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Theoretical Foundations of Gas-Dynamic Processes in Centrifugal Separators under Variable Flow Regimes

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Abstract

This paper presents a theoretical description of gas-dynamic separation in centrifugal separators operating under variable flow regimes typical of natural gas production. The analysis connects swirl generation, radial pressure gradients, residence time, and interphase momentum exchange with criteria for annular-film formation, droplet capture, and liquid carry-over. Novelty is obtained by unifying critical-velocity reasoning for centrifugal tray elements with recent publications on cyclone and hydrocyclone geometry effects, turbulence closure sensitivity, and CFD-based flow-field interpretation. The work aims to clarify how inlet-rate transients affect the balance between centrifugal forcing and axial transport, thereby altering separation efficiency and pressure loss. Comparative analysis and dimensional reasoning are applied to synthesize relationships among Reynolds, swirl, and Stokes numbers and to interpret published flow-structure observations. The discussion maps design parameters to operational envelopes relevant to field separators and to retuning via selective plugging. The results support engineering decisions for production-facility specialists dealing with fluctuating well streams.

Keywords: Centrifugal separator, Gas–liquid separation, Swirling flow, Liquid carryover, and Critical velocity.

1. Introduction

For production facilities serving high-rate gas wells, inlet conditions fluctuate because of reservoir depletion, intermittent liquid loading, separator train switching, and transient wellhead throttling (Akter *et al*., 2023). Under such conditions, centrifugal separation devices face two coupled sensitivities: the swirl field that provides radial segregation depends nonlinearly on inlet momentum, and the interphase exchange (droplet inertia, film formation, entrainment, and re-entrainment) shifts when axial transport begins to dominate over centrifugal forcing. In practice, the same mechanical design can alternate between stable annular-film capture and intensified carryover regimes, creating metering distortions and operational risk for downstream equipment in gas-gathering networks.

The goal of this study is to develop a consistent theoretical interpretation of gas-dynamic processes in centrifugal separators operating under variable flow regimes, with direct application to production-engineering tasks typical of large gas fields. Three tasks follow from the goal:

1) to formalize how the swirl-induced pressure field and residence time depend on flow rate and geometry for centrifugal separators;
2) to interpret regime transitions that govern film formation and carryover when inlet conditions vary;
3) to derive engineering-oriented implications for operational retuning of centrifugal elements, with emphasis on maintaining effective velocities and limiting carryover under transient inflow.

Novelty is expressed through a synthesis that aligns regime-based critical-velocity logic for centrifugal elements with recent peer-reviewed analyses of cyclone/hydrocyclone internal flow fields, turbulence-model sensitivity, and geometry-driven performance shifts, forming a single analytical narrative that can be used in design review and operational decision-making.

2. Methodology

The literature base was established to encompass: regime physics of gas–liquid cyclones, sensitivity of structural parameters, CFD reliability, and engineering interpretation of swirling separators under varying inlet conditions. Y. Bai (2021) examined the mechanisms of bubble flow and separation behavior in gas–liquid cyclone separators. D. Chen (2025a) studied how geometric parameters alter separation performance in gas–liquid cyclone separators. J. Chen (2025b) proposed a secondary separation cyclone concept and evaluated internal flow restructuring by numerical modeling.

C. Li *et al*. (2023) combined numerical simulation and experiments for a downhole spiral gas–liquid separator, linking the swirl structure to separation behavior. V. Mykhailiuk (2024) analyzed the feasibility limits of CFD modeling for gas separators and outlined practical modeling constraints. G. Seon (2022) compared RANS and LES predictions for a cyclone-type oil separator, linking turbulent structure to efficiency and pressure loss. P. Thongnoi (2024) focused on time-step selection for RANS-based cyclone CFD to control numerical stability of swirling flows. Y. Wang (2024) evaluated curved-inlet hydrocyclone structural effects on internal flow field formation. D. Zhao (2025) assessed the influence on axial-flow hydrocyclone performance.

Zhang *et al*. (2025) investigated flow-field features and separation performance in a compact series gas–liquid separator designed around cyclone principles. Industrial engineering observations on centrifugal tray elements, including tangential entry, annular-film capture, and retuning through selective plugging, were used for operational interpretation.

A comparative analytical method was applied to reconcile differences in separator geometries (gas–liquid cyclone, series compact separator, hydrocyclone analogs) within a unified swirl-flow description. Source analysis was combined with dimensional reasoning (Reynolds, swirl intensity measures, Stokes-type droplet response) to interpret regime transitions without introducing unverified numerical claims. A synthesis method was employed to map reported qualitative flow-structure findings to an operational envelope logic suitable for production engineering decisions. Attention was paid to numerical-method limitations noted in the sources (turbulence closure and time-step sensitivity) to avoid overstating predictive certainty.

3. Results

Gas-dynamic separation in centrifugal devices can be represented through coupled balances in a swirling, predominantly axisymmetric flow. An azimuthal velocity component generates a radial pressure gradient, which drives phase segregation. At the same time, axial transport determines the residence time and the likelihood that droplets will reach the wall and coalesce into a stable film. When inlet conditions vary, the separator moves along a continuum in which:

- swirl intensity rises with inlet tangential momentum, strengthening radial segregation but raising pressure loss;
- axial velocity growth shortens residence time, weakening capture despite more vigorous swirl;

- interphase behavior shifts because droplet inertia and film stability depend on both shear and residence time.

This coupled nature is observed in cyclone-type separators, where changes in flow structure affect both efficiency and pressure drop, with turbulence intensity patterns influencing the dispersed phase's ability to migrate toward the wall region. Findings summarized for cyclone-type oil separators indicate that strong turbulent kinetic energy near the upper section can hinder migration toward the wall, while reduced tangential velocity near the lower section weakens centrifugal separation (Seon *et al*., 2022).

For gas-liquid cyclone separators, regime description becomes more specific because the separated liquid frequently forms a wall film, while carryover occurs through re-entrainment or incomplete film formation. The bubble-flow analysis and separation characterization for a gas–liquid cyclone separator emphasize a mechanistic interpretation of gas–liquid structure, providing a basis for distinguishing stable capture from conditions that intensify entrainment (Bai *et al*., 2021).

Building on that foundation, structural-parameter studies in gas–liquid cyclone separators provide direct evidence that geometric choices reshape the internal flow and, consequently, the separation response. Chen *et al*. (2025a) explicitly show that separation performance in gas–liquid cyclone separators is sensitive to structural parameters, indicating that geometry variation reshapes the internal flow organization governing droplet–wall interaction and carryover risk. A related numerical study by Chen *et al*. (2025b) proposes a secondary separation cyclone as a design pathway to improve the capture of fine, dispersed fractions through internal flow restructuring.

When variable inlet regimes are emphasized, the separator must be interpreted as a system with an operational envelope rather than a single design point. Zhang *et al*. (2025) proposed a compact series gas–liquid separator based on cyclone principles to mitigate liquid carryover and improve wellhead metering reliability. This orientation is directly aligned with production-engineering needs at gas-gathering facilities: even moderate carryover can bias flow-meters, accelerate corrosion/erosion, and desta-bilize downstream control. Under inlet transients, the same separator geometry may exhibit different dominant loss mechanisms-pressure drop dominated by inlet swirl generation at higher flow rates, versus carryover dominated by insufficient residence time at lower or rapidly changing flow conditions - so design interpretation benefits from separating these con-tributions and connecting them to measurable operating variables.

The practical feasibility of CFD-based decision support under variable flow regimes depends on the numerical reliability of CFD for swirling flows. Mykhailiuk *et al*. (2024) highlight feasibility considerations and modeling constraints for CFD-based analysis of gas separators. Thongnoi *et al*. (2024) show that time-step selection in RANS cyclone simulations directly affects the stability and interpretation of predicted swirling-flow structures. Together with the RANS/LES comparison findings on cyclone-type separators (Seon *et al*., 2022), these publications support a methodological result: for variable regimes, CFD interpretation should be used primarily to identify robust qualitative flow-structure shifts (vortex core movement, near-wall shear zones, recirculation regions) rather than to claim high-precision efficiency predictions without targeted validation.

Hydrocyclone results provide a transferable analog for the swirl field, as hydrocyclones share the exact swirl-induced radial segregation mechanism, despite differences in phase properties. Structural-parameter analysis of a composite curved-inlet hydrocyclone ties the inlet geometry to internal flow-field changes (Wang *et al*., 2024), and the influence of inlet velocity on axial-flow hydrocyclone performance further supports the notion that inlet momentum strongly reshapes separation behavior (Zhao *et al*., 2025).

From a theoretical viewpoint, these findings reinforce the general scaling result: the separation response is governed by the competition between centrifugal acceleration (proportional to the square of tangential velocity over a characteristic radius) and axial transport time. At the same time, turbulence modifies the effective diffusivity that counteracts segregation.

A field-oriented operational result arises when the published regime logic is interpreted through centrifugal tray operation in gas-treatment practice. A separator tray equipped with multiple centrifugal elements supplied through tangential openings or an impeller-type inlet creates combined rotational and axial motion; droplets migrate toward the wall, form a film, and drain toward the liquid-removal zone, while the cleaned gas exits through the upper outlet. This operating scheme supports an envelope-based strategy in which maintaining an effective velocity range within each centrifugal element is more productive than maximizing absolute throughput, because both excessive velocity, associated with film stripping and droplet detachment, and insufficient velocity, associated with unstable annular-film formation and weak centrifugal separation, reduce capture efficiency. Under variable regimes, selective plugging of chosen elements provides discrete control over the effective flow area, shifting element-level velocity back toward a stable operating band without mechanical disassembly.

Fig. 1 integrates the regime logic into a compact separator schematic that emphasizes the physical chain from swirl generation to film drainage and carryover pathways, adapted from the gas–liquid cyclone separator schematic information discussed in (Bai *et al*., 2021).

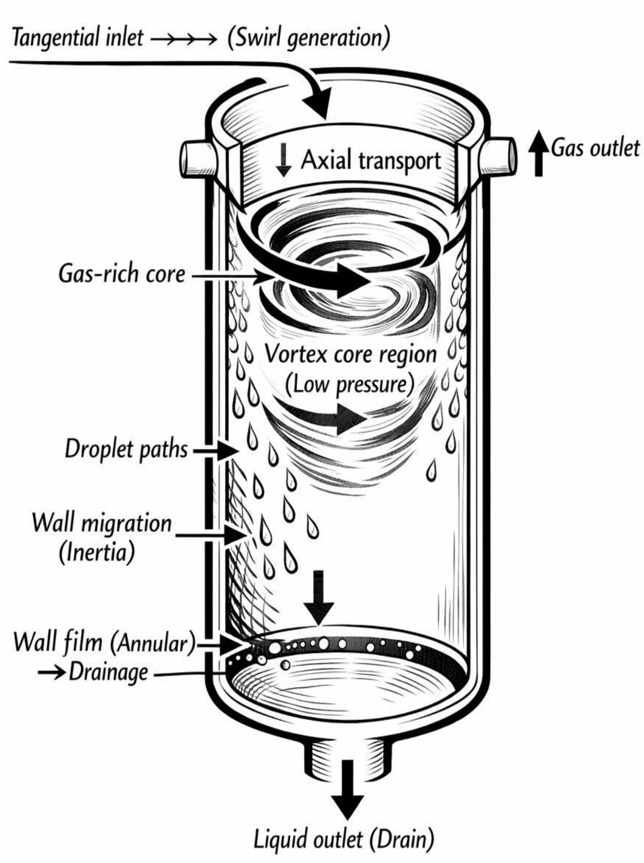

Fig. 1: Conceptual flow organization in a gas–liquid cyclone element under variable inlet regimes (adapted from Bai *et al*., 2021).

Under higher inlet momentum, swirl strengthens, and radial segregation accelerates; however, near-wall shear rises, and the probability of film stripping increases. Conversely, under lower or rapidly changing inlet momentum, residence time and near-wall capture can become insufficient, thereby increasing carryover. The **Fig. 1** formalizes an interpretation that can be used for operational diagnostics: carryover episodes can originate either from over-swirl (film breakup) or under-swirl/under-residence (incomplete migration), and mitigation strategies differ accordingly.

4. Discussion

The analytical synthesis supports a production-engineering viewpoint: variable regimes should be treated as trajectories across a separation envelope rather than disturbances around a single steady design point. Published cyclone and hydrocyclone studies confirm that geometry and inlet conditions restructure the internal flow field, systematically altering separation response (Chen *et al*., 2025a; Wang *et al*., 2024; Zhao *et al*., 2025).

At the same time, sources focused on turbulence modeling and numerical settings show that swirl-dominated devices are sensitive to closure and discretization choices (Seon *et al*., 2022; Thongnoi *et al*., 2024), so CFD-derived conclusions require careful interpretation, especially when inlet transients are the operational focus.

Table 1 organizes the regime transitions most relevant to centrifugal separators under inlet variability, linking each transition to dominant gas-dynamic drivers and engineering consequences. The table utilizes the published mechanistic framework for bubble/film behavior in gas–liquid cyclones (Bai *et al*., 2021), structural sensitivity for gas–liquid cyclones (Chen *et al*., 2025a), and the influence of inlet conditions highlighted for hydrocyclone-type separators (Wang *et al*., 2024; Zhao *et al*., 2025).

Table 1: Regime transitions and gas-dynamic drivers in centrifugal separators under variable inlet conditions (Bai *et al*., 2021; Chen *et al.,* 2025a; Seon *et al*., 2022; Wang *et al*., 2024; Zhao *et al*., 2025; Zhang *et al*., 2025).

Regime/transition (qualitative)	**Dominant gas-dynamic driver**	**Separation consequence**	**Practical indicator in operation**
Stable near-wall capture with continuous film	Swirl strong enough to sustain radial segregation; residence time adequate	High capture, stable drainage	Low carryover, repeatable pressure loss pattern
Transition toward carryover from under-swirl / short residence	Reduced tangential momentum and/or increased axial velocity	Droplets fail to reach the wall; incomplete film	Carryover rises during rate drops or rapid ramping
Transition toward carryover from over-shear / film stripping	Very high near-wall shear and turbulence intensity	Film breakup and re-entrainment	Carryover rises during rate spikes; pressure loss rises
Geometry-driven shift in vortex structure under the same flow rate	Inlet/structure changes alter vortex core position and recirculation	Capture changes without a significant rate change	Sensitivity to hardware configuration

A direct operational bridge to field practice follows from centrifugal tray operation in field gas-treatment systems. Selective plugging of centrifugal elements provides a discrete means of controlling element-level velocity and maintaining operation within an effective regime band without dismantling the tray or associated piping.

In gas fields with large throughput swings, this approach offers a pragmatic response to inlet variability: rather than accepting degraded separation under off-design conditions, the effective flow area is adjusted so that each active element operates closer to its stable velocity window. From an engineering standpoint, such retuning reduces downtime risk and supports more stable wellhead metering and better protection of downstream equipment.

Table 2 compares modeling strategies suitable for interpreting variable regimes, drawing on published evidence that higher-fidelity turbulence resolution can better reproduce complex swirling structures (Seon *et al*., 2022). In contrast, industrial CFD feasibility work and time-step guidance highlight constraints that must be managed for reliable inference (Mykhailiuk *et al*., 2024; Esekhaigbe *et al*., 2023; Thongnoi *et al*., 2024).

Table 2: Modeling approaches for centrifugal separators under variable regimes and their interpretive strength (Bai *et al*., 2021; Mykhailiuk *et al*., 2024; Seon *et al*., 2022; Thongnoi *et al*., 2024; Zhang *et al*., 2025).

Modeling approach	Strength for variable regimes	Main limitation under a vigorous swirl	Recommended use case in engineering practice
RANS with steady boundary conditions	Fast screening of geometry sensitivity	Averaging masks transient vortex dynamics	Parametric comparison of design variants and pressure-loss trends
Hybrid RANS/LES or LES (where feasible)	Better capture of vortex breakdown, turbulent structures	High computational cost and setup sensitivity	Diagnostic studies for carryover mechanisms and vortex restructuring
CFD feasibility-oriented industrial workflows	Practical implementation in production engineering	Predictive accuracy is limited by input data and closures	Decision support with conservative interpretation, emphasizing trends
Regime-based analytical envelope reasoning	Transparent linkage to operating variables	Limited quantitative precision for complex geometries	Rapid operational assessment and retuning logic

The two tables jointly support a unified decision logic: (i) use analytical envelope reasoning to classify the likely origin of carryover episodes under transient operation; (ii) use CFD selectively, focusing on robust flow-structure changes rather than absolute efficiency values; (iii) apply operational retuning (such as selective element plugging and inlet-device-aware distribution management) to bring element-level velocities into an effective band, minimizing both under-swirl carryover and over-shear re-entrainment.

5. Conclusion

Task 1 is resolved through a consolidated gas-dynamic description, in which swirl-induced radial pressure gradients and axial residence time jointly govern segregation, while turbulence modulates near-wall transport. This description explains why inlet-rate transients can either strengthen or weaken separation, depending on whether centrifugal forcing or axial transport becomes the dominant factor. Task 2 is resolved by linking published geometry-sensitivity findings for gas–liquid cyclones and hydrocyclone analogs to regime transitions that control film formation and carryover; geometric parameters alter vortex organization, shifting capture even at comparable nominal flow rates. Task 3 is resolved through an engineering implication for field operations: under variable inlet regimes typical of gas-gathering infrastructure, maintaining effective element - level velocities offers a practical control target, and selective plugging of centrifugal elements provides a fast, repeatable retuning pathway that aligns with production engineering constraints and metering reliability requirements.

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7. Conflicts of interest

The author declares no conflicts of interest.

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