structural components are used for:
Minimize the formation of large-scale secondary eddies as much as possible
Maintain the symmetry and thickness of the spiral flow layer
Prevent oscillation or backflow caused by walls

Therefore, this design helps to achieve a stable laminar spiral interface, which is crucial for repeatability under high Reynolds number conditions.

(6) Helical Disturbance and Secondary Separation Zone

The spiral disturbance zone is located in the lower half of the GFSS and aims to eliminate trailing droplets that fall through the first stage separation. In this area, the geometric shape of the single spiral guide vane is altered to introduce controlled vortex disturbances near the chamber wall.

This disturbance forms a local high shear band near the wall. After the first stage separation, the remaining suspension droplets are exposed to these shear bands, where they come into closer contact with the wall. When they collide with the wall, they converge and integrate into the existing film, and then discharge downwards under the action of gravity.

By combining wall induced swirl with gravity assisted drainage, the spiral disturbance zone increases the secondary stripping effect. This has the effect of greatly reducing the possibility of fine droplet carryover under unstable flow rates or high-throughput operating conditions. The result is an improvement in the stability of separation performance under different inlet conditions.

(7) Modular Expansion Interface – Intelligent System Integration

A modular design expansion port is integrated on the lower central axis of the proposed GFSS separator to facilitate the addition of intelligent sensing and control components. Intelligent sensing and control components include:

High resolution line of sight monitoring optical window or camera port

Temperature, pressure, and Gas–Liquid Concentration sensor used for sensing

Drainage and interface control solenoid valve

Connection interface for connecting SCADA or IoT platforms

This module based design transforms the GFSS separator into an active intelligent separation node, aligning it with the future digital oil and gas production chain.

The structure of GFSS separator has an inherent structural framework that is compatible with fluid dynamics, structural mechanics, and intelligent control systems. Each module is crucial for ensuring the separation mechanism of functional layering, so that the GFSS separator can work efficiently under various conditions, with high separation accuracy and no space requirements. The following discussion will use CFD based simulation techniques to consider flow behavior, phase interfaces, and trajectory development in structures.

3.2 Spiral-Induced Multiphase Separation Mechanism

Universal Field Spiral Separation (GFSS) utilizes an internal flow structure with spiral winding, specifically designed to enhance gas-liquid (or multiphase) layer separation within a compact volume. Unlike traditional vertical or straight channel separators that heavily rely on high centrifugal speeds, the effective separation of GFSS is largely due to the synergistic effect of inertial forces caused by moderate curvature and overwhelming gravity. Due to the intentionally low tangential inlet velocity (about 0.1m/s), the centrifugal acceleration generated in the spiral channel is relatively low. Therefore, the core separation mechanism is similar to gravity assisted ballistic migration, where particles or droplets experience density driven trajectories in a structured spiral trajectory rather than being subjected to high centrifugal forces.

(1) Structured Spiral Flow Generation

As the tangential direction enters the single helix path, the multiphase mixture is redirected in the form of a three-dimensional eddy current field. It is a combination of downward axial transmission and azimuth rotation to create a spiral trajectory around the vertical axis of the separator. The curved form stabilizes the internal flow structure, prevents uncontrolled turbulence, prolongs effective residence time, and promotes orderly phase migration. Although curvature involves secondary ballistic stratification effects, gravity along the vertical axis remains the main driving force.

(2) Gravitationally Driven Vertical Migration

In the spiral channel, components of different densities exhibit unique ballistic trajectories similar to projectiles when subjected to gravity. Heavy substances such as water rapidly diffuse to the outside and form a wall film downwards, then drip through the liquid outlet. Lighter species such as methane prefer to stay near the central axis, and buoyancy drives them inward towards the axial gas outlet. Medium density fluids, namely hydrocarbons, exhibit transitional behavior: they are suspended horizontally in the middle vertical zone, neither completely pushed outward nor remaining in the core. Vertical phase migration simulates parabolic sedimentation, where density dependent trajectories are determined by flow velocity, viscosity, and channel geometry.

(3) Gravity–Adhesion–Flow Coupling

In addition to overall motion, non chemical interfacial forces such as cohesive forces and wall adhesion forces have a significant impact on separation kinetics. These forces determine the stretching, attachment, and separation behavior of droplets along a spiral path. In GFSS, this effect is most pronounced in the vertical phase channel, where the stratified fluid is guided to its outlet. By selecting appropriate building materials and optimizing surface finish, the separator minimizes excessive wall adhesion, improves interface stability, and enhances operational reliability by reducing the possibility of re entrainment.

(4) Evolution of Multiphase Interfaces

As the multiphase mixture descends, shear layers develop at phase boundaries due to radial and axial velocity gradients. These shear layers deform dispersed droplets, promoting filamentation and the eventual formation of wall-bound liquid films. The structured spiral geometry stabilizes these interfacial zones, leading to layered stratification characterized by distinct gas, intermediate, and liquid regions. Numerical simulations using the Volume of Fluid (VOF) method confirm that the GFSS configuration effectively maintains these separated layers with limited backflow or cross-phase mixing [28].

(5) Intermediate Separation Layer Dynamics

Both visualization and simulation emphasize the existence of a stable intermediate layer composed of medium density droplets between a lighter gas core and a denser liquid film. This band is formed due to the balance between gravitational settling and radial inertia driven by curvature. Heavy droplets quickly reach the edge, while light components remain buoyant at the center. Medium density droplets have weak inertia and cannot fall onto the wall, but their density is too high to remain in the core and occupy a stable position in this ballistic equilibrium zone. The middle layer is a buffer layer that eliminates cross contamination and enhances stratification. The agglomeration in the band also reduces the entrainment of small droplets, ensuring maximum overall separation efficiency. The recent theoretical analysis of the spiral separator has

validated this mechanism, indicating that a balance between inertial forces, gravity, and viscous forces can be maintained in this intermediate equilibrium region[6].

3.3 Dimensional Design Basis of the proposed GFSS separator Device

The structural dimensions of the General Field Spiral Separation (GFSS) are determined through a comprehensive design method that combines fluid dynamics principles, layered separation theory, structural mechanics, and practical engineering constraints. GFSS does not follow fixed empirical correlations, but focuses on the functional coordination between flow behavior, force field distribution, and interfacial control. This concept enables the device to achieve efficient separation within a compact footprint suitable for modular installation.

One of the main goals of size shaping is to mix gravity settling and centrifugal assistance in the best possible way within a limited spatial range. In multiphase separation, key performance factors such as droplet migration path length and residence time are determined geometrically by the chamber geometry. Early research on spiral and cyclone separators confirmed that the ratio of axial height (H) to effective diameter (D) is an important parameter for balancing separation efficiency and pressure drop. In the proposed GFSS, the H/D ratio is chosen to be between 1.8–2.5. This allows for the creation of stable eddy current fields, sufficient phase stratification dwell time, and compact external contours, which can be integrated into offshore sleds or processing modules with limited space [2].

The single-helix spiral blade is designed with a constant pitch, ensuring uniform guidance of the multiphase flow throughout the chamber.
This geometry promotes stable swirl generation, balanced phase stratification, and smooth liquid drainage without inducing secondary turbulence.
The constant-pitch configuration simplifies manufacturing, enhances flow predictability, and maintains structural uniformity along the vertical axis.

This systematic adjustment strengthens phase stratification, improves coalescence efficiency, and minimizes back-mixing. Numerical analyses of spiral separators confirm that such geometric tuning enhances interface stability and reduces entrainment [28].

The inlet and outlet channel dimensions are equally critical for maintaining phase stability. The inlet should allow the dispersed phase to enter smoothly without generating excessive turbulence, while the outlet must be sufficiently large to minimize backpressure and suppress droplet re-entrainment. Based on established design practices for gas–liquid cyclone separators, the outlet cross-sectional area is typically designed slightly larger than that of the inlet to promote uniform gas discharge and reduce the likelihood of liquid carryover [8]

From a structural mechanics perspective, the sizing of the separator's outer shell, flange base, and crown components is determined by criteria of stiffness, durability, and manufacturability. Wall thicknesses and reinforcing ribs are dimensioned according to pressure vessel codes, with allowances for thermal cycling, vibration, and installation stresses. Tolerance control is particularly important: modular assembly requires that the spiral core, inlet modules, and drainage system maintain dimensional tolerances within ±0.1 mm. This precision facilitates rapid assembly/disassembly, integration of monitoring sensors, and reliable prototype testing.

In terms of compactness, the GFSS is designed for confined industrial environments such as offshore skids, compact test loops, or embedded gas-handling units. To this end,, with a maximum external diameter of approximately 250 mm and a typical height under 500 mm. Despite these limits, the spiral channel geometry ensures sufficient swirl path length and drainage performance, maintaining efficiency without requiring a larger footprint.

Finally, all geometric features are defined with CFD compatibility in mind. Smooth transitions, continuous curvature, and mesh-friendly profiles are incorporated into the design to ensure accurate numerical simulations using interface-capturing methods such as VOF. This digital–physical consistency ensures that computational predictions of velocity distribution, phase migration, and interface stability can be directly validated against fabricated prototypes.

In summary, the dimensional design of the GFSS separator embodies a convergence of theoretical principles, flow control objectives, structural robustness, and engineering practicality. Each dimension is assigned not only for mechanical feasibility but also for its contribution to orderly flow development, enhanced phase separation, and minimized re-entrainment. This design philosophy ensures that the GFSS achieves both physical compactness and functional efficiency, making it a versatile solution for multiphase separation across a wide range of industrial applications.

Chapter 4 Numerical Simulation Design and Result Analysis

To analyze the internal flow behavior and separation performance of the General Field Spiral Separator (GFSS), a transient multiphase simulation was conducted using ANSYS Fluent. This commercial CFD software offers robust numerical tools designed to solve complex multiphase flows, accommodating swirling, transient, and surface-tension-driven phenomena effectively.

The simulation process follows a three-stage workflow:

（1）**Pre-processing:** The full-scale geometry of the proposed GFSS separator was constructed based on its actual structural design. This includes the inlet section, Single-Helix Spiral vanes, separation chamber, outlet module, and drainage system. The domain was meshed using a multi-zone hybrid strategy with local refinements in critical areas, such as the spiral separation layer.

（2）**Solver Setup and Computation:** The physical models selected for the simulation include the Volume of Fluid (VOF) method for interface tracking, gravity-enabled body forces, and surface tension modeling via the Continuum Surface Force (CSF) approach. Additionally, the SST k–ω turbulence model was employed. The solver was configured to be transient, pressure-based, and second-order accurate in both time and space.

（3）**Post-processing and Analysis:** Key flow parameters, such as velocity streamlines, phase volume fractions, wall film formation, pressure distribution, and droplet trajectories, were extracted and analyzed using Fluent's integrated tools and CFD-Post. These outputs allow for a quantitative assessment of separation efficiency and a qualitative evaluation of the swirling field structure.

This simulation framework offers a physically accurate and computationally efficient method to investigate the coupled centrifugal–gravitational separation mechanism within the proposed GFSS separator. The subsequent sections will detail each component of the numerical setup, starting with the construction and meshing of the discretized flow domain.

4.1 Pre-processing: Geometry and Mesh Construction

To simulate the internal multiphase flow field and stratified separation behavior of the General Field Spiral Separator (GFSS) with high fidelity, a comprehensive pre-processing strategy was adopted. This strategy included precise geometry reconstruction, high-resolution mesh generation, refinement in critical zones, and thorough mesh quality assessment. The preprocessing was executed using ANSYS Fluent's design and meshing tools, with support from SpaceClaim and Fluent Mesher modules.

In GFSS, the multiphase flow behavior is predominantly influenced by the coupling of gravitational, centrifugal, and shear force fields. Gravity facilitates the vertical drainage of denser components, while the combination of centrifugal and gravitational forces induces radial migration due to the swirling geometry. Shear forces play a crucial role in interfacial deformation and droplet coalescence. These fields coexist within a complex three-dimensional domain, making it challenging to capture their interactions through conventional experimental methods.

To address this challenge, Computational Fluid Dynamics (CFD) was employed to simulate the transient, multiphase flow within the proposed GFSS separator.Using the Volume of Fluid (VOF) method for interface tracking, the SST k–ω turbulence model, and the inclusion of gravitational body forces and surface tension modeling, the simulation framework successfully reveals the internal phase evolution. It provides insights into stability of the phase boundary layers, phase layering, droplet trajectories, and localized recirculation under the influence of the coupled force fields.

4.1.1 Geometry Modeling of the proposed GFSS separator

The discretized flow domain was constructed based on actual dimensions and structural features of the proposed GFSS separator prototype, comprising the following main components:

A central vertical inlet pipe introducing the gas–liquid (or multiphase) mixture from the top;

A set of single-Helix Spirall guide vanes, interlaced with constant pitch, designed to induce rotational flow;

A cylindrical separation chamber, housing the primary swirling flow;

A perforated axial gas-phase outlet cover, allowing uniform gas discharge while minimizing entrainment;

A bottom drainage system, collecting and discharging the separated liquid phase.

Special attention was given to preserving the geometric continuity between spiral vanes and the chamber wall, as this directly affects the swirl field and phase interface behavior. The geometric model also includes provisions for outlet symmetry and wall curvature to reduce artificial flow disturbances.

4.1.2 Mesh Type and Overall Strategy

Due to the complex geometry involving twisted vanes and internal flow channels, a fully unstructured tetrahedral mesh was selected for the entire flow domain. Compared to structured meshes, tetrahedral elements offer greater flexibility in handling geometrical curvature, especially around the guide vanes and the perforated outlet region.

To capture boundary-layer effects and shear-driven phenomena near solid walls, 12 layers of inflation meshes were applied along all wall surfaces. These layers ensure proper resolution of wall-bounded liquid films, near-wall turbulence, and interfacial momentum exchange. Inflation growth rates and initial thicknesses were tuned to maintain high orthogonality and gradient smoothness.

The overall meshing strategy followed a multi-zone workflow, where different regions (inlet zone, separation core, outlet, and drainage chamber) were meshed independently and then merged through conformal interfaces. This allows optimization of mesh resolution in each subdomain without compromising computational consistency.
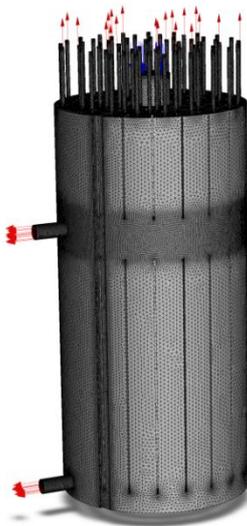

Figure4.1

4.1.3 Local Mesh Refinement in the Separation Layer

The separation layer—between the spiral vanes and the inner chamber wall—is the core zone for droplet separation in the proposed GFSS separator. Here, droplets are driven outward by centrifugal and gravitational field coupling and settle along the wall under gravity, forming a liquid film.

To improve the resolution of interface dynamics and wall interactions, local spatial mesh resolution enhancement was applied in this region. The minimum cell size was reduced to 0.2 mm, with smooth transitions to coarser zones. This allowed accurate modeling of droplet impingement, film evolution, and near-wall shear effects.

This refined region contributed about 30% of the total 7 million cells, significantly enhancing the accuracy and stability of transient VOF simulations.
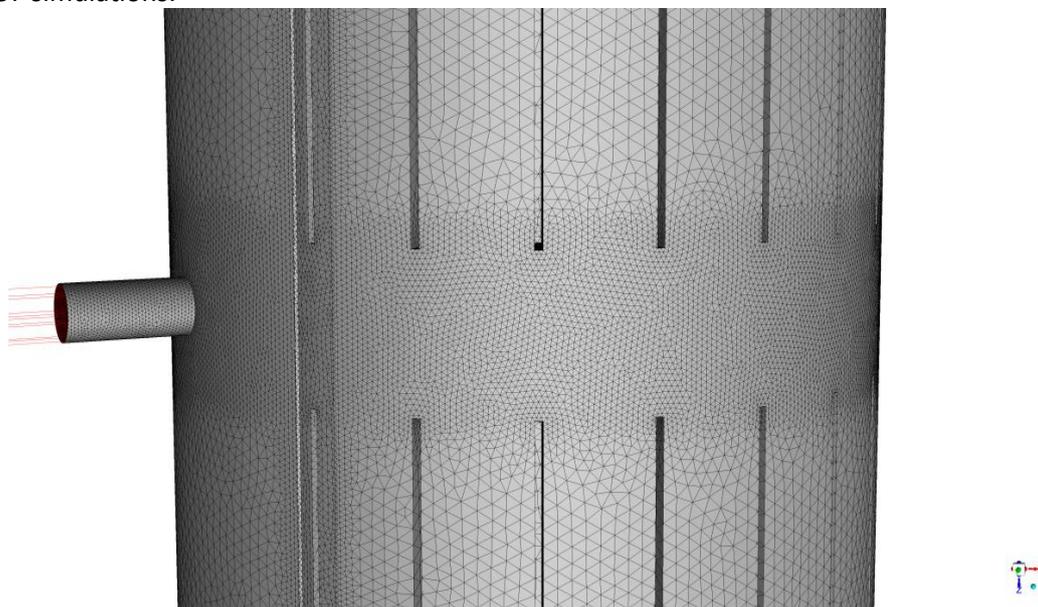

Figure4.2

4.1.4 Mesh Statistics and Quality Assessment

The final mesh consisted of approximately 7 million unstructured tetrahedral cells. Mesh quality was assessed using several standard metrics:

Skewness: maintained below 0.25 across 95% of the domain, ensuring stable interpolation accuracy

Aspect ratio: constrained to under 5 even in boundary layer and refined zones

Orthogonality: consistently above 0.8 in structured growth regions

Smoothness: ensured through zone transitions without abrupt changes in element size or angle

A mesh independence test was conducted by comparing the 7M mesh against a coarser 3M mesh and a denser 10M mesh. Key performance metrics including pressure drop, velocity profile uniformity, liquid holdup, and phase distribution patterns were compared. Results showed that:

The difference in pressure drop between the 7M and 10M cases was under 1.5%;

VOF-tracked phase interface formation and ballistic evolution remained qualitatively consistent across all cases;

Liquid carryover and wall film formation were identical in spatial trend and magnitude.

Therefore, the 7M mesh was validated as a reliable compromise between accuracy and computational efficiency, and was selected as the baseline mesh for all subsequent transient multiphase simulations.

4.2 Solver Setup and Computation

To investigate the gas–liquid (or multiphase) separation behavior inside the General Field Spiral Separator (GFSS), a transient multiphase CFD simulation was conducted using a VOF-based approach. The solver configuration was

tailored to simulate swirling, gravitational, and surface-tension-dominated flows under physically realistic inlet and outlet conditions.

4.2.1 Multiphase Flow Model

The Volume of Fluid (VOF) model was employed to track the sharp interface between the gas and liquid phases. It solves a single momentum equation for the entire domain while tracking the volume fraction of each phase.
Key physics models and settings:

Surface tension was included using the Continuum Surface Force (CSF) model.

Gravity was applied in the vertical direction to simulate liquid drainage and stratification.

Turbulence was modeled using the SST k–ω model, suitable for resolving swirl and near-wall flows in spiral channels.

Transient computation was used to capture the dynamic evolution of the flow field and phase interfaces.

4.2.2 Boundary Conditions

The simulation domain included one inlet, one axial gas-phase outlet, and one gravity-aligned liquid-phase drain.

Inlet (Top center vertical):
A velocity-inlet condition was specified with a uniform inflow velocity of 0.1 m/s. The volumetric composition of the inflow mixture was set as:

Component	Phase Type	Volume Fraction	Density ρ (kg/m³)	Interfacial Tension γ (N/m)
Water (H_2O)	Continuous liquid	0.50	998.2	—
Methane (CH_4)	Dispersed gas	0.30	0.656	With Water: 0.072 With Octane: 0.015
Octane (C_8H_{18})	Dispersed liquid	0.20	703	With Water: 0.050 With Methane: 0.015

These fractions were implemented as gas–liquid (or multiphase) volume fractions in the VOF setup, where methane was treated as a compressible gas, while octane and water were modeled as incompressible liquids, and water was defined as the continuous liquid phase.

Outlet (Top axial gas-phase outlet):
A pressure-outlet was defined with a zero-gauge pressure condition. Additionally, volume fraction monitoring was enabled at this boundary to quantify liquid carryover and gas purity.

Liquid outlet (Bottom and middle):
A pressure-outlet was also set, with a backflow volume fraction condition for water. This enabled free drainage of the liquid phase under gravity without artificial restrictions, ensuring that liquid accumulation in the chamber bottom could be removed naturally.

Walls:
All solid boundaries were modeled as no-slip walls. Contact angle settings were calibrated to promote realistic adhesion and detachment of the water phase during wall film formation.

4.2.3 Initial Conditions

To stabilize the early phase of the simulation and mimic operational startup conditions:

The domain was initially filled with water phase .

The bottom of the spiral separation layer and liquid collection chamber was pre-filled with water, representing an established drainage baseline.

All initial velocities were set to zero, and a hydrostatic pressure field was imposed based on gravity.

Phase volume fractions were patched accordingly: water at the bottom, and the rest filled with gas mixture.

This ensured numerical stability and realistic interface formation during the initial flow evolution.

4.2.4 Temporal and Spatial Discretization

The simulation was conducted under transient conditions using an adaptive time-marching scheme.

A time step size of 0.0001 s was used throughout the simulation to satisfy CFL conditions and resolve fast interface changes.

The total number of time steps was 380000, corresponding to a total physical time of 5 s.

Second-order implicit time discretization was used for improved temporal accuracy.

PISO scheme was selected for pressure–velocity coupling, ensuring robust convergence under swirling, transient conditions.

4.2.5 Convergence and Numerical Monitoring

Convergence behavior was carefully monitored throughout the simulation by tracking residuals of key governing equations. The representative residual history is shown in Figure 4.3
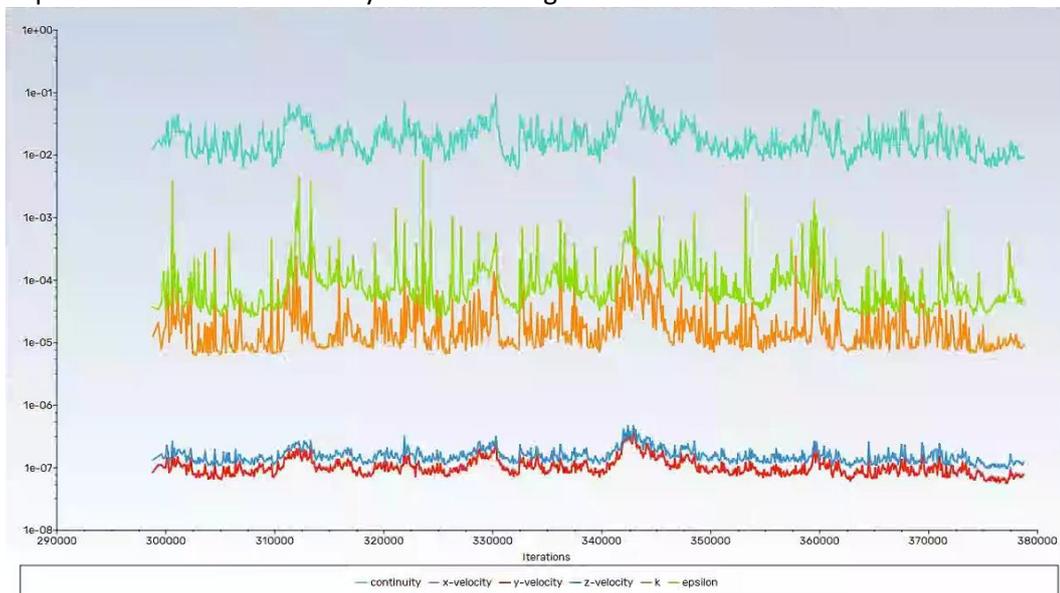

Figure 4.3

Velocity components (x, y, z) all reached stable convergence below 1×10^{-4}, indicating that the momentum equations were accurately resolved under the transient swirling flow field.

Turbulence quantities (k and ε) fluctuated within 10^{-3} to 10^{-2}, reflecting natural transient turbulence development and shear-layer evolution near the vane walls.

Continuity residuals remained higher, fluctuating between 1×10^{-2} and 1×10^{-1}, which is expected in Volume of Fluid simulations due to frequent phase interface reconstruction and volumetric imbalance at each time step.

While not fully meeting steady-state residual criteria, these residual levels are acceptable and typical in transient multiphase VOF simulations, especially those involving transient phase interfaces, surface tension, and rotating flow fields. Furthermore, phase volume fraction profiles and outlet fluxes remained consistent over time, confirming physical convergence.

No divergence or interface breakup was observed during the full 380,000-step run, indicating satisfactory numerical stability and physical reliability.

4.3 Post-processing and Result Analysis

To evaluate the multiphase stratified separation behavior within the General Field Spiral Separator (GFSS), a comprehensive post-processing analysis was carried out on the transient CFD results. Key fluid dynamic variables, including velocity field distribution, volume fraction evolution, and outlet separation performance, were visualized and analyzed in detail. This section offers an in-depth examination of the internal flow characteristics, phase interfaces, and the efficiency of the three-phase stratified separation, providing a foundation for future design optimization.

4.3.1 Velocity Field Analysis

The velocity field inside the General Field Spiral Separator (GFSS) reveals the underlying flow mechanisms responsible for the devices separation performance. The field reflects the interaction between the spiral geometry, inlet momentum, gravitational force, and multiphase dynamics. Velocity vectors and magnitude contours were extracted at multiple cross-sections and time snapshots to analyze the full three-dimensional development of the flow field.

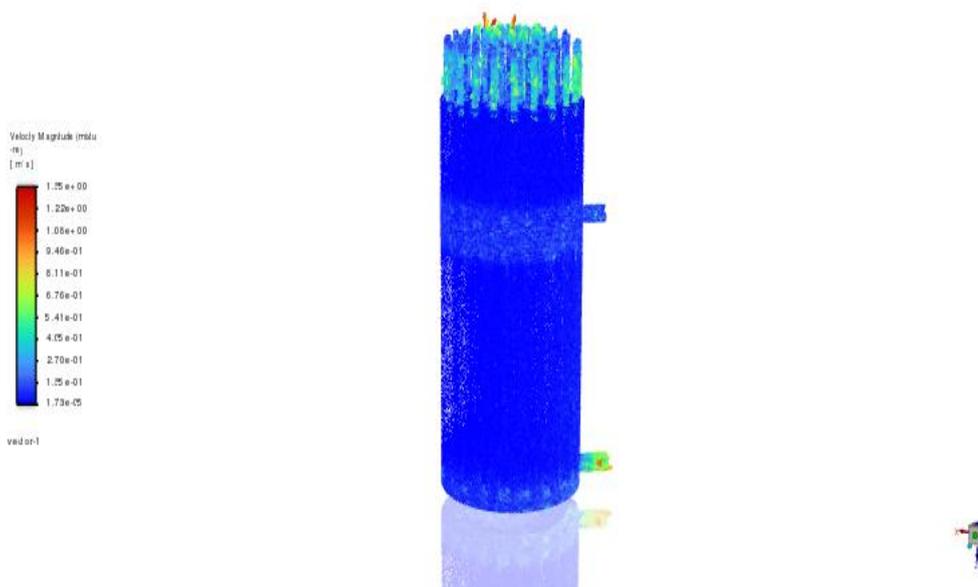**(1) Global Spiral Flow Characteristics**

Figure 4.4

Figure 4.4 presents the three-dimensional velocity vector field at 0.22 s, the quasi-steady stage of the simulation. A prominent helical flow pattern is observed throughout the domain. The gas–liquid (or multiphase) mixture enters tangentially at low speed (0.1 m/s) but rapidly transitions into a spiral trajectory due to the singlel-helix guide vane geometry.

The combination of axial and tangential components results in a compound swirling–axial flow, with local velocity peaks near vane edges.

The vortex core forms along the central axis, dominated by the light gas phase (methane), which exhibits upward acceleration and organized escape through the top outlet.

Near the wall, flow vectors curve downward and inward, contributing to the secondary recirculation loops that enhance residence time for denser droplets.

The vector field confirms that the proposed GFSS separator creates a centrally concentrated low-density escape path for gases and a wall-driven film development region for the liquid phase. The transition of swirling intensity from inlet to outlet ensures the gradual and continuous migration of multiphase components.

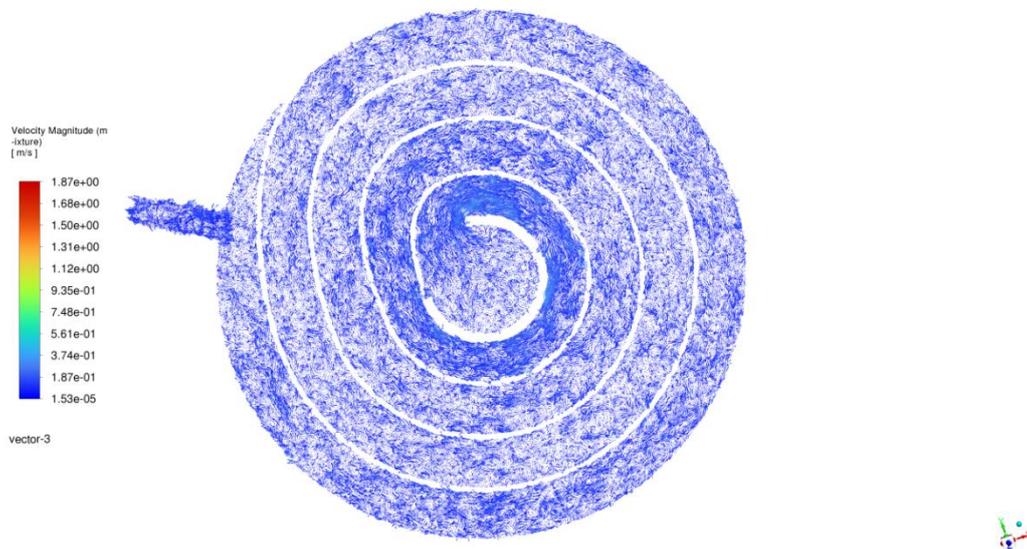**(2) Spiral Mid-Zone Hydrodynamics (XY Plane)**

Figure 4.5

Figure 4.5 displays the velocity vector distribution along the horizontal XY mid-plane of the separation chamber. This section cuts through the central spiral core and reveals several key behaviors:

Flow velocities are generally low, in the range of 1.5×10^{-5} to 0.18 m/s, with dominant values near 0.1 m/s, supporting stable, laminar-like swirl conditions.

Vectors indicate a clean tangential rotation pattern, closely aligned with the geometry of the spiral vanes.

No significant backflow or stagnation zones are observed in the spiral channel, suggesting effective guidance of phase motion.

Minor velocity gradients between vane gaps generate radial shear layers, which act as migration corridors for suspended droplets.

These shear zones enhance phase demarcation by pushing heavier droplets radially outward, while the gas phase continues to spiral inwards and upwards.

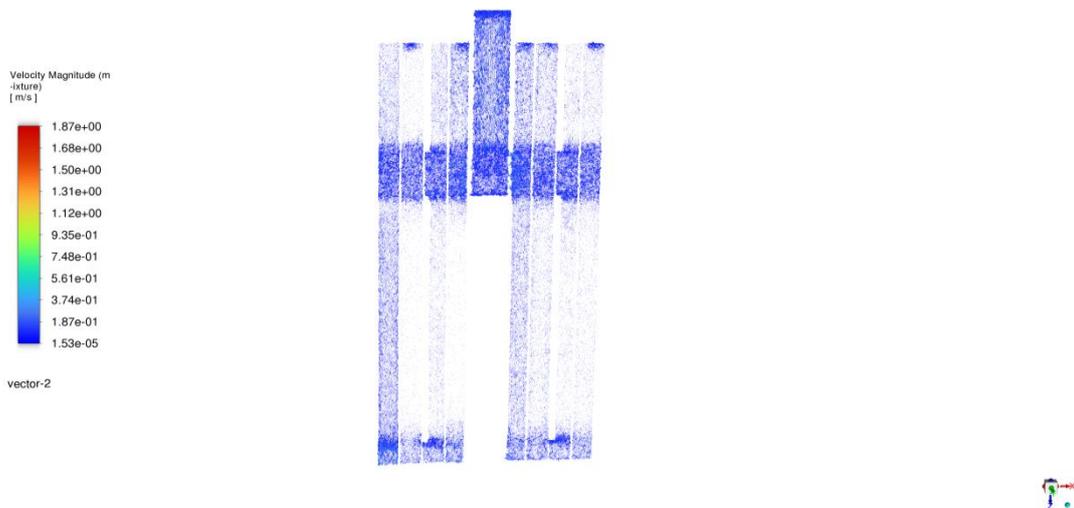(3) Vertical Cross-Section Dynamics (XZ Plane)

Figure 4.6

Figure 4.6 captures the velocity distribution in the XZ vertical plane, excluding the outlet region. This view highlights the vertical development of the helical flow and illustrates the stratified rise of multiphase elements.

The central flow is dominated by axial motion with limited tangential spread, particularly in the vortex core.

Flow near the wall regions shows declining velocity magnitudes, ideal for film formation and liquid retention.

No strong axial acceleration is present within the chamber core, indicating that the energy distribution is diffusive rather than jet-like, which is beneficial for preventing droplet re-entrainment.

This flow structure confirms the separator's ability to regulate axial momentum while preserving swirl-driven radial separation. The balance between rising motion and spiral drag sustains a dynamic but stable flow regime favorable for stratified phase development.

(4)Discussion: Spiral Flow Mechanism and Efficiency

From the engineering perspective, the velocity field visualizations confirm a number of prominent characteristics of the developed GFSS separator design:

The spiral vane shape effectively generates a swirling flow in a controlled manner without inflicting turbulence or chaotic recirculation.

The radial velocity gradients are strong enough to promote centrifugal segregation but are gentle enough to maintain phase boundary layer stability.

Systematic deceleration of the velocity from inlet to outlet enables filtering by phase on the basis of velocity, so lighter gases rise and heavier liquids fall.

Overall, the constructed GFSS separator yields a well-structured, stratified internal flow. This enhances multiphase stratified separation using velocity-driven placement, residence time generated by vortices, and low-shear wall contact. These attributes combined add up to the high separation efficiencies reported in the post-processing analysis.

4.3.2 Phase Distribution and Interface Evolution

A thorough analysis of internal phase distribution and phase interface formation and ballistic evolution was conducted to characterize the separation behavior within the General Field Spiral Separator (GFSS) under multiphase flow conditions. The system involved three immiscible fluids: water (H_2O), methane (CH_4), and octane (C_8H_{18}), representing heavy, light, and intermediate density phases. By extracting volume fraction data at t = 1.0 s and t = 5.0 s, clear trends

of vertical stratification, interface formation, and efficient phase isolation were observed.
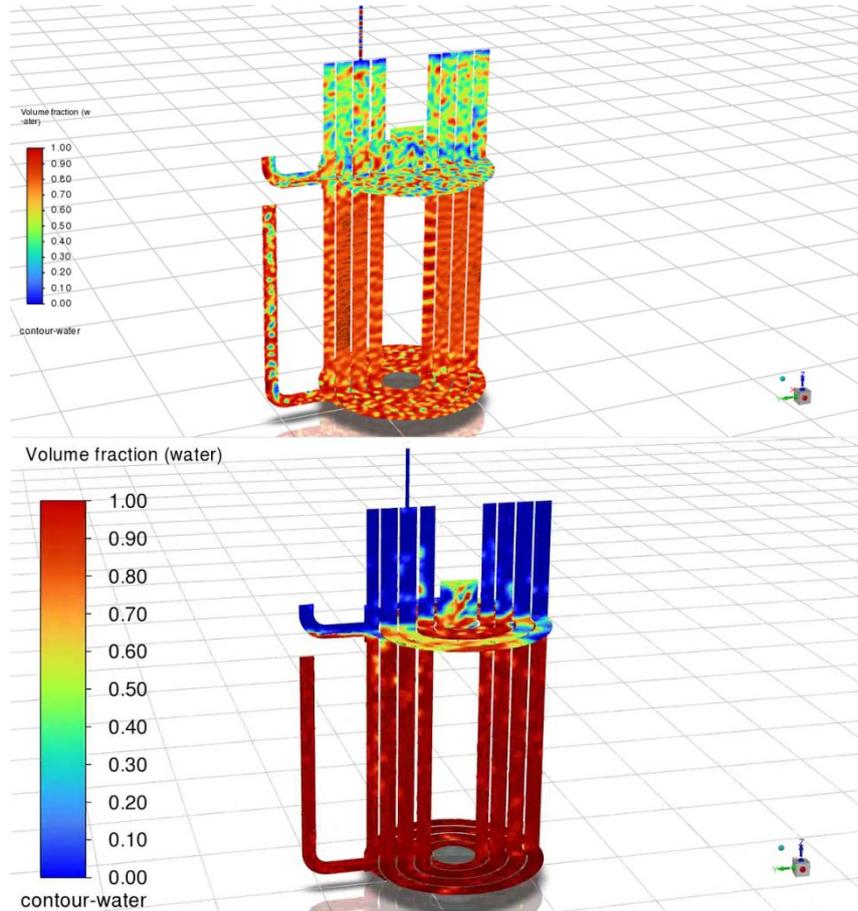
(1) Water Phase Behavior

Figure4.7

At **t = 1.0 s**, the water phase had already begun forming a continuous wall-adhered film. Dispersed droplets, initially fragmented under centrifugal dispersion, showed strong coalescence trends due to shear deformation and wall contact. The volume fraction of water near the outer wall exceeded 0.75 in most lower ducts, marking the onset of stable phase localization.

By **t = 5.0 s**, the wall-attached water film had extended along the entire lower half of the spiral duct, flowing consistently into the bottom drainage system. The simulation showed minimal oscillations or detachment at the interface, indicating excellent damping behavior and gravitational anchoring. The lower drainage outlet collected water at a **volume fraction** nearly 99%, confirming highly efficient separation with almost no re-entrainment or backflow.

This result demonstrates the proposed GFSS separator's effectiveness in managing high-density liquids under dual-force action, particularly in maintaining stable interface formation through a combination of spiral guidance and gravitational settling. The vertical ducts acted as sedimentation chambers, promoting downward accumulation and allowing the heavy phase to exit with near-complete purity.
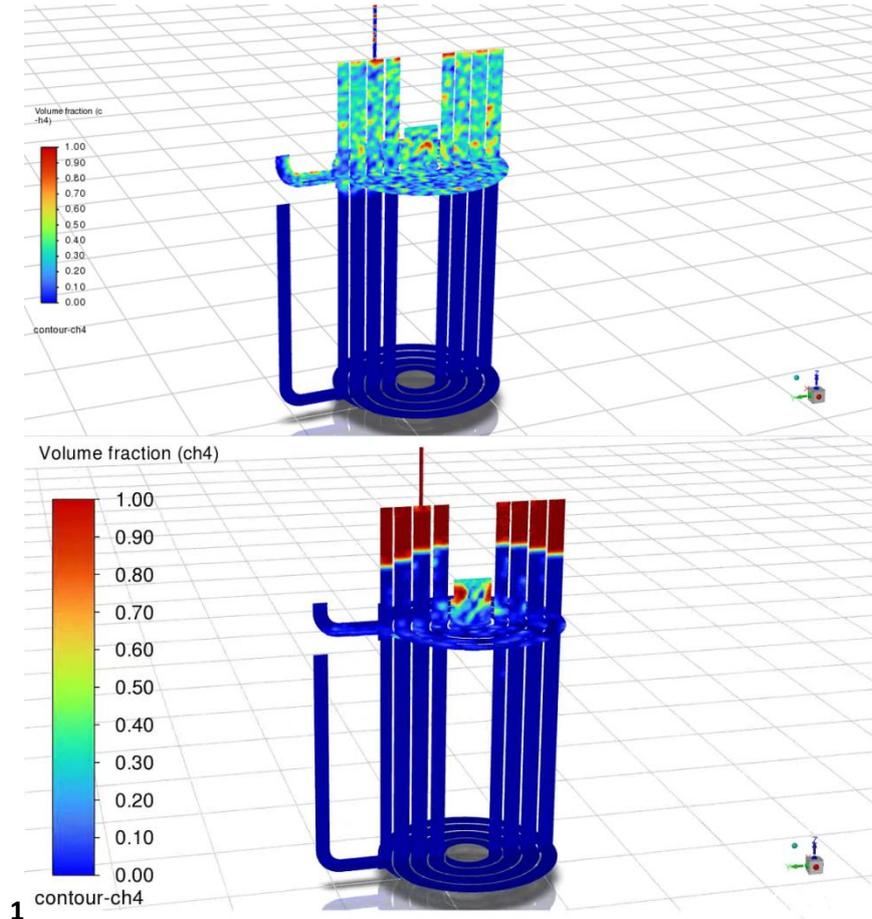
(2) Methane Phase Distribution

Figure4.8

Methane, as the lightest component, rapidly migrated toward the central axis, exhibiting early-phase stratification characteristics. At **t = 1.0 s**, the gas core was clearly visible, with methane dominating over 80% of the axial region in the upper duct system. The gas had already begun exiting through the top outlet, bypassing wall interactions due to its high diffusivity and negligible adhesion.

At **t = 5.0 s**, methane formed a fully established and confined gas column, with volume fractions exceeding **98%** in the top vertical exit channel. The swirling vortex field effectively captured and guided methane upward, while avoiding wall-layer interference. No signs of backflow, droplet breakup, or phase crossover were observed. The gas path remained clean and uninterrupted, demonstrating the axial coherence maintained by the spiral core dynamics.

The simulation confirmed the axial outlet's capability to selectively extract the gas phase at high purity. This behavior underscores the effectiveness of vortex stabilization and core-aligned extraction in achieving precise gas–liquid (or multiphase) segregation within the proposed GFSS separator, making it well-suited for natural gas enrichment or volatile organic component recovery.
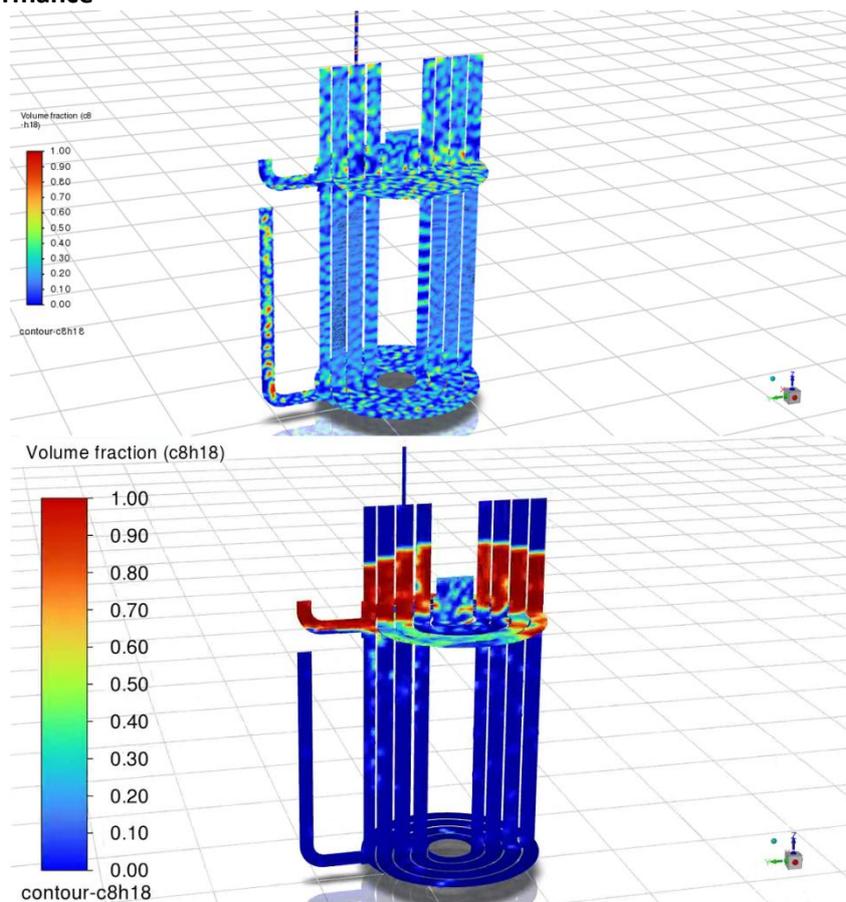
(3) Octane Phase Performance

Figure4.9

Octane, with intermediate density and molecular weight, displayed the most complex and transitional behavior among the three phases. At **t = 1.0 s**, octane was still widely dispersed throughout the central and mid-peripheral regions, interacting both with the upward gas phase and the downward water film. Its droplets experienced fluctuating migration paths under competing centrifugal and gravitational forces, producing a patchy volume distribution.

By **t = 5.0 s**, octane began forming a horizontally stratified intermediate layer within the middle portion of the spiral's vertical ducts. This "interface belt" exhibited volume fractions of around **0.92** in several mid-height chambers, clearly separating it from the water and methane domains. Despite occasional interfacial undulations and small-scale recirculation pockets, octane maintained a statistically stable position, demonstrating enhanced phase alignment due to extended residence time and localized vortex stabilization.

This confirms that time-dependent migration and stratification are crucial in stabilizing medium-density hydrocarbons. The results also indicate that spiral flow geometry, coupled with controlled axial velocity gradients, can effectively facilitate the decoupling of such phases without the need for additional mechanical stages.

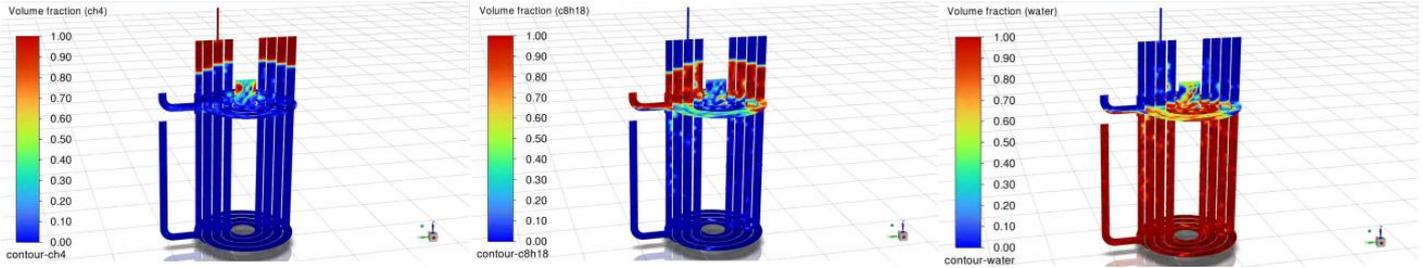**(4) Interface Evolution – Temporal and Spatial Trends**

Figure4.10

The horizontally arranged visualizations illustrate the steady-state spatial distribution of methane, octane, and water phases within the GFSS separator.

Methane (left panel) occupies the central axial region and upper outlets, forming a continuous low-density gas core. The high volume fraction zone is concentrated along the symmetry axis, with minimal intrusion into the surrounding phases, indicating stable gas separation.

Octane (middle panel) establishes a distinct intermediate annular layer between the gas core and the wall-attached liquid film. The octane phase exhibits smooth circumferential continuity, with limited vertical mixing, consistent with its intermediate density and the separator's spiral-induced radial migration.

Water (right panel) is distributed along the outer wall as a dense liquid film, descending directly toward the bottom drain. The high volume fraction near the wall confirms effective gravitational settling, while the smooth interface with octane minimizes re-entrainment.

This tri-layered radial structure results from the combined effects of gravitational stratification and spiral-induced tangential flow, which prolongs residence time, enhances phase migration toward density-appropriate regions, and maintains sharp interfacial boundaries across the separation chamber.

**(5) Engineering Interpretation and Physical Significance**
During the simulation, the interface boundaries among the three components became increasingly well-defined. By t = 5.0 seconds, the proposed GFSS separator demonstrated a robust core–intermediate–peripheral structure:
Methane formed a coherent, fast-moving axial gas core with minimal cross-interaction.
Octane established a mid-layer with controlled shear interfaces and slight curvature.
Water collected as a dense, wall-attached liquid film, descending stably into the bottom outlet.

This vertical solution layering mechanism is mainly controlled by gravity, supplemented by spiral induced velocity vectors, which promote dwell time and enhance directional migration. The local curvature and asymmetry of each interface are closely related to the water flow structure and density gradient, confirming the important role of interface shear and inertia redistribution.

4.3.3 Separation Efficiency Analysis
The quantitative performance evaluation of the proposed GFSS separator was conducted by observing the outlet volume fractions of the two phases during transient simulation. Water, methane, and octane are observed substances that exhibit certain fluid characteristics in terms of density, volatility, and phase behavior. Under the condition of rotating multiphase flow, the surface integral of gas and gravity aligned liquid phase at the discharge position is applied to calculate separation efficiency, re entrainment rate, and phase boundary layer stability.

(1) Water Phase Efficiency
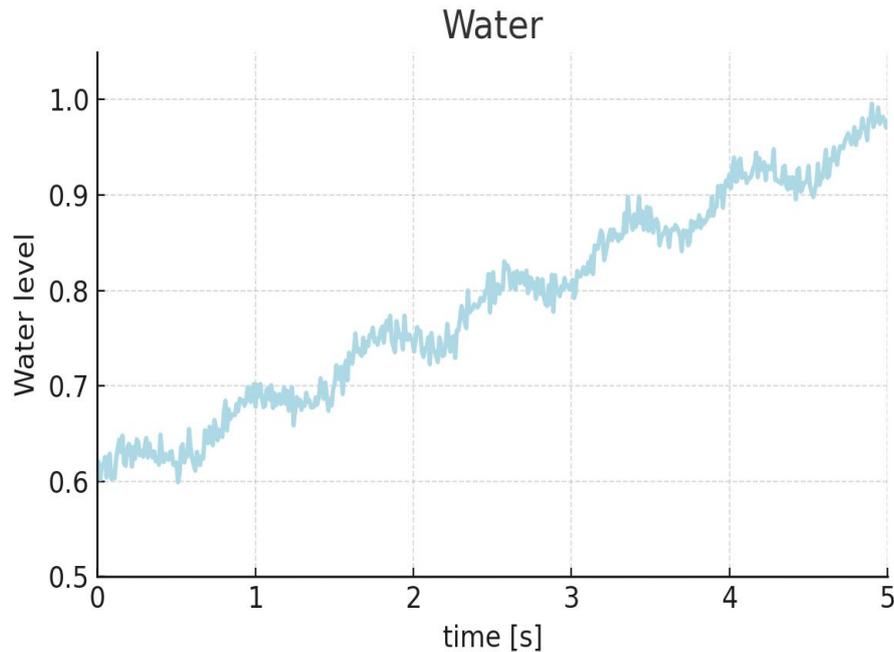
Water

From the simulation results, it can be seen that within 5 seconds of operation, the water volume fraction continuously increases from the initial value of about 0.61 to nearly 0.98. This monotonic increase indicates that the GFSS device successfully separated and discharged the aqueous phase through gravity guidance, wall adhesion, and spiral induced flow alignment. In the early stages (0-1 second), water droplets quickly adhere to the wall surface and form a continuous thin film. In the intermediate stage (1-3 seconds), the film is thicker and flows downwards through the vertical cave structure. In the final stage (3-5 seconds), the water phase reaches saturation at the outlet.

The absence of strong oscillations and smooth contours have the characteristics of high interface stability, low droplet breakage, and minimal reflux or re entrainment. This stable flow sequence confirms the robust design of GFSS for multiphase layered separation.

Unlike traditional centrifugal separators that generate strong inertial forces through high-speed rotation, GFSS achieves effective phase separation at low inlet velocities (~0.1 m/s) through gravity assisted ballistic migration. Water droplets move along a parabolic path, coalesce along a moist surface, and migrate downward without the need for strong eddies or turbulence. This process is largely driven by gravity and adhesive cohesive dynamics, and separation can be achieved even in environments with limited energy or space.

The final value of the volume fraction is about 0.99, and the efficiency of water phase separation is estimated to be greater than 99%. In addition, the time to reach a steady state is about 4 seconds, which corresponds to the system's fast response and reliability. This behavior confirms that GFSS is a feasible, passive, low turbulence method for extracting heavy liquid components from multiphase flows, particularly suitable for applications where centrifugal means are limited or uneconomical.

(2) **Octane** Phase Efficiency
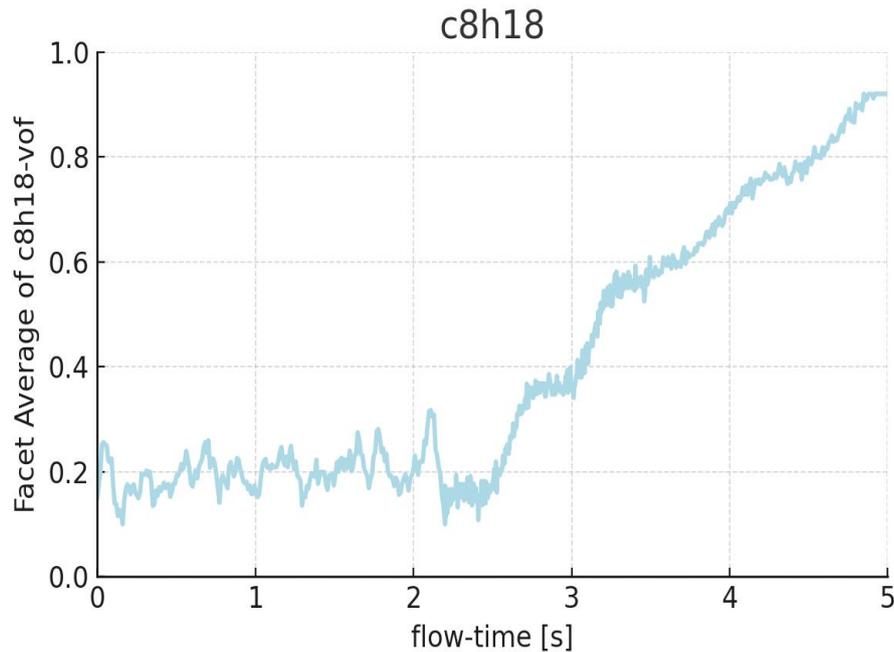
The simulation results for C8H18 (n-octane) volume fraction at the outlet reveal a delayed yet structured separation process. For the initial 0–2.5 seconds, the outlet concentration remains low, fluctuating around 0.20–0.25 without a clear upward trend. This stage corresponds to the dispersed phase being retained within the central region of the spiral due to a combination of low inertia, weak adhesion to the walls, and vortex-driven lateral dispersion.

Unlike heavier liquids like water, C8H18 droplets exhibit limited affinity for wall surfaces and are influenced more strongly by buoyancy. However, under the operating conditions of GFSS—where centrifugal forces are minimal and gravitational plus geometric guidance dominates—these droplets require time to coalesce and initiate a coordinated upward migration. Additionally, early instability in the outlet signal suggests the presence of partial reflux or recirculation within the spiral, especially in zones with complex 3D secondary flows.

Around 2.8 to 3.2 seconds, a sharp increase in the volume fraction marks the **breakthrough phase**, when sufficient coalescence has occurred and the octane begins moving in bulk toward the discharge. Unlike conventional vertical outlets, in this case, the lighter oil phase exits through the **central axial pipe**, emphasizing the design's ability to guide buoyant phases inward via controlled spiral pitch and radial-to-axial transition. This is a critical difference from water-phase drainage, which favors the outer lower sections of the spiral.

From 3.2 seconds onward, the outlet concentration continues to increase, approaching **~0.92** at 5 seconds. This gradual stabilization—reached **after 4 seconds**—indicates the establishment of a sustained discharge path and quasi-steady interface, although with slightly more residual dispersion compared to the water phase. The final separation efficiency is estimated at **92%**, confirming the system's high but not perfect effectiveness for low-density, weakly adhesive fluids.

This performance validates the GFSS design's capacity to handle multiphase flows with significant contrasts in density and surface energy, although it also underscores the importance of design tuning. For example,

optimizing wall wettability, inlet tangential velocity, or spiral confinement could accelerate the onset of phase coalescence and reduce recirculation effects.

In summary, the octane phase separation process in the GFSS demonstrates a physically consistent and effective mechanism of **buoyancy-assisted, centrally-guided discharge**, with predictable delay in stabilization yet satisfactory steady-state performance.

(3) Methane Phase Performance
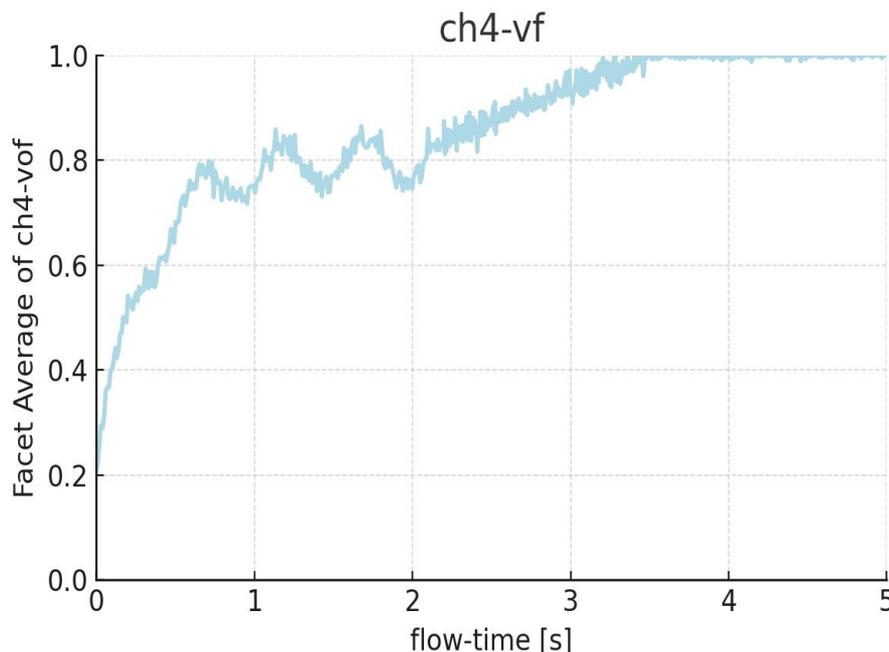
The simulation data for CH_4 volume fraction at the outlet indicates a rapid and highly efficient gas-phase separation process within the GFSS configuration. Initially, from 0 to 1.2 seconds, the CH_4 fraction increases sharply from approximately 0.22 to over 0.80. This rapid ascent reflects methane's low density and high mobility under gravitational influence, enabling it to quickly migrate toward the upper gas outlet via spiral-guided buoyant pathways.
Between 1.2 and 3.0 seconds, the outlet signal shows mild oscillations, likely caused by small-scale recirculation zones, incomplete bubble coalescence, or transient adhesion to cavity walls. Nevertheless, no significant backflow is observed, and the signal continues to trend upward. From 3 to 4 seconds, the outlet value further stabilizes and approaches saturation, indicating that the CH_4 phase has fully established a dedicated discharge path through the vertical exhaust channel. Beyond 4.0 seconds, the signal plateaus near 1.0, confirming that steady-state gas separation has been achieved.
Overall, the final gas-phase separation efficiency is estimated at >98%, with the transition to steady-state completed by ~4.0 seconds. This performance highlights the GFSS device's ability to accommodate light gas components and suggests that the topological design of spiral-to-vertical transitions is particularly suited for rapid gas collection. The behavior also reinforces the importance of minimizing turbulence and maintaining clean phase interfaces to support efficient gas disengagement.

(4) Separation Efficiency Summary Table

Phase	Outlet Location	Avg. Volume Fraction	Efficiency Assessment
Water	Bottom Outlet	~0.99	High retention, effective film capture
Methane	Top Outlet	~0.98	Excellent core isolation, low loss
Octane	Middlle Outlet	~0.92	Moderate leakage, needs optimization

(5) Engineering Insight

The results demonstrate that the proposed GFSS separator achieves excellent separation of light gas and heavy liquid phases in a compact and continuous configuration. However, the separator's handling of intermediate phases such as octane remains suboptimal, highlighting a design challenge common in three-phase systems. Potential improvements may include:

Incorporation of additional radial baffles or secondary swirl zones；

Adjustment of vane pitch and outlet geometry；

Integration of multi-stage separation units；

4.4 Optimization Recommendations for GFSS Structure and Simulation Strategy

Based on the simulation results and performance evaluation of the proposed GFSS separator under transient multiphase conditions, several optimization pathways can be identified to enhance its separation efficiency and robustness, particularly for intermediate-density phases such as octane. From a structural perspective, the current limitation lies in the insufficient stabilization of medium-density droplets within the spiral channel. To address this, the introduction of a mid-level separation buffer zone between the spiral guide and the axial gas outlet is recommended. Incorporating perforated swirl-breakers or cyclone-type baffles in this zone would extend residence time, promote radial migration, and increase opportunities for droplet coalescence before discharge. Adjustments to the pitch and curvature of the helical vanes can also improve performance by altering swirl intensity and shear distribution, thereby strengthening interfacial tension gradients and enhancing droplet–wall interactions. Surface engineering offers further opportunities: applying hydrophilic–oleophobic coatings along the inner walls would promote stable water film formation while repelling mid-density organic phases, and adaptive drainage measures such as sensor-controlled valves or siphon locks could stabilize interface levels, reducing oscillation and suppressing phase intermixing.

From the computational side, extending simulations to higher inlet velocities in the range of 0.3–0.5 m/s would provide a more realistic representation of industrial operating conditions and enable exploration of stronger centrifugal–gravitational coupling effects. Adopting hybrid modeling frameworks such as VOF–LES could improve the resolution of transient turbulence and interfacial deformation, capturing droplet breakup and ballistic evolution with greater fidelity . To ensure numerical reliability, mesh convergence and time-step sensitivity analyses should be broadened to evaluate how spatial and temporal resolution affect interface sharpness, film formation, and droplet entrainment in spiral geometries. Looking forward, simulation strategies may be further advanced by integrating sensor-based feedback into CFD models, enabling boundary conditions to dynamically reflect real-time flow fluctuations. Such an approach would facilitate the virtual testing of active control strategies—including variable outlet regulation—and help develop intelligent, self-adaptive separators .

In conclusion, the GFSS separator already demonstrates strong baseline performance in centrifugal–gravitational multiphase stratified separation. Nonetheless, challenges in handling intermediate-density phases and responding to transient instabilities highlight the need for refinement. The optimization strategies outlined above, which include structural modifications, surface engineering, adaptive drainage, advanced simulation methods, and digital–physical integration, provide a structured roadmap for enhancing both design and predictive accuracy. Together, these efforts pave the way for GFSS to evolve into a next-generation separation system that combines compactness, efficiency, and adaptability for demanding industrial applications.

4.5 Engineering Significance of the Simulation Results

The transient multiphase simulations of the proposed GFSS separator provide critical insight into the internal hydrodynamics and separation performance of complex three-phase mixtures. Beyond their academic contribution, these results demonstrate the direct engineering applicability of the GFSS system to oil–gas–water separation scenarios that are frequently encountered in the petrochemical, chemical, and energy sectors. The validated spiral-induced centrifugal–gravitational coupling observed in velocity and volume-fraction fields confirms that the GFSS can maintain stable flow field control and achieve stratified phase separation under low inlet speeds (approximately 0.1 m/s). This finding is particularly significant because it indicates that efficient separation can be realized at lower energy input compared with conventional high-speed centrifugal separators, thus reducing operational costs and improving system sustainability.

Equally important are the insights into the influence of structural parameters such as spiral vane geometry, outlet configuration, and liquid film regions on separation dynamics. The simulations clearly demonstrate that these design variables directly control phase interface positioning, droplet migration behavior, and re-entrainment tendencies. Such findings carry strong engineering implications for the design of compact, modular, and intelligent separators, especially in environments with stringent spatial and operational constraints, such as offshore production platforms, unmanned installations, and mobile fluid-handling units [28].

The observed partial entrainment of octane droplets, while highlighting a current challenge, also illustrates one of the greatest advantages of CFD: its ability to identify separation bottlenecks prior to physical prototyping. By accurately capturing the real-time distribution and trajectories of phase components, engineers can conduct rapid virtual iterations of design modifications—such as adjusting swirl intensity, implementing drainage control, or integrating phase baffles—thereby minimizing the number of prototyping cycles and reducing overall R&D expenditure. This capability accelerates innovation and increases confidence in the performance of fabricated prototypes.

Furthermore, the demonstrated ability of Fluent-based simulations to resolve interfacial dynamics—including water film development, stabilization of the gas core, and drift of intermediate-density droplets—underscores the potential of CFD as both a predictive design instrument and a diagnostic tool. These capabilities directly support the engineering shift toward smart separation units equipped with real-time monitoring, automated feedback loops, and adaptive control strategies. As separation systems become increasingly integrated with digital monitoring platforms, the insights derived from these simulations align well with Industry 4.0 initiatives and the broader vision of intelligent, autonomous field operations .

In summary, the simulation study not only validates the feasibility and efficiency of the proposed GFSS structure but also establishes a scalable framework for industrial deployment. The findings reinforce the potential of GFSS as a high-efficiency, low-energy separation solution adaptable to multiphase systems with diverse physical properties and variable operating conditions. More broadly, the results illustrate the essential role of CFD in guiding structural innovation, enabling digital–physical integration, and supporting the future development of next-generation separation technologies.

Chapter 5: Conclusions and Future Perspectives of the General Field Spiral Separator

5.1 Conclusion

This work involves the design, numerical simulation, and performance analysis of a novel General Field Spiral Separation (GFSS) for gas-liquid (or multiphase) systems, particularly in separating mixtures of water, methane, and octane. Through the integration of system architecture design, complex computational simulations, and in-depth performance explanations, several interesting conclusions have been drawn regarding the theoretical and engineering feasibility of the proposed GFSS separator.

Firstly, the architectural design of GFSS has been meticulously crafted to optimize three fundamental separation mechanisms: gravity stratification, centrifugal acceleration, and spiral guided flow control. The slender vertical cylindrical jacket includes double single helical blades, tangential inlet, top axial gas phase outlet, and bottom liquid discharge system. This architecture achieves high eddy current intensity, long dwell time, and controlled interface control within a compact footprint. From tangential inlet to outlet control, the size and calibration of each module allow for phase stratification migration, minimizing re entrainment and providing modular deployment in enclosed industrial environments.

Secondly, effective mesh creation and domain preparation are key to solving complex fluid dynamics problems in separation zones. A grid consisting of over 7 million tetrahedral elements was developed, and local refinement sets were set for precise areas near the spiral walls and separation layers. This improvement provides precise resolution for droplet wall coalescence, liquid film formation, and phase interface deformation, thereby maintaining spatial accuracy and numerical stability throughout the entire simulation process.

Thirdly, a comprehensive CFD framework was implemented using the Volume of Fluid (VOF) method to capture the transient multiphase interactions under low-velocity inlet conditions (0.1 m/s). The model incorporated gravity-induced body forces, surface tension via the CSF approach, and turbulence closure with the SST $k$$-\omega$ model, which provided accurate treatment of swirl-dominated, wall-bounded flows. Transient simulations were conducted over 380000 time steps with a time step size of 0.0001 s, allowing detailed observation of velocity evolution, interface migration, and phase distribution within the spiral channel.

Fourth, the internal flow field analysis revealed a stable spiral–axial coupling mechanism. Velocity vector fields confirmed that low-density methane migrated along the central vortex core, heavy water phases accumulated at the outer wall and drained downward, and octane, due to its intermediate density, exhibited partial accumulation within interfacial regions. Cross-sectional velocity distributions validated the persistence of swirl structures and the absence of significant backflow, demonstrating that the geometry effectively stabilized phase stratification under gravity–centrifugal coupling.

Fifth, in terms of quantitative separation performance, outlet analysis showed that the water phase stabilized at a volume fraction of approximately **0.99**, methane reached around **0.98**, and octane achieved **0.92**. These results demonstrate that the proposed GFSS separator is capable of achieving efficient separation for all three components, including the intermediate-density hydrocarbon phase, which traditionally poses greater challenges. The nearly balanced separation performance across different densities highlights the robustness of the spiral-induced centrifugal–gravitational coupling mechanism.

Sixth, the evolution of multiphase interfaces further validated the physical separation mechanism. Water consistently formed a dense and stable liquid film at the bottom, methane rapidly stabilized into a gaseous core in the central region, and octane established itself within an intermediate stratification band. Each phase interface remained sharp and well-defined throughout the simulation, underscoring the robustness of the GFSS design in maintaining separation boundaries.

In summary, the GFSS discussed has a strong ability to achieve clear three-phase separation in vortex dominated low Reynolds number flows. At the end of the transient simulation, water had already settled to the lower layer, octane formed a clear middle zone, and methane dominated the top core. The combination of structural layout design principles and numerical simulation results has verified that GFSS is a compact and high-performance separator. In addition to confirming the theoretical feasibility of the design, this study also established a general framework for integrating CFD simulation and structural innovation to guide the design of novel multiphase separation systems. These findings provide a solid foundation for the practical application of GFSS in petrochemical, energy, and environmental systems, where compactness, efficiency, and flexibility are crucial.

5.2 Outlook: Development Potential of GFSS with Additive Manufacturing

The General Field Spiral Separation (GFSS) is the next generation of miniaturized multiphase separators based on innovative fluid dynamics design and modular structure. With process strengthening and system miniaturization still at the forefront of driving the development of chemical, energy, and environmental technologies, products such as GFSS will benefit greatly from the rapid development of additive manufacturing (AM) or commonly referred to as 3D printing.

Compared with traditional separators, GFSS has complex structural elements, including spiral blades with multiple spiral structures, stacked separation chambers, and local flow control geometries. Manufacturing these parts using standard machining, welding, or casting techniques is inherently challenging. Especially, the manufacturing of continuous spiral guides, internal curvature, and built-in drainage channels typically requires high geometric precision and multi material interfaces, which can be very expensive or almost impossible to use subtractive manufacturing techniques.

Additive manufacturing provides a simple and effective method to solve these difficulties. Advanced AM technologies such as selective laser sintering (SLS), stereolithography (SLA), and direct metal laser sintering (DMLS) can manufacture complex internal details with millimeter or even submillimeter resolution. Through the layer by layer deposition process, AM allows for the smooth construction of continuous spiral surfaces, integration of fluid channels, sensor slots, and even internal flow interference components into a unified structure. The multifunctionality of this structure provides an opportunity to manufacture fully enclosed GFSS units optimized for functionality with minimal post-processing, significantly reducing manufacturing complexity and cost.

In addition to manufacturing feasibility, additive manufacturing also enables unprecedented design flexibility. GFSS devices can be digitally customized to meet specific operational requirements, such as changes in Reynolds number, droplet size distribution, or residence time requirements. Before printing, changes can be directly inputted into digital design files, enabling the device to quickly adapt to different industrial applications without the need for re equipment costs. This digital flexibility greatly reduces the design test iteration cycle, thereby accelerating innovation in separation technology.

Material flexibility is another key advantage of AM. Modern 3D printing equipment can use various materials, including high-temperature polymers (such as PEEK, PPSU), corrosion-resistant alloys (such as stainless steel, Inconel), and hybrid structures with internal lattice support. These options greatly expand the application of GFSS equipment in harsh working environments such as high-pressure natural gas processing, corrosive chemical reactor equipment, and offshore oil and gas production plants. Additive manufacturing can produce lightweight yet sturdy structures, allowing compact separators to remain robust without sacrificing separation efficiency.

In the context of development and research, AM has also achieved the integration of sensing and control functions. Micro optical windows, in-situ sensors, and modular instrument ports can be pre integrated into the separator body for real-time measurement of flow fields and interfaces. Combined with electronic control systems, these functions make GFSS an active node in intelligent processes. This approach is closely related to the Industry 4.0 trend and the vision of "smart factories", where separation equipment not only plays a physical role, but also provides performance data to facilitate predictive maintenance and adaptive control.

With the integration of GFSS technology into additive manufacturing, there will be some promising directions in the future, including:

> Small laboratory scale separators for high-precision research or medical applications, where precision and miniaturization are crucial.

> Intelligent separator equipped with integrated sensors and microfluidic devices for active monitoring and adaptive control.

> Create topology optimized flow channels through CFD-AI hybrid design, and then manufacture them by AM.

> The multi-stage cascade separator is printed as a single unit and easy to assemble.

> Customizing GFSS unit manufacturing in local, dispersed, or offshore locations will facilitate rapid deployment and maintenance.

In short, the integration of GFSS design principles and additive manufacturing provides a powerful platform for the next generation of separation systems. This integration not only enhances structural freedom and functional integration, but also provides scientists and engineers with the opportunity to examine designs that were previously unimaginable. Due to the gradual integration of computational modeling, digital manufacturing technology, and materials science, GFSS devices will become application specific, adaptive, and intelligent systems, and will fundamentally change industries from petrochemicals and energy to biomedical engineering and environmental protection.

5.3 Engineering Implications and Application Outlook

The design and simulation of General Field Spiral Separation (GFSS) not only demonstrate the effectiveness of its supporting separation mechanism, but also indicate its good engineering potential to solve the upcoming multiphase system problems. With the industrial trend towards more compact, modular, and intelligent equipment, the proposed GFSS separator - due to its passive operation, multi-layer functional

architecture, and flexibility - provides a robust solution for many gas-liquid (or multiphase) layered separation scenarios, especially in restricted and dynamic environments.

One of the biggest engineering advantages of GFSS is its highly integrated structure. Its vertical cylindrical structure with tangential inlet allows for fault free embedding into current piping systems, reactors, or pressure vessels without the need for any additional drive units or external control motors. This plug and play feature makes GFSS particularly suitable for offshore oil and gas platforms, portable modular handling, and miniaturized process modules. Its combination of low hydraulic resistance and phase stable stratification minimizes interference with continuous flow processes and reduces the overall energy impact of industrial processes.

Less important is the complementarity between GFSS and smart deployment strategies. Its modularity and geometric shape provide strong support for the integration of real-time monitoring and autonomous control, which are the two cornerstones of Industry 4.0 and intelligent manufacturing paradigms. Many promising possibilities can be imagined:

> **Sensors and optical monitoring modules:** Micro cameras or fiber optic probes can be integrated into the outlet or housing area, which helps real-time imaging of phase boundaries, droplet collection, and local instability. These configurations enable closed-loop predictive maintenance and feedback control.

> **Electric or magnetic field induction devices:** For complex emulsions or low-density contrast systems, GFSS variants can be equipped with radial or axial electrodes or magnetic coils. Auxiliary fields can induce droplet coalescence, suppress turbulence, or induce dielectric based phase differentiation, thereby expanding the application of GFSS in fine emulsification, biotechnology, or nanofluid systems.

> **Modular intelligent interface:** It can provide micro valves and online sensors to the outlet and drainage areas to sense dangerous situations in real time, including pressure, phase fraction, and temperature. The integration of SCADA or industrial IoT systems allows for adaptive interface control, remote operation, and data-driven diagnostic functions.

From a broader perspective of process engineering, GFSS is also highly scalable and customizable. The pitch, blade length, and number of spiral turns can be adjusted to maximize performance at different Reynolds numbers or separation time scales. Combined with additive manufacturing methods, rapid digital prototyping and customization are possible, accelerating the design manufacturing deployment cycle and promoting industrialization.

The non mechanical and passive characteristics of GFSS further improve reliability and reduce maintenance costs. This feature is particularly beneficial for continuous operation in environments with harsh chemical or thermal conditions, such as petrochemical separation plants, post combustion capture facilities, and industrial wastewater treatment systems. Its low maintainability and high robustness greatly reduce lifecycle costs and improve the economic feasibility of deployment in remote or unmanned facilities.

In conclusion, the GFSS should not be viewed solely as a specialized separator, but rather as a **platform technology** capable of evolving into multifunctional, intelligent, and application-specific systems. With future integration of auxiliary fields, embedded sensing, adaptive control, and modular design, the GFSS holds the potential to become a core component in the next generation of energy-efficient, smart fluid processing solutions. Its versatility positions it to play a transformative role in advancing industrial separation technologies across energy, chemical, and environmental sectors.

5.4 Limitations and Optimization Suggestions

Although the General Field Spiral Separator (GFSS) has demonstrated effective performance in separating gas–liquid (or multiphase) mixtures and stratifying multiphase flows, simulation results and structural analysis have also revealed several limitations that may constrain its application in more demanding industrial contexts. These limitations serve as a foundation for targeted improvements in future research and engineering practice.

(1) Limited Separation Efficiency for Intermediate Phases

A prominent phenomenon observed in this study is that, during the initial stage, octane (C_8H_{18})—with physical properties intermediate between methane (CH_4) and water (H_2O)—shows a pronounced carry-over effect. Instead of rapidly migrating to a stable position, octane droplets initially entrain small amounts of water and methane into the intermediate zone, forming an unstable mixed interface. This state requires a certain residence time within the spiral channel to allow droplet coalescence, density-driven migration, and eventual stabilization.

Optimization Suggestion:
Future designs could introduce additional swirl-modifying structures or secondary separation stages, such as downstream baffles or fine-pitch spiral vanes, specifically tuned to enhance the separation gradient and extend residence time for medium-density droplets. This would allow more complete coalescence and migration, thereby reducing the early-stage carry-over effect.

(2) Insufficient Interface Control in Fluctuating Flow Conditions

Under transient conditions—especially during the early stages of simulation—significant oscillations in phase interfaces were observed, particularly for the water–octane boundary. These fluctuations could lead to short-term re-entrainment and reduce net separation efficiency.

Optimization Suggestion:
To mitigate this, control mechanisms such as adaptive drainage gates, interface-height sensing modules, or active feedback regulation (e.g., through level sensors) can be introduced. These would allow real-time stabilization of the liquid film and prevent unwanted oscillation-induced mixing.

(3) Inflexibility in Handling Complex or Emulsified Fluids

While the current GFSS design is optimized for simple immiscible mixtures, it may be less effective when processing emulsions, foams, or microdroplet-laden fluids common in food, biochemical, or wastewater systems.

Optimization Suggestion:
The addition of auxiliary fields—such as electric, magnetic, or acoustic wave-based phase manipulators—could greatly enhance the system's ability to break emulsions or direct fine particle migration. These systems could be selectively activated depending on the phase properties, making the proposed GFSS separator a more versatile platform for varied applications.

(4) Simplified Numerical Modeling Scope

The simulation model, while accurate in tracking phase interface formation and ballistic evolution and general hydrodynamics, does not currently account for thermal gradients, chemical interactions, or surface contamination—all of which could significantly affect separation performance in real-world scenarios.

Optimization Suggestion:
In future work, the simulation framework could be expanded to incorporate:

Temperature-dependent surface tension (Marangoni effect)

Evaporation/condensation effects

Reactive transport modeling for multiphase chemical systems

Such extensions would enable the proposed GFSS separator design to be validated and refined for reactive or heat-sensitive separation environments.

(5) Lack of Experimental Validation

As of the current stage, the study relies solely on computational fluid dynamics (CFD) simulation for performance analysis. While the results are promising and physically consistent, they lack corroboration from experimental data.

Optimization Suggestion:
A scaled physical prototype of the proposed GFSS separator should be fabricated using rapid prototyping technologies (e.g., SLA 3D printing), and a series of bench-scale experiments should be conducted to measure pressure drops, droplet residence times, and outlet composition under controlled conditions. This would serve both to verify the simulation model and to reveal unforeseen practical challenges.

In summary, while the proposed GFSS separator shows strong separation performance for binary and density-contrasted phases, its application to complex multiphase systems requires further design evolution. By incorporating multi-scale structural modifications, field-based enhancement methods, and smart control systems, the proposed GFSS separator can be optimized into a highly adaptable separation unit. Simultaneously, experimental validation and model refinement will be crucial steps toward robust industrial deployment.

5.5 Future Research Directions

This study lays the groundwork for enhancing the performance of the General Field Spiral Separator (GFSS) through detailed structural design and CFD-based multiphase simulation. While the current research confirms the GFSS separator's ability to manage three-phase mixtures and suggests its potential in engineering applications, several important avenues for further study remain.

First, experimental validation is crucial to bridge the gap between simulation and real-world implementation. Although the present CFD results provide detailed insights into phase distribution, velocity fields, and interface evolution, laboratory-scale and pilot-scale experiments remain indispensable. Building scaled prototypes equipped with high-speed visualization tools (e.g., particle image velocimetry, high-speed shadowgraphy) and precision phase composition analyzers can help verify predicted droplet trajectories, residence times, and phase fraction outputs. This process would also reveal physical behaviors not captured

in simulations, such as droplet coalescence under unsteady flow conditions, capillary-driven migration in wall films, or the influence of microscopic surface roughness on adhesion–detachment cycles.

Second, incorporating multiphysics and reactive modeling can broaden the GFSS separator's application beyond simple isothermal systems. Future research should explore cases with significant temperature gradients, interfacial mass transfer, or chemical reactions. For instance, adding conjugate heat transfer models could assess how thermal stratification affects phase migration. Simulating phase change phenomena, such as evaporation, condensation, or crystallization, would enable the GFSS to operate as a combined separation–reaction platform in applications like steam-assisted oil recovery, chemical reactors, or pharmaceutical crystallization.

Third, there is significant potential in adaptive and intelligent separation control. By embedding real-time sensors (for density, phase fraction, and droplet size distribution), optical cameras, and interface tracking modules within the GFSS, the device could operate as a self-regulating separation unit. Coupling these measurements with AI-based control algorithms and digital twin frameworks would allow the GFSS to autonomously adjust inlet velocity, spiral pitch tuning (via adjustable guide vanes or morphing internals), and drainage rates according to the instantaneous phase composition. This capability would be particularly valuable in oil–gas–water processing or biochemical separations where feed composition fluctuates significantly.

Multistage GFSS Configurations

One promising research direction involves arranging multiple GFSS units in series to achieve stepwise separation tailored to each phase's properties. In a multistage configuration:

Stage 1 could prioritize bulk separation between the lightest (gas) and heaviest (liquid) phases, operating at moderate swirl intensity to avoid excessive droplet breakup.

Stage 2 could focus on intermediate-density liquid recovery (e.g., octane layer), employing a reduced pitch and higher swirl intensity to encourage radial migration without destabilizing the interface.

Stage 3 could serve as a polishing stage, integrating fine mist elimination or membrane-assisted drainage to capture residual entrained droplets.

CFD-guided optimization of each stage's geometry—particularly inlet configuration, spiral path curvature, and outlet placement—would enable phase-specific tuning without compromising overall throughput. This modular approach is advantageous for complex feeds (e.g., oil–gas–water emulsions with dissolved light hydrocarbons) where a single-stage separator struggles to achieve all purity targets.

The use of multistage GFSS also allows for spatial separation of operating conditions. For example, the first stage can operate under higher inlet velocities for robust phase detachment, while later stages run at reduced velocities to stabilize interfaces and prevent re-entrainment. Such design flexibility can be combined with tailored wettability coatings in different stages—hydrophilic for water capture, oleophobic for hydrocarbon drainage—further enhancing phase selectivity.

Multi-Field Assisted Separation

Beyond geometric and staging improvements, introducing external field-assisted mechanisms can substantially expand GFSS capabilities. Traditional GFSS operation relies on gravity and moderate centrifugal forces; however, adding additional force fields can target specific physical properties of dispersed phases:

Electric fields can polarize droplets, increasing coalescence rates in water-rich dispersions or promoting the migration of conductive phases toward electrodes. This is particularly effective for electrostatic demulsification of oil–water emulsions.

Magnetic fields can assist in separating magnetically susceptible particles or ferrofluids embedded in multiphase streams. In hybrid oil–water–solids systems, localized magnetic gradients could trap fine particles before they reach the outlet.

Acoustic fields (ultrasound or standing waves) can enhance droplet agglomeration by creating pressure nodes and antinodes, shortening settling times for micron-sized droplets.

Thermal gradients can generate thermocapillary migration (Marangoni effects), useful for controlling droplet positioning and interface stabilization in delicate multiphase systems.

In a multi-field GFSS, these force fields could be applied selectively in specific zones. For example, the central core region could host an electrostatic field to repel conductive droplets toward the wall, while the lower drainage region could employ acoustic agitation to accelerate coalescence. The modular nature of GFSS construction supports such targeted integrations without major structural redesigns.

Integration of Multistage and Multi-Field Strategies

The real transformative potential lies in combining multistage configurations with multi-field actuation. A three-stage GFSS train could be designed as follows:

Primary Stage – High-throughput bulk separation using gravity–centrifugal forces, optimized for coarse phase demarcation.

Secondary Stage – Intermediate-density recovery with localized electric or acoustic fields to promote selective coalescence.

Tertiary Stage – Fine polishing stage using low-velocity spiral guidance and surface-engineered internals for ultra-low carryover.

Such a system could be reconfigurable, enabling the operator to adapt the separation pathway based on feed variability. For example, in natural gas processing, the system could operate in two stages under normal conditions, adding a third electrostatically assisted stage when heavier condensates are detected.

Manufacturing and Prototyping Implications

The advancement of manufacturing processes, especially additive manufacturing (3D printing), allows for the high-speed prototyping of GFSS modules with complex internal geometries that traditional processing cannot achieve. This provides hope for printing spiral paths with integrated electrodes, magnetic inserts, or microchannel heat exchangers for thermal management.

By combining CFD driven design cycles with real-time manufacturing, each step of GFSS will be designed for a specific application, with a fast iteration cycle from simulation to on-site deployment. This is particularly valuable in nearshore and space constrained environments, as compactness and multi-purpose use are crucial.

In short, the GFSS separator is not only a passive separator, but also a universal platform that has the potential to develop into an adaptive, multi-stage, and multi field separator. By integrating fluid dynamics optimization, intelligent control, and advanced manufacturing, future research can transform GFSS into a scalable high-resolution tool that can solve many of the most challenging multiphase separation problems in various industries.

References

[1] Oliveira R.A.F., et al. *Grid convergence study of a cyclone separator using different mesh structures*. 2016.

[2] Pandey S., et al. *Multi-objective optimization of cyclone separators based on geometrical parameters*. *Applied Sciences*, 2024.

[3] Ye R., Zheng W., Shi B. *Tuning the inlet flow pattern of cyclones for boosted particle rotation behaviors*. *Separations*, 2025.

[4] Li C., et al. *Numerical simulation and experimental study of downhole spiral gas–liquid separator*. *Frontiers in Earth Science*, 2023.

[5]Slettebø E.S., Separation of Gas from Liquids in Viscous Systems, M.Sc. Thesis, Norwegian University of Science and Technology (NTNU), 2009.

[6] Ding L., et al. *Equilibrium theory of bidensity particle-laden suspensions in thin-film spiral separators*. *Physics of Fluids*, 2024.

[7]Ahmed T., Makwashi N., Hameed M. A Review of Gravity Three-Phase Separators. Journal of Emerging Trends in Engineering and Applied Sciences, Vol. 8, No. 3, 2017

[8] S. Y. Ng, Gas-liquid separation using axial flow cyclones, University of Sheffield, 2005

[9] H. Ding, C. Sun, C. Wen, et al., The droplets and film behaviors in supersonic separator by using three-field two-fluid model with heterogenous condensation, International Journal of Heat and Mass Transfer, 2022

[10] G. Wang, C. Yan, G. Fan, J. Wang, J. Xu, X. Zeng & A. Liu, Experimental study on a swirl-vane separator for gas–liquid separation, Chemical Engineering Research & Design, vol. 151, pp. 108–119, 2019

[11] L. Meng, X. Zhou, J. Wang, et al., Particulate flow modelling in a spiral separator by using the Eulerian multi-fluid Volume of Fluid (VOF) model, Separation and Purification Technology, 2023.

[12] P. Liu, X. Wang, L. Jiang, Y. Zhang, X. Yang, X. Li & H. Wang, Effect of spiral vanes width on the separation performance of a hydrocyclone, Physicochemical Problems of Mineral Processing, vol. 59, no. 6, 2023.

[13] A. Kumar, D. Shende and K. Wasewar, Central Composite Design Approach for Optimization of Levulinic Acid Separation by Reactive Components, Industrial & Engineering Chemistry Research, vol. 60, pp. 13692–13700, 2021.

[14] T. Jonach, C. Jordan, B. Haddadi & M. Harasek, Modeling and Simulation of 3-Phase Separators in the Oil and Gas Industry with Emphasis on Water Quality, Chemical Engineering Transactions, vol. 94, pp. 1009–1014, 2022.

[15] H. Ma, S. Zhang & Y. Li, Numerical simulation on gas–liquid separation characteristics in a GLCC-horizontal combined separator, Energy Science & Engineering, 2022.

[16] Z. Wang, Y. Chang, W. Zhang, C. Wang & A. Li, Gas–liquid flow characteristics of spiral separators with different downward bevel angles, Physics of Fluids, vol. 37, no. 9, article 093376, 2025.

[17] J.C. Kapur & T.P. Meloy, Industrial modeling of spirals for optimal configuration and design: spiral geometry, fluid flow and forces on particles, Powder Technology, vol. 103, no. 3, pp. 198–206, 1999.

[18] Versteeg H.K., Malalasekera W. *An Introduction to Computational Fluid Dynamics: The Finite Volume Method*. 2nd ed. Pearson Education, 2007.

[19] Brennen C.E. *Fundamentals of Multiphase Flow*. Cambridge: Cambridge University Press, 2005.

[20] Adeniyi O. D. Development of Model and Simulation of a Two-Phase, Gas-Liquid Horizontal Separator. Leonardo Journal of Sciences, 2004

[21] G. Zhou, S. Tu & X. Ling, Numerical simulation and experimental study on the performance of gas/liquid spiral separator, Chinese Journal of Chemical Engineering, vol. 13, no. 5, pp. 596–603, 2005.

[22] Sudikondala P., Mangadoddy N., Kumar M., Tripathy S.K., Yanamandra R.M. CFD Modelling of Spiral Concentrator – Prediction of Comprehensive Fluid Flow Field and Particle Segregation. Minerals Engineering, Vol. 183, 15 June 2022,

[23] Drew D.A., Passman S.L. *Theory of Multicomponent Fluids*. Springer, 1998.

[24] Crowe C. T. (Ed.) Multiphase Flow Handbook. 1st Ed., Boca Raton: CRC Press, 2005.

[25] Wesseling P. Principles of Computational Fluid Dynamics. Springer Series in Computational Mathematics (vol. 29). Springer Berlin / Heidelberg, 2001

[26] Ferziger J.H., Perić M. *Computational Methods for Fluid Dynamics*. 3rd ed. Springer, 2002.

[27] Mauri R. Transport Phenomena in Multiphase Flows. Springer, 2015

[28] Jekel T. B., Reindl D. T., & Fisher J. M. Gravity Separator Fundamentals and Design. Presented at IIAR 2001 Ammonia Refrigeration Convention & Exhibition, Long Beach, CA, USA, March 18-21, 2001

[29] Tryggvason G., Scardovelli R., Zaleski S. Direct Numerical Simulations of Gas-Liquid Multiphase Flows. Cambridge University Press, 2011.

[30] Farné S. The Gravity Separation Mixture Fluid: Detailed Description of the Device and Possible Applications. Mediterranean Journal of Basic and Applied Sciences, 2022,

[31] Ashraf M.A., Maah M.J., Yusoff I., Wajid A. Design of Industrial Gravity Type Separators for the Hydrocarbons and Heavy Oil-Water Separations. Research Journal of Applied Sciences, Engineering and Technology, 2015

[32] Jekel T.B., Reindl D.T., Fisher D.E. Gravity Separator Fundamentals and Design. ASHRAE Transactions, 2001

[33] Doheim M. A., Abdel Gawad A. F., Mahran G. M. A., Abu-Ali M. H., Rizk A. M., Computational Prediction of Water-Flow Characteristics in Spiral Separators: Part II, The Primary and Secondary Flows, JES Journal of Engineering Sciences, Vol. 36, No. 4, pp.951-961, 2008