# Centrifugal Separation & Disk Stack Technology for Industrial Gas Cleaning Applications

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# Executive summary

Centrifugal separation is a compact, high-field particle-removal technology used to control dispersed phases across a wide range of industrial applications.

Centrifugal separation is used where gravity settling is too slow, too weak, or too space-intensive to remove fine particles from a carrier fluid. By replacing gravity with a rotating force field that can reach thousands of times gravitational acceleration, compact equipment can achieve separation duties that would otherwise require very large settling vessels. Disk stack centrifuges are among the most effective compact separators because they divide the process stream into many thin layers, greatly shortening the radial migration distance required for particles or droplets to reach a collecting surface. This principle underpins their use across clarification, concentration, polishing, and multiphase separation duties in process industries.

Disk stack technology has traditionally been most widely applied in liquid–solid and liquid–liquid service, especially in biotechnology, food processing, chemical production, and fuel purification. In those settings, the key concerns are clarification efficiency, grade efficiency, flow distribution through the disc gaps, solids transport, and scale-up from laboratory or pilot equipment to plant operation.

In gas-related applications, however, the challenge changes. Aerosols, oil mist, and fine suspended droplets are strongly coupled to the gas phase, and their removal depends not only on centrifugal force but also on drag law, residence time, internal flow stability, and pressure loss. For this reason, gas-phase separation requires a broader engineering treatment that connects separator geometry with aerosol mechanics, internal hydrodynamics, and separation system design. Separator performance is governed by the complete separation chain rather than by rotational speed alone. The decisive engineering questions are how particles are generated, how they move in the rotating flow, how quickly they migrate toward a wall or disc surface, how uniformly the separation channels are loaded, whether separated matter is transported away without re-entrainment, and whether the outlet and discharge system remains stable under real operating conditions. This same systems perspective is relevant across both established liquid-phase duties and gas-phase industrial applications, including bioprocess clarification, fuel and oil purification, blow-by gas cleaning, and oil-mist removal.

This white paper examines centrifugal separation, and especially disk stack technology, as a compact separation platform whose performance depends on the interaction between centrifugal forces, particle transport, internal flow behaviour, and separation-system design. It explains the fundamentals of centrifugal separation, develops the gas–particle perspective needed for aerosol and mist service, describes disk stack geometry and internal flow mechanisms, and examines how particle generation, migration, capture, drainage, and discharge collectively determine practical separator performance. By linking separation physics with hydrodynamics and process integration, the paper provides an engineering framework for understanding, evaluating, and applying centrifugal separation technologies across traditional liquid-phase duties and emerging aerosol, condensate, and gas-treatment applications.

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# Background

As industrial processes demand higher efficiency, lower emissions, and compact designs, centrifugal separation is becoming increasingly important across modern process industries.

Centrifugal separation is one of the most established and widely applied methods for accelerating the removal of dispersed particles or droplets from liquid and gas streams. It is selected where a dispersed phase must be removed from a continuous phase but natural settling is too slow for a practical plant design. The attraction of the method lies in its compactness. Instead of waiting for particles to settle under gravity, the process places them in a rotating field that can impose very high apparent body forces and sharply accelerate migration toward a collection boundary. In industrial terms, this makes centrifuges attractive wherever throughput must be high, footprint must be limited, or the particles are too fine for gravity clarification to be economical. Disk stack centrifuges occupy a particularly important position within this equipment family. Their internal stack of conical discs multiplies the effective settling area while keeping the machine compact. This feature has made them central to clarification and separation duties in biotechnology, pharmaceuticals, dairy processing, fine chemicals, petrochemicals, and environmental systems. In these fields, the technology has often been framed in terms of Sigma theory, clarification area, product sensitivity, and throughput scaling. Those concepts remain important, but they are only part of the overall picture.

A broader view is required when the continuous phase is a gas. In gas cleaning, crankcase ventilation, oil-mist control, and aerosol treatment, the dispersed phase is usually much finer than in classical slurry clarification.

Particle diameters often extend into the low-micrometer or even submicrometer range, where viscous drag strongly opposes migration and residence times are often limited by the flow system rather than by the separator alone. As a result, a machine that is effective in a liquid clarification duty cannot simply be assumed to be equally effective in a gas-side aerosol duty. The governing framework must be extended to include aerosol drag, droplet growth or agglomeration, pressure loss, and the possibility that the target dispersed phase may need to be created before it can be removed. This broader framing is especially valuable because it brings apparently different applications into one consistent engineering language. Mammalian cell harvest, oil–water polishing, blow-by gas cleaning, machining mist capture, cooking oil-fume control, and condensate-based gas treatment all ask the same fundamental question: can the dispersed phase be driven to a collecting surface before it escapes with the carrier stream?

At first glance, these applications appear very different. In practice, however, they are governed by the same underlying challenge: whether particles or droplets can be generated, transported, separated, and removed efficiently under the available hydrodynamic conditions.

The answer therefore depends not only on centrifugal force, but also on residence time, particle characteristics, flow behaviour, collection mechanisms, and the ability to prevent re-entrainment after capture. Viewed in this way, centrifugal separation becomes a system-level engineering challenge rather than simply a question of rotational speed or equipment geometry.

# 2 Fundamentals of Centrifugal Separation

Centrifugal separation intensifies particle migration by replacing gravity with high rotational forces, enabling compact and efficient separation of fine dispersed phases.

## 2.1 Centrifugal Force and Particle Motion

At the most basic level, centrifugal separation replaces gravitational settling with settling in a rotating field. A particle of mass $m$, located at radius $r$ in a rotor spinning at angular speed $\omega$, experiences centrifugal acceleration proportional to $\omega^2 r$. As a result, the outward driving field is much stronger than gravity and increases with radius.

The basic logic is the same as in gravity settling: a driving force pushes the dispersed phase relative to the fluid, and a resisting force opposes that motion. What changes is the scale of the driving field and the geometry through which the particle must travel.

The centrifugal acceleration acting on a particle can be written as

$$a_c = \omega^2 r \tag{1}$$

where

- $a_c$ = centrifugal acceleration (m/s$^2$),
- $\omega$ = angular velocity of the rotor (rad/s),
- $r$ = radial distance from the axis of rotation (m).

The corresponding centrifugal force acting on a particle of mass $m$ becomes

$$F_c = m\omega^2 r \tag{2}$$

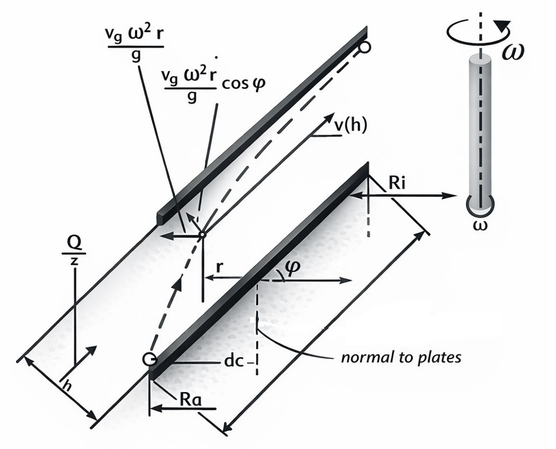
This force replaces the gravitational force $mg$ used in conventional sedimentation theory. The ratio between centrifugal acceleration and gravitational acceleration is often expressed as the relative centrifugal force (RCF):

$$\text{RCF} = \frac{\omega^2 r}{g} \tag{3}$$

where

- $g$ = gravitational acceleration (9.81 m/s$^2$).

Typical centrifuges operate at RCF values ranging from several hundred to several thousand times gravitational acceleration, which explains why centrifugal separation can remove particles that would settle extremely slowly under gravity.[1,2]



## 2.2 Particle Migration and Separator Scaling (Sigma Theory)

In a practical separator, performance is not determined by centrifugal force alone. The relevant comparison is between the rate at which a particle migrates toward a wall and the time available before it exits the machine. This is why disk stack centrifuges are highly effective: by splitting the flow into many narrow passages, they reduce the migration distance required for capture.

Classical Sigma theory expresses this benefit through an equivalent settling area, allowing a centrifuge to be compared with a gravity settler. This remains one of the most widely used engineering frameworks for first-pass design and scale-up. However, Sigma theory should be regarded as an idealized or first-order design approach because it assumes simplified settling behaviour and does not explicitly account for non-ideal flow patterns, turbulence, particle interactions, coalescence, or high solids loading that may influence practical separator performance.

In centrifugal clarification, particle motion is commonly described using a Stokes-type force balance between centrifugal force and viscous drag. For small particles at low Reynolds numbers, the radial migration velocity can be approximated by

$$v_r = \frac{d_p^2(\rho_p - \rho_f)\,\omega^2 r}{18\mu} \tag{4}$$

where

- $v_r$ = radial migration velocity of the particle (m/s),
- $d_p$ = particle diameter (m),
- $\rho_p$ = particle density (kg/m$^3$),
- $\rho_f$ = fluid density (kg/m$^3$),
- $\mu$ = dynamic viscosity of the fluid (Pa·s).

This expression shows that migration velocity increases with particle size, density difference, rotational speed, and radial position within the centrifuge.

Sigma theory uses these principles to relate centrifuge capacity to an equivalent gravitational settling area. The throughput of a clarifying centrifuge can be written in simplified form as

$$Q = v_g \Sigma \tag{5}$$

where

- $Q$ = volumetric feed flow rate (m$^3$/s),
- $v_g$ = settling velocity under gravity (m/s),
- $\Sigma$ = equivalent settling area of the centrifuge (m$^2$).

The parameter $\Sigma$ depends on centrifuge geometry, disc number, radii, and rotational speed. In disk stack centrifuges, the large number of discs dramatically increases $\Sigma$, enabling high throughput in a compact device. The basic throughput formulation used in liquid clarification can still be applied in gas-phase centrifugal separation. However, the particle migration term must be reformulated using gas properties and aerosol transport physics. For very small droplets, non-continuum slip effects modify the drag behaviour and can alter the effective migration velocity relative to classical Stokes-law predictions.[3,4]

## 2.3 Performance Metrics

Another important performance concept is the critical particle diameter, often called the cut size. This is the diameter of a particle that is just recovered under stated operating conditions. Particles significantly larger than this size are preferentially captured, whereas particles significantly smaller are increasingly likely to escape with the clarified stream. A single total-efficiency number therefore hides important information, and grade-efficiency curves are often more informative because they show how recovery varies across the particle-size distribution. This becomes especially important in gas-side aerosol service, where only part of the distribution may be effectively removed.

The critical particle diameter can be estimated by rearranging the migration-velocity relation so that the radial travel distance equals the available residence time. In simplified form this yields

$$d_c \approx \sqrt{\frac{18\mu v_f}{(\rho_p - \rho_f)\omega^2 r}} \tag{6}$$

- $d_c$ = critical particle diameter (m),
- $v_f$ =characteristic average velocity through the separation channel, related to the residence time available for particle migration (m/s).

where larger centrifugal fields and density differences reduce the cut size, while higher fluid velocity and viscosity increase it. This proportionality is intended to illustrate the dominant parameter dependencies rather than serve as a universal design equation, since the exact cut size also depends on separator geometry, migration distance, residence-time distribution, and flow non-idealities.

Particles larger than $d_c$ migrate fast enough to reach a collecting surface before leaving the separator, whereas smaller particles remain entrained in the fluid stream.

In practice, real separators do not produce a perfectly sharp cut size. Instead, separation efficiency varies gradually with particle diameter. This behaviour is represented by the grade-efficiency curve $T(d)$, which gives the fraction of particles of diameter $d$ that are captured by the separator.

The cut-size concept therefore remains useful in both liquid and gas service. In gas-phase applications, the predicted cut size shifts because viscous drag, slip correction, and aerosol transport effects modify the migration velocity of small droplets or particles relative to their behaviour in liquids.

**Different gas-cleaning separation duties**

In gas-cleaning applications, two broad centrifugal-separation duties are especially relevant. The first is gas–liquid aerosol separation, where liquid droplets, oil mist, or other dispersed liquid phases are removed from a gas stream. The second is gas–solid particle separation, where solid particles are removed from a gas stream under the action of centrifugal forces.

Although the governing principles remain similar in both cases, particle transport is primarily governed by the balance between centrifugal forces and aerodynamic drag. Separator performance therefore depends on particle size, particle or droplet density, gas viscosity, gas velocity, residence time, centrifugal field strength, internal flow behaviour, and re-entrainment control.

The dominant physical mechanisms, however, differ depending on the nature of the dispersed phase. In gas–liquid aerosol separation, droplet size, coalescence behaviour, wall-film transport, drainage, and re-entrainment can strongly influence overall separator performance. In gas–solid particle separation, particle density, shape, dust loading, deposition behaviour, and possible resuspension are often more important. For very fine particles and droplets, additional effects such as slip correction, Brownian diffusion, and turbulence may also influence transport and capture efficiency, causing deviations from ideal drag-controlled behaviour.

3

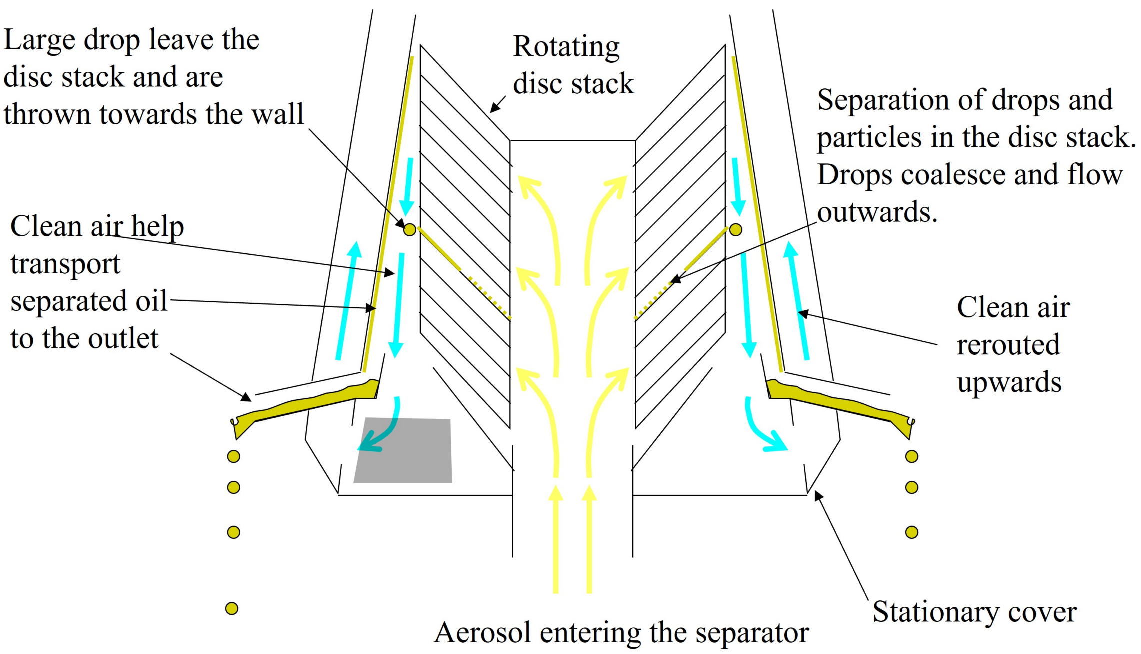
# Disk Stack Separator Design and Working Principle

Disk stack centrifuges enhance separation performance by dividing the flow into thin layers, minimizing migration distance while maximizing effective separation area.

## 3.1 Disk Stack Separator Design and Core Operating Principle

A disk stack centrifuge consists of a high-speed rotating bowl containing multiple conical discs arranged with narrow spacing. These discs create many thin separation channels through which the process stream flows. The purpose of the stack is to reduce the migration distance required for the dispersed phase to reach a solid boundary while preserving high throughput in a compact volume.

In classical clarification service, the feed enters the bowl, is accelerated into the rotating field, passes through the disc stack, and separates into a clarified stream and a concentrated dispersed phase collected at larger radii or in dedicated holding zones.



## 3.2 Practical Design Variations in Disk Stack Separators

### Centrifugal pump and discharge behaviour

In many modern centrifugal separation systems, the upper section contains flow-control and discharge components that recover pressure and guide the separated fluid from the rotating zone to the outlet. These components are not merely accessories but energy-conversion devices that transform part of the rotational kinetic energy of the rotating fluid into useful discharge pressure. They therefore play a decisive role in pressure recovery, discharge stability, and operating range.

Poor performance of the discharge system can reduce overall separator efficiency even when the disc stack itself is operating effectively, because unstable outlet flow, backflow, vortex formation, or pressure losses may disturb the internal hydrodynamic structure.

### Solids handling and separator configuration

Separator architecture also changes with solids load and process requirements. In some disc-stack centrifuges, solids accumulate in a sludge space and are removed periodically, either manually or through automatic discharge mechanisms. In applications involving higher solids concentrations, alternative centrifuge designs such as decanters may be preferred because they provide continuous solids removal. This distinction is important because practical performance depends not only on separation within the disc stack but also on how efficiently separated solids are transported away from the separation zone before they can disturb the internal flow field or reduce separation efficiency.

## 3.3 Adaptation to Gas-Phase and Rotating Particle Separators

Gas-side disc-type centrifuges adapt the same general principle to aerosols and oil mist. In automotive blow-by service, for example, conical discs arranged close together create narrow rotating passages that strip gas from the disc spaces while forcing the heavier oil droplets to deposit on the discs. The droplets then agglomerate, move outward under centrifugal action, and return to the oil circuit through drainage features.

One particularly important detail is that the gas and the separated liquid need not move in the same direction: the gas may pass inward through the disc gaps while the collected liquid film is transported outward toward the sump. This internal counter-pattern is one reason why disc-type gas separators can remain effective under demanding engine conditions.

### Related rotating separator concepts

Related rotating particle separators used in gas-cleaning and condensed-contaminant service follow the same broad logic even when their geometry differs from a classical conical disc stack. In rotating channel-based separators, the gas enters many narrow rotating passages, fine droplets are driven to the wall, a liquid film forms and travels along the wall, and larger droplets are ultimately discharged and collected.

A further distinction from classical liquid-phase disk stack centrifuges is that gas-side separators do not necessarily require a rotating liquid-filled bowl or container. In many gas-cleaning designs, the main rotating component is instead a disc pack, rotor, or set of rotating channels placed inside a stationary housing. The gas passes through these rotating passages, while droplets or particles migrate to the surfaces, form deposits or liquid films, and are then drained or collected. This makes gas-side designs mechanically and hydraulically different from liquid centrifuges, even though the underlying centrifugal-separation principle remains closely related.

These machines are not identical to classic disk stack centrifuges, but they employ closely related centrifugal-separation principles in the sense that they use rotation to create short migration paths and intense particle–wall interaction in a compact device.

# 4 Gas–Solid Particle Behaviour in Centrifugal Fields

Particle removal in gas systems is governed by the balance between centrifugal driving forces and drag-dominated transport, especially in the micron and submicron range.

## 4.1 Particle Dynamics and Separation Limits in Gas-Phase Systems

In gas-phase centrifugal separation, the dispersed phase may consist of solid particles, liquid droplets, oil mist, or condensate aerosols carried by a continuous gas stream. The separation task is to make this dispersed phase migrate away from the gas flow and reach a collecting surface before it exits the separator. Although the driving principle is centrifugal acceleration, the controlling physics is often dominated by aerodynamic drag and the limited time available for particle migration.

Large particles or droplets have enough inertia to deviate from the gas streamlines and move toward walls, disc surfaces, or rotating channel boundaries. Smaller particles follow the gas motion more closely and are more difficult to remove. This is especially important in the low-micrometre and submicrometre range, where drag, slip correction, Brownian diffusion, and local turbulence may strongly affect transport. As a result, gas-side centrifugal separation cannot be evaluated from rotational speed alone.

The key question is whether the particle can cross the required migration distance during its residence time in the separator. Narrow rotating channels, disc gaps, and compact rotating passages improve separation by shortening this distance and increasing particle–wall interaction. However, higher gas flow can reduce residence time, increase pressure drop, and promote re-entrainment. Separator performance is therefore controlled by the combined effect of centrifugal field strength, gas velocity, particle diameter, density difference, viscosity, geometry, and internal flow stability.

For this reason, gas-side separator performance is best described using cut size and grade efficiency. The cut size indicates the approximate particle diameter at which capture becomes probable under defined operating conditions. A grade-efficiency curve is even more informative because it shows how removal changes across the full particle-size distribution. This is essential for aerosol and mist applications, where a single total-efficiency value may hide poor removal of the finest particles.

Separation also continues after initial particle capture. Droplets that deposit on a rotating surface may coalesce into a liquid film, move along the wall, and drain toward a collection zone. If the film breaks up again, or if high local gas shear strips liquid from the surface, previously captured material may become re-entrained. Net removal efficiency therefore depends on the full sequence of migration, deposition, coalescence, wall-film transport, drainage, and outlet stability.[5]

In addition to particle-scale transport mechanisms, the underlying rotating flow field also plays an important role in separator performance. Rotation generates centrifugal pressure gradients and may induce secondary flow structures associated with Coriolis effects, which can influence residence-time distributions, channel loading, and particle transport. Consequently, successful separator design requires consideration of both particle migration physics and the hydrodynamic behaviour of the rotating fluid.

## 4.2 Particle Formation, Industrial Characteristics, and Dynamic Behaviour

The way particles are formed also matters. In blow-by gas, the dispersed phase originates from combustion blow-by and oil entrainment in the crankcase. In machining systems, oil mist is produced by evaporation, atomization, impact, and high-speed dispersion. In cooking emissions, aerosols are formed from condensed greasy vapours and fine oily particles. In high-temperature process streams, a separator may only work if the target compound has already condensed sufficiently to form a removable mist.

If the upstream saturation ratio is too low and the aerosol never forms, even a well-designed centrifuge may show little or no measurable separation. This is a crucial process insight because it shows that separator performance may be limited by upstream phase generation rather than by separator mechanics alone.

In heavy-duty diesel engines, a large fraction of blow-by gases originates from combustion leakage past the piston rings, while the remainder may arise from auxiliary components and associated engine subsystems.

Measurements from development work at Rotera and GDev, together with observations reported in the literature, indicate that crankcase oil aerosols are strongly concentrated in the fine size range. In some studies, more than ninety percent of droplets were found below approximately 3 $\mu$m, with a large proportion below 2 $\mu$m and a substantial fraction below 1 $\mu$m. This distribution explains why centrifugal or active disc-type separators are increasingly required to meet modern oil-mist removal targets.[1]

A further practical complication is that the dispersed phase may change inside the machine. Droplets may agglomerate, coalesce on surfaces, merge into films, or break up again near exits and discharge zones. Fragile droplets can also be altered by feed acceleration and internal shear. This means the separator is not always acting on a fixed particle population.

In some systems, it is simultaneously separating, conditioning, and redistributing the dispersed phase. From an engineering standpoint, that makes measurement, modelling, and scale-up more challenging, but also more important.

5

# Internal Flow Behaviour and Separation Mechanisms

Separation inside disk stack systems is driven by complex interactions between flow structure, particle transport, wall-film formation, and re-entrainment dynamics.

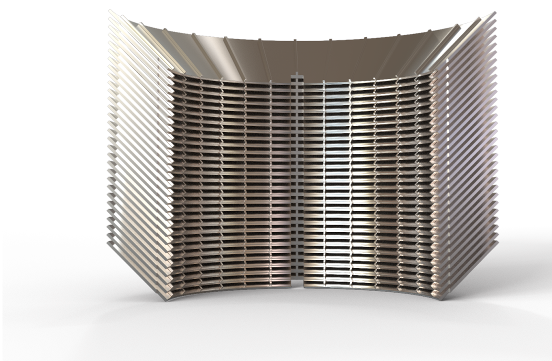
## 5.1 Non-Ideal Flow, Channel Loading, and Spacer Effects

Real disk stack separators do not operate under perfectly uniform, idealized laminar conditions. Both older and newer studies show that flow within the separation channels is shaped by inlet effects, gap geometry, spacer elements, and local changes in throughput. Secondary flows, local vortices, transition effects, and non-uniform loading are therefore not exceptional details but part of the normal hydrodynamic reality of the machine. This is one reason simple ideal models often overpredict practical performance.

This complexity is characteristic of rotating fluid systems more broadly. In an analogous way to atmospheric flow near the rotating Earth, where rotation, pressure gradients, and boundary-layer effects give rise to secondary motion and complex flow structures, rotating separator channels can develop non-uniform velocity fields, vortices, and cross-channel transport. The analogy is not one of scale, but of physics: rotation modifies the momentum balance and can make the internal flow field strongly three-dimensional.

Detailed simulation work on rotating fluid flow inside disc-stack separation channels shows that the flow can form localized vortices and deviate from the ideal streamline path. Velocity distributions are often non-uniform across the gap, with local variations arising from rotation, inlet conditions, gap geometry, spacer elements, and operating regime. The consequence is that particles do not experience one single representative hydrodynamic environment but rather a position-dependent one, and this affects both capture and transport after capture.

In some reported studies, a significant portion of the heavier dispersed phase was observed to settle in the distributor region before reaching the full disc stack, highlighting the importance of inlet and pre-separation effects.



**Spacer effects and secondary flow**

Spacers or caulks between discs add another layer of complexity. They disturb local flow, create non-uniform channel loading, and can induce vortex-shaped secondary motion transverse to the main gap direction. These effects are not purely negative. Under some circumstances, secondary flow can assist transport of very fine particles toward a collecting boundary. Under others, it can resuspend already separated material or reduce the effective use of the available clarification surface.

The net result is that the same hydrodynamic feature may help or harm performance depending on the operating regime and particle class.[6,7]

## 5.2 Deposition, Film Dynamics, and Overall Separation Mechanisms

Visualization studies of deposition inside disk stack separators make this behaviour more tangible. Deposition can begin non-uniformly, develop preferentially in certain regions, and evolve over time rather than instantly filling the machine in a homogeneous way. The return transport of separated solids or droplets along disc undersides can be uneven in both space and time. This means that even if particles have been captured from the main flow, overall efficiency still depends on whether the machine can move that separated material away from the active clarification region quickly and reliably.

In gas-side rotating separators, an additional wall-film mechanism often appears. Fine mist droplets are first driven to the wall, then merge into a liquid film that travels along the rotating surface, and later may break up into larger droplets near a discharge or channel exit before final collection. Separation is therefore best understood not as one event but as a chain consisting of migration, capture, surface transport, film behaviour, and discharge.

Weakness in any one of these steps can reduce the net removal efficiency even if the initial droplet–wall capture is strong.

### Re-entrainment and drainage design

A critical design concern in rotating gas separators is the possibility that liquid films leaving a disc edge can break up again into fine droplets and become re-entrained in the gas stream. Separator geometries therefore often include collection rings or drainage channels intended to intercept the film and guide it toward the rotor bottom before re-atomization occurs.

### Flow stability and performance limits

Flow stability is also important. In gas-side disc-type oil separators, performance can change markedly as flow rate increases and transitional or turbulent flow begins to dominate certain internal regions. Under those conditions, grade efficiency and total separation can deteriorate, and pressure losses can become more influential.

Some studies have shown that, when appropriate non-dimensional variables are used, performance data from a wide operating range can collapse onto a common grade-efficiency relationship. This result is valuable because it suggests that apparently complex operating maps can sometimes be reduced to a more transferable predictive form.

### Coupled transport mechanisms

The motion of the dispersed phase in rotating separators may involve several coupled mechanisms: vortex-driven pre-separation in the inlet region, radial migration toward the disc surfaces under centrifugal force, axial or radial gas transport patterns determined by the separator geometry, and tangential liquid transport along disc surfaces toward drainage zones.[8]

# 6 Industrial Relevance and Application Areas

Disk stack and centrifugal separation technologies remain highly relevant across established process industries and emerging gas-treatment applications.

Disk stack centrifuges originated and remain widely used in liquid-phase separation duties, including bioprocessing, pharmaceutical manufacturing, food processing, fuel purification, oil–water separation, and fine-particle clarification. These established applications demonstrate the ability of disk stack technology to provide high separation efficiency, compact design, and industrial scalability across a broad range of process industries.

Beyond these traditional liquid-phase applications, centrifugal separation has become increasingly important in gas-cleaning service, where aerosols, oil mist, and fine particles must be removed from gas streams under demanding operating conditions.

In engine systems, disc-type centrifugal separators have become especially important for blow-by gas cleaning. These systems address the increasing difficulty of removing very fine oil particles from crankcase ventilation streams under stricter legislation and changing engine architectures. Compared with passive labyrinths, demisters, and other inertial systems, active disc-type centrifugal separators can provide improved fine-particle removal and may be less sensitive to certain operating conditions than passive inertial devices. Some designs also incorporate pressure-recovery or pumping features that can partially offset internal pressure losses. Their integration into engine components such as cylinder-head covers also makes them attractive from a packaging perspective.

Closed crankcase ventilation systems must remove oil aerosols not only for emission compliance but also to prevent fouling of intercoolers, compressor wheels, and turbocharger components. Accumulation of oil droplets in these regions can lead to deposit formation and performance deterioration during long-term operation.

Industrial air cleaning provides another significant application area. Rotating-disk and disc-type centrifugal devices are used to remove oil mist from metalworking operations and related industrial aerosols. The main drivers are worker exposure, regulatory pressure, equipment cleanliness, and the need to control emissions without excessive pressure drop. Studies on these devices show that geometry can strongly influence capture efficiency and may, in some operating regimes, be as important as increases in rotational speed or motor power.

A related but distinct case is the treatment of greasy aerosol streams such as cooking oil fumes. While these systems are not always classical conical disk stack centrifuges, they employ related centrifugal-separation principles of rotating surfaces and intensified centrifugal interaction to capture fine oily particles from gas. Their engineering importance lies in demonstrating how rotating-disk concepts can be adapted beyond conventional process-plant equipment into compact, pressure-sensitive air-treatment devices.

Emerging gas-treatment concepts further extend the industrial relevance of rotational particle separation. In carbon-capture systems, centrifugal separation can support downstream gas–liquid separation by reducing aerosol carryover, solvent mist, and droplet entrainment after absorption or regeneration steps. Related gas-cleaning applications may also include marine exhaust treatment, where fine droplets, particles, or acid-gas-related aerosols associated with SOx control must be managed. These applications remain more process-specific than conventional clarification service, but they show that centrifugal separation may have a future role in compact gas-treatment systems if particle formation, contact time, and downstream collection are engineered together.[9]

# 7 GDev Applied Expertise and Industrial Implementation

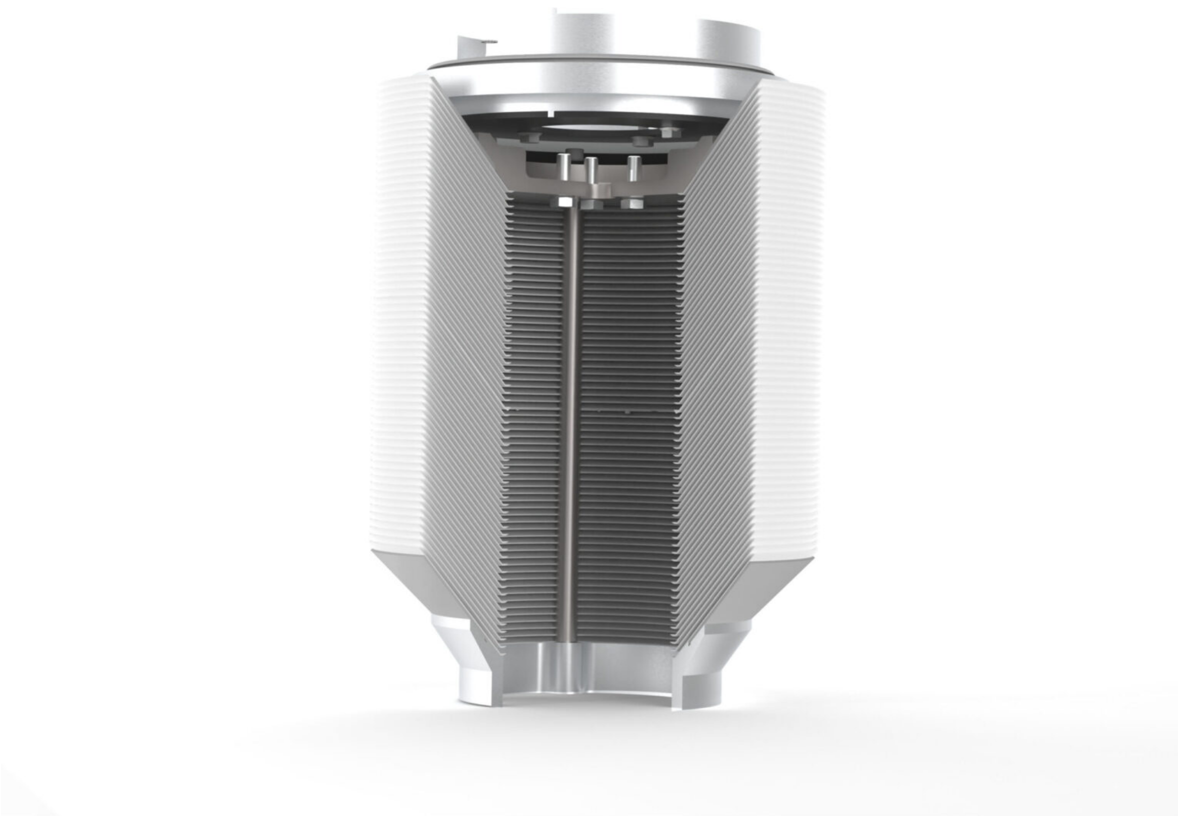
GDev builds on a Swedish separation heritage rooted in disc stack and centrifugal technology development. GDev is an innovation-driven engineering and research company with strong competence in disc stack and centrifugal separation, while our origins in 3nine provide an established industrial track record through patented disc stack oil-mist systems designed for compact operation, high purification, low maintenance, and recovery of separated liquid. This background is important because it demonstrates that the organization's separation know-how has not been developed only in theory or pilot work, but also through commercially proven equipment designed for demanding industrial environments.

That experience is directly relevant to current work on carbon capture and gas-treatment systems. GDev is actively developing carbon-dioxide capture and separation technologies, including collaborations related to waste-to-energy power plants and BECCS applications, projects with industrial and academic partners, and participation in the ACCELERATE Centre at KTH, funded by the Swedish Foundation for Strategic Research (SSF), together with industrial and university partners. Taken together, these activities demonstrate the company's involvement in process development, pilot validation, and scale-up across a range of industrial applications, including carbon management, gas cleaning, and advanced separation technologies.

Within carbon-capture applications, this competence is especially relevant downstream of absorber and desorber systems, where gas–liquid separation quality can influence solvent losses, aerosol carryover, downstream equipment cleanliness, and overall process robustness. With our background in rotating separation, liquid recovery, and compact separator design, GDev develops solutions for the polishing and conditioning stages that follow gas–liquid contact processes. In that context, our strength lies in translating disc stack and centrifugal know-how into compact separation solutions for modern capture loops where reliability, maintainability, and solvent management are critical.

The same separation platform also lends itself to emerging solid–gas applications. In pharmaceutical process operations, published reviews emphasize the importance of controlled airflow, drying-gas management, particle motion, and solids handling for product quality and process stability. Tablet and particle processing systems depend on maintaining the right balance between suspension, drying, deposition, and removal of unwanted fines from the process gas. Based on this understanding, GDev is developing specialized solid–gas separation solutions for particle recovery, extending our core expertise in compact, high-efficiency rotating separation to new industrial challenges.

From a white-paper perspective, this gives GDev a coherent technology narrative across three domains. First, the heritage from separation of oil mist in industrial machining processes demonstrates practical success in gas-side liquid-droplet separation. Second, the current carbon-capture work shows how that expertise is being extended into gas–liquid systems connected to absorber and desorber process trains. Third, the solid–gas development path points toward new value creation in sectors such as pharmaceuticals, where fine-particle control is part of product quality, process economy, and environmental performance. In this context, our contribution is not only that we develop separators, but that we adapt separation science across adjacent process industries through compact design, centrifugal intensification, and application-specific engineering.



# 8 Outlook

Future development will be shaped by integration of modelling, system design, and emerging gas-phase applications.

Future developments in centrifugal separation are expected to rely increasingly on improved integration between particle generation, transport, separation, and collection, in addition to continued advances in separator hardware and operating conditions. Across both established and emerging applications, it is becoming increasingly clear that separator performance cannot be evaluated in isolation from the surrounding process.

In traditional liquid clarification duties, separator design has historically focused on throughput, clarification efficiency, and solids handling. In many modern applications, however, the challenge extends beyond the separator itself. Aerosol generation, droplet formation, condensation behaviour, residence-time management, wall-film transport, and re-entrainment can all influence overall performance as strongly as the centrifugal field. As a result, future development is expected to place greater emphasis on understanding and controlling the complete separation chain rather than optimizing individual equipment parameters alone.

This trend is particularly visible in gas-phase applications involving oil mist, aerosols, condensates, and emerging gas-treatment systems. In these cases, successful separation often depends not only on how efficiently particles are captured, but also on how they are generated, conditioned, transported, collected, and ultimately removed from the process. The separator therefore becomes part of an integrated process solution rather than a standalone mechanical device.

At the same time, growing industrial interest in compact and energy-efficient process equipment continues to create opportunities for centrifugal separation technologies. Their ability to provide high separation intensity within a relatively small footprint remains attractive wherever space, pressure drop, maintenance requirements, or process integration are important design constraints.

Viewed from this broader perspective, disk stack and related centrifugal separation technologies are likely to continue expanding beyond their traditional role in liquid clarification and liquid–liquid separation. Their future relevance will increasingly depend on how effectively separation science, hydrodynamics, particle transport, and process integration can be combined to address new industrial challenges across liquid, aerosol, and gas-treatment applications.

# 9 Conclusion

Centrifugal separation should be understood as a system-level particle-removal platform governed by coupled physics, hydrodynamics, and process conditions.

Centrifugal separation, and disk stack technology in particular, should be viewed as a broad particle-removal platform rather than as a technology limited to conventional liquid clarification. By replacing gravity with a high-intensity rotational force field, centrifugal systems enable compact and efficient removal of dispersed phases across a wide range of industrial applications involving liquids, aerosols, condensates, and fine particles.

The central message of this white paper is that separator performance is governed by the complete separation chain rather than by centrifugal force alone. Particles or droplets must first exist in a removable form, then migrate through the carrier fluid, reach a collecting surface, remain captured, and finally be transported away without significant re-entrainment. Hydrodynamics, residence time, particle-size distribution, wall-film behaviour, drainage, and outlet stability therefore play roles that are often as important as rotational speed itself. Understanding these coupled mechanisms is essential for realistic performance prediction, successful scale-up, and reliable industrial operation.

Viewed from this perspective, disk stack separators can be regarded as part of a broader class of high-intensity separation technologies in which geometry, flow behaviour, and particle transport work together to determine performance. The same engineering principles that govern clarification of biological or chemical process streams also apply to oil-mist removal, aerosol treatment, condensate separation, and other gas-phase applications. Although the specific operating conditions differ, the underlying challenge remains the same: ensuring that dispersed matter can be transported efficiently from the carrier phase to a stable collection pathway.

For engineers and decision-makers, this means that separator evaluation should extend beyond nominal capacity or rotational speed alone. Parameters such as particle characteristics, residence time, flow distribution, capture efficiency, drainage behaviour, and process integration all contribute to practical performance. When considered together, these factors provide a more complete basis for equipment selection, design, troubleshooting, and scale-up.

Ultimately, the continued relevance of centrifugal separation lies in its ability to combine high separation intensity with compact design and broad applicability. As industrial processes increasingly demand efficient particle control, reduced footprint, and robust operation across diverse process environments, disk stack and related centrifugal technologies are expected to remain important tools for addressing both established and emerging separation challenges through the integration of separation science, hydrodynamics, and process design.

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