

Review

Air-Assist Atomization: From Unified Mechanisms to Cross-Disciplinary Custom Design and Intelligent Control

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Abstract

Air-assist atomization exploits high-velocity gas streams to shear liquid phases, achieving fine droplets at supply pressures significantly lower than those required by conventional pressure atomization. This technology is extensively deployed across diverse sectors, including pesticide spraying, food spray drying, sanitization/disinfection, and combustion atomization. Although specific operational fields dictate vastly contrasting droplet size distributions, velocities, and deposition uniformities—with target diameters spanning from $<50\text{ }\mu\text{m}$ to $>200\text{ }\mu\text{m}$ —their foundational atomization mechanisms remain inherently unified, governed primarily by toroidal vortex-induced primary breakup and Kelvin–Helmholtz/Rayleigh–Taylor (KH–RT) or Taylor Analogy Breakup (TAB) secondary breakup. This review systematically parses the atomization mechanisms, critical performance metrics, numerical simulation frameworks, and experimental characterization methodologies of air-assist nozzles. Crucially, from a novel “cross-disciplinary custom design” perspective, we contrast the optimal droplet parameter windows across the agricultural, food, sanitization, and combustion sectors (e.g., electrostatic plant protection yields a 203–1350% increase in abaxial leaf deposition; mine wind-assisted misting achieves a $>90\%$ collection efficiency for PM_{10} dust; and SCR air-assisted injectors reduce the Sauter Mean Diameter (SMD) to $25\text{ }\mu\text{m}$). Synthesized insights reveal that segmented VOF-to-DPM transition frameworks, corner-vortex-induced breakup theories, and closed-loop adaptive control architectures possess substantial cross-domain migration value. Current bottleneck challenges are highlighted, including the mesh dependency of droplet collision–coalescence models in dense spray regimes, the absence of robust atomization constitutive formulations for non-Newtonian fluids, and the ongoing paradigm shift from open-loop presetting to intelligent closed-loop regulation. This work establishes a comprehensive theoretical foundation and technical roadmap for cross-disciplinary integration and next-generation smart nozzle design in air-assist atomization.

Keywords: air-assist atomization; breakup mechanisms; cross-disciplinary applications; numerical simulations; intelligent nozzles



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1. Introduction

Atomization defines the physical transition wherein a continuous liquid phase is disintegrated into a discrete population of droplets [1–3]. Traditional pressure atomization relies strictly on the kinetic energy of high-pressure liquid injection, whereby a jet

discharges into a quiescent gas environment and undergoes destabilization and fragmental rupture driven by Kelvin–Helmholtz (KH) instabilities. Within this paradigm, the intact jet breakup length scales proportionally with the injection velocity, while scaling inversely with the liquid viscosity and surface tension [4,5]. However, this method suffers from inherent constraints: reducing droplet size demands escalated injection pressures, which exponentially amplify energy consumption and escalate reliance on heavy-duty pump assemblies. Furthermore, when processing highly viscous fluids, pressure atomization efficiency plummets precipitously, yielding significantly coarsened droplet diameters [6].

In contrast, air-assist atomization leverages the kinetic energy of a high-velocity gas stream to bypass the limitations of liquid pressure energy [7]. The pronounced velocity differential between the gas and liquid phases generates intense aerodynamic shear stress, which dramatically amplifies KH instabilities and strips the liquid columns or sheets into elongated ligaments and fine droplets [8]. This mechanism secures equivalent or superior atomization fineness at liquid feed pressures orders of magnitude lower than those required by pressure atomization. From an energetic standpoint, air-assist nozzles directly exploit the expansion work of compressed air, enabling highly efficient momentum transfer; consequently, to attain an identical target droplet diameter, the required liquid pressure can be abated by over a factor of ten.

Depending on the spatial domain where the gas and liquid mix, air-assist nozzles are broadly categorized into internal-mixing and external-mixing configurations [2]. Internal-mixing nozzles foster exhaustive pre-mixing within an internal chamber, culminating in exceptionally fine sprays and narrow droplet size distributions [8]. However, they mandate rigorous manufacturing tolerances, are susceptible to clogging, and run the risk of backflow into the liquid supply line under elevated gas-to-liquid ratios (GLRs). Conversely, external-mixing nozzles feature structural simplicity and robust anti-clogging traits. Because their gas and liquid streams are regulated independently, they offer superior operational flexibility; nonetheless, they suffer from compromised atomization efficiency, and their resultant droplet size distributions are highly sensitive to external flow field disturbances. The choice between these two architectures ultimately represents a fundamental engineering trade-off between atomization quality and system reliability.

This technology underpins vital operations across agricultural plant protection, aerospace, food processing, and mining engineering. A core shared imperative across these domains is the precise control of droplet size. For instance, crop protection generally requires droplets of approximately 150–400 μm to balance drift suppression and canopy coverage, whereas electrostatic or air-assisted fine-spray systems may employ smaller droplets of approximately 35–100 μm under controlled airflow conditions [9,10]. Combustion atomization typically requires ultra-fine droplets with SMD values below 50 μm , and some air-assisted injection systems can further reduce the target SMD to approximately 6.5–25 μm [11,12]. Mine dust suppression for respirable PM10 capture generally benefits from droplets in the approximate range of 20–100 μm , which enhances inertial impaction while avoiding excessive drift [13,14]. Food spray drying usually operates over a broader range, commonly 50–200 μm , depending on feed rheology, product morphology, and drying kinetics [15]. While air-assist atomization permits continuous, wide-range adjustments of droplet size via tuning the gas-to-liquid ratio, identifying and maintaining the precise optimal parameter set remains a critical challenge for engineering optimization.

A parallel universal requirement is spray deposition and coverage uniformity. In spray drying, the spatial uniformity of gas-droplet mixing dictates the drying kinetics and product moisture consistency; in combustors, it governs flame stability and pollutant emission profiles; and in sanitization scenarios, it ensures comprehensive multi-surface and volumetric coverage [16–18]. This uniformity is inherently a multiscale, multiphase coupled

fluid dynamics problem. Moreover, balancing power consumption against atomization efficiency remains a perennial engineering challenge. While pressure atomization relies on high-pressure pumps (operating from several to tens of MPa), air-assist atomization necessitates air compressors. Although the total energy expenditure of air-assist systems is not necessarily lower to achieve a given fineness, their decisive advantage lies in the ability to dynamically modulate droplet size in situ without altering the nozzle geometry [19–21]. This capability makes them uniquely suited for precision agriculture and other fields requiring real-time, adaptive adjustments.

Existing literature reviews typically isolate specific applications and operational challenges. For example, reviews on agricultural atomization predominantly address canopy drift mitigation and deposition coverage, while those on spray drying focus heavily on thermodynamic heat transfer and evaporation kinetics. Similarly, reviews on SCR atomization are largely confined to urea deposit mitigation and in-pipe flow field disturbances. While valuable within their respective domains, these isolated perspectives obscure the underlying physical commonalities of air-assist nozzles. There remains a critical void in the literature for a comprehensive review that establishes a unified framework rooted in foundational multiphase fluid physics to systematically contrast these fields. This manuscript differentiates itself from existing literature by using primary and secondary breakup mechanisms as a unified theoretical baseline to explain how the exact same aerodynamic shear forces are “customized” to yield vastly divergent droplet requirements—such as tuning the mechanism to achieve $\sim 25\ \mu\text{m}$ droplets for SCR injection versus $100\text{--}200\ \mu\text{m}$ droplets for food spray drying. Furthermore, unlike existing reviews, we uniquely distill methodologies with high cross-domain migration value, demonstrating how computational tools like segmented VOF-to-DPM transition frameworks and corner-vortex breakup theories can be translated seamlessly across agricultural, environmental, and combustion engineering.

To systematically navigate these multifaceted dimensions, this review is structured as follows: Section 2 parses the foundational atomization mechanisms (primary and secondary breakup), details the key performance metrics (including SMD and droplet velocity), and evaluates contemporary numerical simulation and experimental diagnostic methodologies. Building upon this theoretical foundation, Section 3 explores the cross-disciplinary customization of these technologies across four distinct application domains: precision agriculture, food spray drying, spatial disinfection, and combustion atomization. Finally, Section 4 synthesizes current technical bottlenecks and outlines future perspectives, highlighting the paradigm shift toward intelligent closed-loop control and sustainable atomization media.

2. Air-Assist Nozzle Atomization Mechanisms and Performance Characterization

Air-assist atomization utilizes the aerodynamic shear forces born from the relative velocity differential between a high-speed gas stream and a low-speed liquid phase to destabilize and disintegrate liquid sheets or columns into fine droplets [1]. By decoupling atomization quality from high liquid supply pressures, this methodology accommodates highly viscous fluids effectively, catalyzing their widespread adoption in aero-engine combustors, mine dust mitigation, agricultural spraying, food spray drying, and diesel engine SCR systems. Unlocking nozzle optimization and successful industrial deployment hinges upon a rigorous understanding of primary and secondary breakup dynamics, precise parameterization of spray metrics, and the implementation of high-fidelity numerical and experimental diagnostics.

2.1. Atomization Process and Breakup Mechanisms

The evolution of an air-assisted spray is classically divided into two distinct sequential regimes: primary breakup and secondary breakup. Primary breakup encompasses the initial destabilization, deformation, and rupture of the continuous liquid core (sheet or column) near the nozzle orifice under aerodynamic forces, yielding coarse ligaments or initial proto-droplets [22]. Secondary breakup defines the subsequent deformation and further fragmentation of these discrete proto-droplets into a finer spray under sustained high-velocity gas flows. While driven by different dominant instabilities, both regimes are collectively dictated by fluid physiochemical properties, kinematic flow parameters, and the boundary conditions imposed by nozzle geometry. A comprehensive comparison of the core characteristics distinguishing primary and secondary breakup is summarized in Table 1.

Table 1. Core Characteristic Comparison Between Primary and Secondary Breakup.

Comparison Item	Primary Breakup	Secondary Breakup
Dominant instabilities	Kelvin–Helmholtz (gas–liquid interfacial shear), Rayleigh–Taylor (droplet acceleration), toroidal vortex intrusion	Kelvin–Helmholtz (relative velocity), Rayleigh–Taylor (acceleration induced by deceleration)
Typical breakup modes	Wave-growth breakup, rim breakup, perforation breakup, toroidal vortex-induced breakup	Bag breakup ($12 < We_d < 80$), stripping/sheet breakup ($80 < We_d < 350$), catastrophic breakup ($We_d > 350$)
Common theories/models	Linear Stability Analysis (LSA), LES-VOF, primary breakup sub-model in CAB model	KH–RT model, TAB model, CAB model (with secondary breakup frequency equation)
Main control parameters	Gas–liquid momentum flux ratio, liquid film thickness, nozzle geometry (orifice diameter, mixing chamber structure)	Initial droplet diameter, gas–liquid relative velocity, gas density, surface tension
Impacts on final spray performance	Determines upper limit of initial droplet size and spatial distribution (e.g., spanwise difference in spray plume)	Determines final SMD and fine structure of droplet size distribution (narrow/wide distribution)

Note: We_d denotes the droplet Weber number, where the subscript d refers to the droplet diameter.

2.1.1. Primary Breakup Mechanisms of Liquid Sheets and Columns

Wave-growth breakup represents the foundational primary disintegration mode in air-assist configurations. When a liquid sheet or column is exposed to a high-speed co-flowing gas stream, microscopic disturbances at the gas–liquid interface are triggered by Kelvin–Helmholtz (KH) instabilities. Driven by aerodynamic shear, these disturbances grow exponentially, forming surface waves that propagate along the stream direction [23]. Linear Stability Analysis (LSA) dictates that the wave growth rate is heavily contingent upon the wavenumber, liquid layer thickness, gas-to-liquid density ratio, and surface tension [24]. Senecal et al. extended the classical formulations of Dombrowski and Johns to derive a dispersion relation specifically tailored for highly viscous liquid sheet atomization, resolving the maximum growth rate to compute the characteristic breakup wavelength and time [25]. For flat-fan atomizers, this mathematical framework accurately predicts the resultant droplet sizes stemming from sheet perforation and rupture within the central spray region. Investigations show that when the liquid sheet Weber number ($We = \rho_g U^2 h / \sigma$) exceeds a critical threshold, wave-growth mechanisms dominate, causing the continuous sheet to rapidly shred into distinct liquid ligaments, which subsequently snap into discrete droplets [26].

Rim and perforation breakup occur predominantly along the peripheral boundaries or localized thin zones of the liquid sheet. In flat-fan nozzle spray fields, the central region of the liquid sheet undergoes intense spatial stretching. Under the competing actions of aerodynamic forces and surface tension, localized thin spots experience perforation. These perforations rapidly expand driven by aerodynamic pressure, tearing the sheet into highly irregular ligaments and large proto-droplets. Concurrently, along the spanwise edges of the sheet, surface tension forces the liquid to retract into a thickened boundary chord, or “rim,” which subsequently undergoes capillary rupture and aerodynamic shearing to yield relatively large droplets. Investigations by Liu & Hung into agricultural flat-fan nozzles revealed that rim breakup governs the spray morphology at low injection pressures < 20 psi; as pressure scales upward, perforation-driven fragmentation becomes the dominant mechanism. In gas-assisted systems, the high velocity of the gas stream forces perforation and rim breakup to occur simultaneously, with their relative dominance varying across distinct spatial coordinates of the near-field spray [26].

Toroidal vortex-induced breakup is an important primary disintegration mechanism unveiled through high-resolution Large Eddy Simulations (LES) coupled with the Volume of Fluid (VOF) method [8,24]. Numerical investigations by Liu et al. on internal-mixing air-assist atomizers demonstrate that within the mixing volume, the high-velocity gas stream issuing from an annular channel creates an axisymmetric array of toroidal vortices enveloping the central liquid column [8]. These toroidal structures periodically penetrate inward from the tip of the liquid core, triggering a severe global instability that drives primary fragmentation. At a gas supply pressure of 0.2 MPa, the liquid core is expelled from the nozzle orifice before undergoing complete disintegration; however, elevating the gas pressure to 0.4 MPa forces complete primary breakup entirely within the internal mixing chamber, compressing the intact liquid core length to a mere 6.4 mm and producing an abundance of fine droplets concentrated between 112.5 and 237.5 μm .

This vortex-induction mechanism explains why air-assist nozzles can achieve fine atomization under a large gas–liquid velocity difference, rather than relying solely on high liquid injection velocity. For example, the reviewed experimental data show that droplet velocities may increase from approximately 15 to 36 m/s in the far field as gas pressure rises from 0.05 to 0.7 MPa, while near-nozzle spray velocities can reach approximately 150–280 m/s. It must be noted that this specific toroidal vortex topology is highly characteristic of confined internal-mixing geometries. In external-mixing configurations, the absence of a mixing chamber allows the gas stream to expand unconfined into the ambient environment, fundamentally altering the vortex topology and mitigating the periodic inward penetration of macroscopic vortices. Consequently, primary breakup in external-mixing nozzles is predominantly governed by unconfined aerodynamic shear and standard Kelvin–Helmholtz wave growth. This dynamic shift is further reflected in numerical modeling requirements; for instance, the CAB model necessitates vastly different breakage constants to accurately capture fragmentation ($k_2 = 13$ for internal mixing versus $k_2 = 1$ for external mixing). Discrepancies in absolute breakup lengths computed via analytical LSA versus high-fidelity LES-VOF range from 30% to 50%, underscoring the necessity of rigorous empirical calibration for specific industrial nozzle geometries. As shown in Figure 1, a liquid jet introduced into the gaseous crossflow experiences aerodynamic forces that intensify the surface instabilities of the liquid column, thus dismantling it into ligaments and further into droplets.

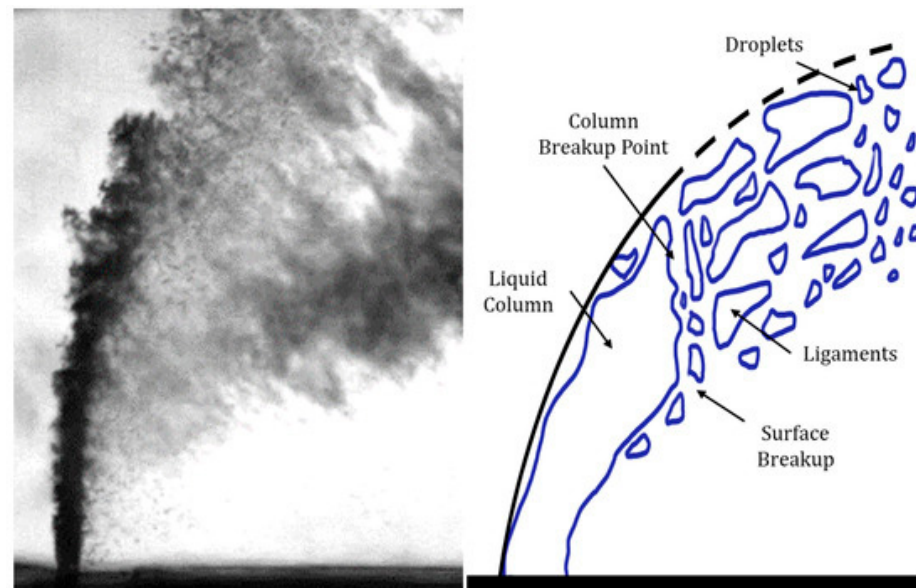


Figure 1. High-speed image (left) and schematic diagram (right) of liquid jet in crossflow. Reprinted from Ref. [27].

2.1.2. Secondary Breakup Mechanisms

Following primary disintegration, the discrete liquid fragments experience secondary breakup driven by aerodynamic drag. The active secondary fragmentation pathway is fundamentally parameterized by the droplet Weber number ($We_d = \rho_g u_r^2 d / \sigma$) and the Ohnesorge number ($Oh = \mu_l / \sqrt{\rho_l \sigma d}$). Across low-viscosity regimes ($Oh < 0.1$), increasing transitions the secondary breakup mode from bag breakup ($12 < We < 80$) to stripping/sheet breakup ($80 < We < 350$), and ultimately to catastrophic breakup ($We > 350$).

The KH–RT model is a standard numerical framework for simulating secondary atomization, elegantly superimposing Kelvin–Helmholtz (shear-driven) and Rayleigh–Taylor (deceleration-driven) instabilities. The KH mechanism models high-frequency wave growth on the droplet surface, dictating the continuous stripping of microscopic child droplets from the parent core. Concurrently, the RT mechanism captures the lower-frequency, long-wavelength disturbances growing on the windward/leeward faces due to rapid aerodynamic deceleration, tracking the catastrophic bulk shattering of the droplet. The model dynamically computes child droplet sizing via the wavelengths of the fastest-growing instability waves. This framework has been successfully embedded in multi-dimensional CFD codes for diesel and air-assist sprays. Ercolano et al. applied the KH–RT framework to an industrial air-assist SCR injector operating at gas velocities up to 294 m/s [18]. Their findings demonstrated high predictive accuracy for downstream droplet sizing, though they noted that near-field simulations required supplementary collision–coalescence sub-models due to high local droplet number densities.

The TAB model (Taylor Analogy Breakup) takes a different theoretical approach, modeling droplet deformation and failure as a forced, damped spring-mass system. Here, surface tension acts as the restorative spring force, liquid viscosity provides the damping dissipation, and aerodynamic drag operates as the external forcing function. Resolving the governing ordinary differential equation for the dimensionless deformation parameter y , which represents the normalized droplet distortion or deformation amplitude in the TAB model, triggers a breakup event when $y > 1$. While computationally efficient and capable of tracking deformation history, the standard TAB model is mathematically bounded to low Weber numbers ($We < 100$). For the intermediate stripping and sheet breakup regime ($100 < We < 350$), selecting the appropriate model is critical. The KH–RT model

naturally accommodates this transition, as its KH sub-component explicitly handles the continuous surface stripping of child droplets characteristic of this regime, before the RT component dominates at higher Weber numbers for catastrophic shattering. Alternatively, hybrid approaches that build upon standard deformation frameworks can be utilized. For instance, Tanner et al. [2] successfully deployed the Cascade Atomization and Breakup (CAB) model to simulate air-assisted food emulsion sprays. By incorporating a sequential cascade droplet creation mechanism into the modified TAB formulations, the CAB model extends the validity of deformation-tracking beyond the $We < 100$ limit, making it a highly recommended hybrid solution for transitional stripping regimes, yielding droplet size distributions that matched empirical data within a 14% relative error margin.

To systematically delineate these diverse atomization theories and models, Table 2 provides a compact comparison of the primary and secondary breakup frameworks discussed above, explicitly outlining their core assumptions, valid operational ranges, and inherent limitations.

Table 2. Comparison of Core Models and Theories for Primary and Secondary Breakup.

Breakup Stage	Model/Theory	Core Assumptions & Disintegration Mechanisms	Range of Applicability & Application Scenarios	Primary Limitations
Primary Breakup	Linear Stability Analysis (LSA)	Predicts the initial aerodynamic-shear-driven instability of liquid films or liquid columns; wave growth is governed by Kelvin–Helmholtz (KH) instability	Applicable to the initial interfacial instability phase prior to liquid film disintegration	Being an analytical approach, it neglects non-linear topological changes; for complex spatial spray distributions, piecewise-based growth rate calculations are typically required.
Primary Breakup	Annular Vortex-Induced Breakup	Assumes a periodic array distribution of high-speed annular gas vortices that continuously penetrate and shear the continuous liquid core	Serves as the dominant breakup mode in internally mixing air-assisted nozzles under low liquid flow rate and high-pressure operating conditions	Highly dependent on the internal mixing chamber geometry; numerical capturing of this process is computationally prohibitive, requiring high-resolution Large Eddy Simulation-Volume of Fluid (LES-VOF) simulations.
Secondary Breakup	Taylor Analogy Breakup (TAB) Model	Models droplet deformation and disintegration as a forced-damped spring-mass system driven by aerodynamic drag.	Restricted to the low Weber number regime ($We < 100$); utilized to simulate the bag breakup mode	Fails to accurately predict child droplet sizes under strong aerodynamic shear (catastrophic breakup conditions)
Secondary Breakup	Cascade Atomization and Breakup (CAB) Model	An extension of the TAB model that introduces a cascading child droplet generation mechanism to simulate multi-stage fragmentation events at higher energy states	Applicable to the high Weber number regime (catastrophic breakup, $We > 350$) as well as non-Newtonian fluids (e.g., food emulsions)	Breakup constants must undergo rigorous empirical calibration for non-Newtonian fluid behaviors and different nozzle geometries
Secondary Breakup	KH-RT Model	Superimposes two instability mechanisms: shear-driven Kelvin–Helmholtz (KH) instability inducing continuous surface stripping, and deceleration-driven Rayleigh–Taylor (RT) instability triggering catastrophic fragmentation	Standard modeling framework for high-velocity gas flows, such as SCR (Selective Catalytic Reduction) system injectors with flow velocities up to 294 m/s, and high aerodynamic drag scenarios	Must be coupled with collision–coalescence sub-models in the near-field high-concentration spray region; otherwise, downstream droplet sizes will be significantly underestimated

2.2. Key Performance Parameters

2.2.1. Sauter Mean Diameter

The Sauter Mean Diameter (Sauter Mean Diameter, SMD) represents the statistical average of a droplet collective, defined as the ratio of the total droplet volume to the total droplet surface area: $D_{32} = \sum n_i d_i^3 / \sum n_i d_i^2$. As a direct barometer of atomization quality, a minimized SMD translates to a highly atomized spray with an elevated specific surface area, which drastically accelerates transport phenomena such as vaporization, chemical combustion, and particulate capture. Table 3 contrasts empirical SMD datasets compiled by Liu et al. (internal-mixing mine nozzle) [8], Ercolano et al. (external-mixing SCR nozzle) [18], and Vankeswaram et al. (air-assist aviation nozzle) [28] under varying gas pressures to highlight how nozzle architecture and operational boundary conditions shape spray fineness.

Table 3. Experimental Comparison of Sauter Mean Diameter (SMD) Under Diverse Gas Pressures.

Gas Supply Pressure (MPa)	Internal-Mixing Mine Nozzle SMD (μm) (Liu et al., 2025 [8])	External-Mixing SCR Injector SMD (μm) (Ercolano et al., 2026 [18])	Hybrid Nozzle (Jet A-1) SMD (μm) (Vankeswaram et al., 2023 [28])	Remarks
0.05	810.4	—	—	Intact liquid column
0.1	~500	—	—	Liquid ligaments start to form
0.2	~200	—	—	Breakup length = 9.3 mm
0.3	~120	—	~120	Complete breakup inside mixing chamber
0.4	78.2	~45	~80	Optimal operating point for mine dust suppression
0.5	58.1	~35	~65	Spray angle begins to decrease
0.6	45	~28	—	Droplet velocity reaches saturation
0.7	99.98	~25	—	Ultra-fine droplets prone to atmospheric drift

Extensive parametric evaluations confirm that the SMD is coupled to the air-to-liquid ratio (ALR), gas operating pressure, fluid rheology, and internal nozzle architecture [29–31]. Vankeswaram et al. demonstrated that systematically shifting the ALR from 0.457 to 0.904 in an air-assist nozzle caused the SMD of water sprays to follow a non-monotonic, rise-then-fall trajectory [28]. Crucially, when testing aviation biofuels against conventional Jet A-1 fuel under identical ALR conditions, the SMD variances remained negligible, validating the excellent “drop-in” compatibility of sustainable aviation fuels (SAFs) from a hydrodynamic standpoint [32].

Furthermore, Liu et al. demonstrated that under a constant water supply pressure of 0.5 MPa, increasing the gas pressure from 0.05 MPa to 0.7 MPa triggered a precipitous 88% drop in SMD (from 810.37 μm down to 99.98 μm) [8]. Power-law regression yielded an empirical scaling law: $D_{32} = 569.4P_G^{-0.9456} - 21.6$ ($R^2 = 0.9993$). In parallel environmental contexts, Peng et al. showed that elevating the operating pressure of wind-assisted dust-suppression systems from 4 MPa to 8 MPa lowered the SMD from 131.9 μm to 27.6 μm , which directly increased the capture efficiency of respirable dust particles from 56% to over 90% [14].

To track the central tendency of volumetric distribution, researchers also utilize the volume median diameter (D_{50}) [33,34]. Ercolano et al. noted that scaling the gas volumetric

flow rate from 8 L/min to 20 L/min compressed the D_{50} from 50 μm to 25 μm while narrowing the distribution span [18]. It is imperative to caution that the absolute SMD values reported across different studies cannot be compared directly without context. The metrics are fundamentally dependent on nozzle architecture (internal vs. external mixing), fluid properties (water vs. hydrocarbon fuels), spatial measurement coordinates relative to the orifice, and the diagnostic principles employed (e.g., localized point-source PDA vs. line-of-sight averaged laser diffraction) [35]. For instance, Ercolano et al. utilized an external-mixing configuration (annular gas gap 0.1 mm, liquid core orifice 1 mm), reporting an SMD of 45 μm at a gas pressure of 0.4 MPa [18]. Under identical pressure conditions, the internal-mixing design of Liu et al. yielded an SMD of 78 μm [8]. This discrepancy is directly attributable to the fundamentally different primary breakup topologies (unconfined shear versus chamber-confined toroidal vortices) and the resulting shifts in gas–liquid momentum exchange efficiency inherent to the external-mixing geometry under these specific flow rates. Consequently, cross-disciplinary meta-analyses should prioritize trends scaled against dimensionless parameters (GLR, We, Oh) rather than absolute numerical values [36–39].

2.2.2. Droplet Size Distribution

The dispersion and uniformity of a droplet ensemble are critical to spray performance, and are mathematically closed in engineering workflows using the Rosin–Rammler distribution function:

$$Q = 1 - \exp\left(-\left(\frac{d}{\bar{d}}\right)^n\right)$$

where Q represents the cumulative volume fraction of droplets possessing a diameter less than d , $\bar{d}$ denotes the characteristic size parameter, and n serves as the distribution uniformity index. A higher n value signifies a highly concentrated droplet population with superior geometric uniformity.

To quantitatively evaluate the width or scatter of the size distribution, the dimensionless span parameter (S_{span}) is conventionally defined as:

$$S_{\text{span}} = \frac{D_{90} - D_{10}}{D_{50}}$$

where D_{10} , D_{50} and D_{90} correspond to the representative droplet diameters at cumulative volume fractions of 10%, 50%, and 90%, respectively. A minimized S_{span} reflects a narrow distribution profile, indicating high atomization homogeneity [40,41].

Both experimental and numerical simulation results demonstrate that airflow-assisted atomization yields a more concentrated particle size distribution compared to traditional pressure-assisted atomization [42,43]. For internal mixed-flow air-assisted nozzles, Liu et al. found that increasing the air source pressure from 0.2 MPa to 0.4 MPa significantly narrowed the peak width of the droplet size distribution, with most droplets falling within the range of 112.5–237.5 μm [8]. In research on aviation biofuel spraying, Vankeswaram et al. reported that under identical nozzle conditions, the differences in S_{span} values among different alternative fuels were less than 10%, confirming their good interchangeability from a particle size distribution perspective [28]. In food spray atomization simulations, Tanner et al. employed a χ^2 distribution instead of a uniform distribution to describe product droplet sizes, achieving a more accurate reproduction of the experimentally measured particle size distribution profile [2].

2.2.3. Droplet Velocity Fields

The droplet velocity determines the droplet's penetration capability, residence time in the airflow, and relative velocity with particulate matter [44,45]. For dust capture, appropriately increasing the droplet velocity facilitates inertial collision; however, excessively high velocities may cause droplets to bypass dust particles or induce secondary entrainment [46,47].

In air-assisted atomization, droplet velocity typically remains lower than the gas velocity, with a distinct slip velocity difference observed between the two [48,49]. Measurements using a phase Doppler interferometer (PDI) by Nie et al. revealed that at 65 cm downstream of the mine-used air-assisted nozzle outlet, axial droplet velocity increased from approximately 15 m/s to nearly 36 m/s when gas pressure rose from 0.05 MPa to 0.7 MPa, though the rate of increase gradually declined [13,50,51]. Structural image velocimetry (SIV) measurements indicated that within a 20 mm range downstream of the nozzle outlet, droplet velocities reached 150–280 m/s, with higher velocities in the core region compared to the peripheral areas [52,53]. Among different nozzle geometries, square and diamond-shaped nozzles exhibited more uniform droplet velocity distributions, whereas circular nozzles showed pronounced central high-speed zones [54,55].

In SCR system applications, Ercolano et al. compared the effects of the single-phase method (using only droplets) versus the two-phase method (combining droplets with annular air jets) on velocity field prediction [18]. Results demonstrated that the two-phase method more accurately reproduced the radial distribution of droplet velocities, with its velocity attenuation trend closely matching experimental data; in contrast, the single-phase method underestimated velocities by approximately 30% at the far field distance (200 mm) [56,57]. This indicates that neglecting momentum exchange between gas jets and droplets significantly compromises the accuracy of penetration depth predictions in engineering CFD simulations [58,59].

2.2.4. Spray Angle and Macroscopic Morphology

The spray angle refers to the diffusion angle of the liquid mist measured from the nozzle outlet, which determines the coverage range of the spray [60,61]. For flat sector nozzles, the spray angle typically ranges between 80° and 120°; for solid or hollow conical nozzles, the spray angle varies depending on application requirements.

The spray angle is influenced by a combination of nozzle geometry, gas–liquid pressure, and flow rate ratio [62]. Peng et al. found that as the spray pressure increased from 4 MPa to 8 MPa, the spray angle gradually decreased from approximately 95° to 75°, indicating more concentrated droplet distribution under high pressure, which facilitates directional spraying over long distances [14]. Additionally, the nozzle installation angle significantly affects spray morphology. Research by Li et al. on the JIPW-G100 gas-assisted spray device demonstrated that increasing the nozzle installation angle from 0° to 60° expanded the spray coverage range from 20.31 m to 29.16 m, but the average droplet size increased from 101.3 µm to 123.7 µm, suggesting that excessive installation angles enhance coverage range at the expense of atomization fineness [63].

Nozzle manufacturing tolerances also significantly influence the spray angle. Measurements conducted by Ercolano et al. on ten commercial gas-assisted nozzles of identical specifications revealed that, due to uneven ring gap processing, the spray angle varies between 19° and 28°, with axial tilt angles reaching $\pm 5^\circ$. Such variability poses substantial challenges for high-precision applications (e.g., SCR urea injection) and must be accounted for in CFD simulations [18].

2.3. Numerical Simulation Methodologies

Modelling air-assist atomization involves resolving complex fluid dynamics across multiple scales, tracking highly distorted multiphase interfaces, and capturing fluid fragmentation. Contemporary numerical architectures are broadly bifurcated into Eulerian methods, Lagrangian methods, or hybrid Eulerian–Lagrangian coupling frameworks [64].

2.3.1. VOF Framework and Interfacial Tracking

The Volume of Fluid (VOF) method is an interface-capturing Eulerian approach that tracks gas–liquid interfaces by solving the volume fraction transport equations. It accurately simulates complex topological changes during fragmentation processes, including liquid film deformation, pore formation, droplet filament formation, and droplet detachment [65]. Liu et al. employed a coupled LES-VOF method to perform high-resolution numerical simulations of mining internal mixing gas-assisted nozzles with a minimum mesh size of 17 μm , successfully capturing the entire process of annular vortices penetrating from the liquid column tip toward the interior and inducing fragmentation [8]. The simulated fracture length of the liquid column exhibited an error of less than 12% compared to high-speed imaging experiments [66–68].

However, the VOF method requires an extremely fine mesh to resolve thin liquid films and microscopic droplets, resulting in high computational costs [69]. Therefore, in practical applications, VOF is typically employed only for primary breakup simulations near the nozzle, with the computational domain limited to a length of several millimeters to tens of millimeters downstream of the nozzle [70,71]. In their simulation of a flat sector nozzle, Liu and Hung confined the VOF domain to just 1.5 mm downstream of the nozzle outlet, where VOF data was passed to the DPM for subsequent calculations, effectively balancing accuracy and efficiency [26]. As shown in Figure 2, the segmented LSA method (b) provides a more accurate representation of particle size variations along the spray direction compared to the global averaging method (a).

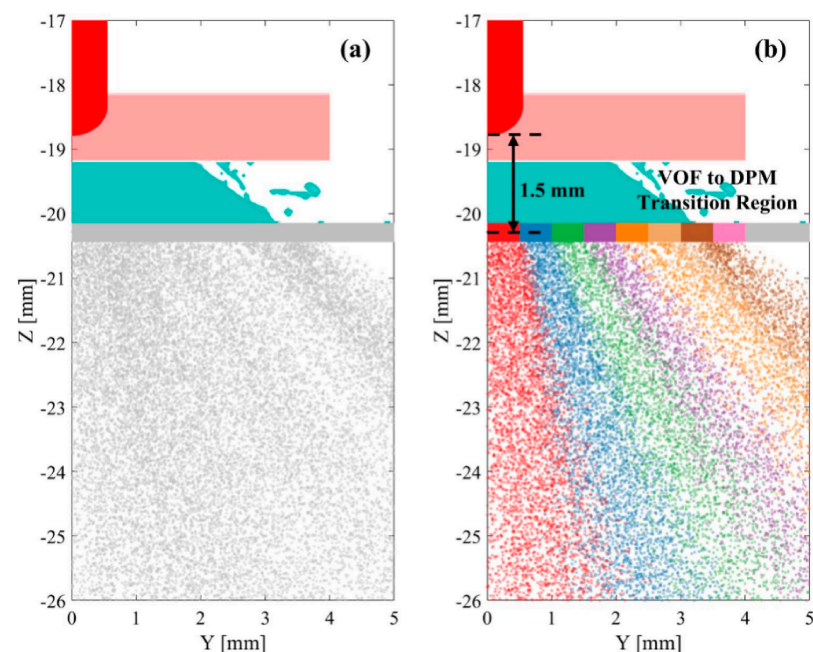


Figure 2. Sample result of combined Eulerian–Lagrangian simulation for flat nozzle spray atomization: (a) averaged LSA method; (b) segment-based LSA method. Reprinted from Ref. [26].

2.3.2. Discrete Phase Modeling (DPM) and Eulerian–Lagrangian Coupling

The Discrete Phase Model (DPM) employs a Lagrangian framework to track the trajectories of droplets/particles, achieving bidirectional coupling through momentum, mass, and energy exchanges with the continuous phase (gas) under an Eulerian framework [72–74]. DPM is well-suited for simulating processes such as secondary breakup, collision, coalescence, and evaporation of droplets, and demonstrates significantly higher computational efficiency than VOF [75,76].

Two typical Euler–Lagrange coupling strategies exist, each relying on fundamental assumptions that strongly dictate the predicted Sauter Mean Diameter (SMD) and droplet size distribution. The first is the “full VOF method,” which simulates the entire primary breakup process and converts droplets into DPM particles when their topological roundness exceeds a specific threshold. This method inherently assumes that once a liquid fragment is sufficiently spherical, its internal flow dynamics and deformation history are negligible, allowing it to be accurately tracked as a point mass. The second is the “interface conversion method,” which generates initial droplets at predefined transition interfaces based on VOF-calculated liquid film velocity, thickness, and breakup theories (e.g., LSA), with subsequent processes handled by DPM. This approach assumes that analytical instability theories can flawlessly bridge the spatial gap across transition planes without fully resolving the physical rupture. Kashani et al. employed this interface conversion method for flat sector nozzles but used globally averaged liquid film parameters that failed to account for spatial variations in spray distribution [77]. To address this, M. Liu and Hung proposed a segment-based VOF-to-DPM conversion method: dividing the spray along its direction into multiple segments (each 0.5 mm wide) at downstream transition interfaces, extracting liquid film velocity and thickness for each segment, calculating corresponding initial droplet diameters via linear stability analysis, and feeding them into DPM [26]. Simulation results showed a spray diameter mean (SMD) of 126.1 μm in the central region and 458.5 μm at the periphery—consistent with experimental measurements of 123.1 μm centrally and 181.5 μm at the edge—while the global averaging method could not capture these directional variations [78,79]. It is critical to highlight that while LSA exhibits significant 30–50% discrepancies when used to predict macroscopic breakup lengths from the nozzle orifice, these uncertainties do not catastrophically propagate in the segmented framework. By utilizing VOF to resolve the highly non-linear near-field flow, LSA is strictly confined to local applications at the transition plane. Because LSA is initialized with exact, VOF-extracted local film parameters rather than idealized global assumptions, the calculated initial droplet diameters remain highly accurate for downstream DPM tracking. Furthermore, the treatment of droplet interactions in the DPM framework is governed by strict collision and coalescence assumptions. Standard stochastic collision models fundamentally assume that only droplets residing within the exact same continuous-phase mesh cell can interact and collide. This spatial assumption renders the predicted coalescence rate—and consequently the final SMD—highly sensitive to grid resolution. If the mesh is overly refined, the statistical number of discrete droplets per cell decreases drastically, which artificially suppresses collision detection frequencies and underestimates coalescence effects in dense near-field sprays. Therefore, relying on these assumptions requires careful grid calibration or the integration of Probability Density Function (PDF) and Population Balance Models (PBM) to correct for collision probability bias.

The determination of the optimal transition segment width—such as the 0.5 mm spatial resolution successfully employed by M. Liu and Hung—must balance gradient resolution against the statistical validity of the applied breakup theory. The segment must be fine enough to capture steep spanwise variations in localized liquid film thickness and velocity, yet remain large enough to encompass characteristic instability wavelengths so that LSA assumptions remain physically meaningful. Furthermore, segmentation strategies must adapt to specific nozzle architectures: while Cartesian linear slicing is appropriate for flat-fan sprays, axisymmetric or circular nozzles necessitate radial or concentric ring segmentation, where resolution scales inversely with the local shear gradient. Crucially, over-refining these transition segments introduces significant computational penalties and numerical risks. Exponentially increasing the number of DPM injection streams into highly refined near-field grids can artificially diminish the parcel count per computational cell.

2.3.3. Large Eddy Simulation (LES) for Multiphase Breakup

Large Eddy Simulation (LES) directly analyzes turbulent vortex structures beyond the filtering scale, while employing a subcell model to simulate small-scale vortices [80,81]. Compared to the RANS method, LES more accurately captures small-scale disturbances induced by turbulent pulsations at the gas–liquid interface, which is critical for triggering primary breakup. Liu et al., using LES with the WALE subcell model combined with VOF simulation, found that when the gas source pressure increased from 0.2 MPa to 0.7 MPa, the peak turbulent kinetic energy in the mixing chamber rose from approximately $20 \text{ m}^2/\text{s}^2$ to $120 \text{ m}^2/\text{s}^2$; turbulent pulsation enhanced unstable waves on the liquid surface, advancing the breakup point forward [8].

For simulating secondary fragmentation in air-assisted nozzles, LES outperforms RANS. Ercolano et al. compared the effects of the RANS $k - \epsilon$ model and the Reynolds Stress Model (RSM) on the spray velocity field, finding that the $k - \epsilon$ model significantly underestimates radial airflow dispersion, resulting in narrower predicted spray width and higher center velocities; whereas the RSM better captures turbulence anisotropy and aligns more closely with PDA experimental data [18]. However, it should be noted that LES requires substantially higher computational costs than RANS, posing challenges for applications in full-scale industrial equipment such as SCR reactors or mine tunnels; thus, a hybrid approach is commonly employed: LES-VOF in the nozzle vicinity and RANS-DPM in the far-field region.

Comprehensively evaluating these methods reveals significant differences in applicability and computational costs: The VOF method (particularly when coupled with LES) accurately captures droplet membrane perforation and annular vortex evolution during primary breakup, though its computational domain is typically limited to millimeter-to-centimeter scales, with single simulations requiring up to 100 h (e.g., Liu et al.'s simulation of 1.4 ms [8]); the DPM method can simulate spray transport at meter-scale scales but requires initial droplet distribution data from experiments or VOF simulations [82,83]. The segmented VOF-to-DPM approach strikes an optimal balance between accuracy and efficiency, making it particularly suitable for predicting longitudinal size variations in flat-surface nozzles. For full-scale industrial applications (e.g., SCR reactors, mine tunnels), a hybrid strategy combining “near-field LES-VOF + far-field RANS-DPM” is recommended. Table 4 summarizes the simulation methods, validation parameters, experimental approaches, error ranges, key findings, and limitations from four representative numerical studies.

Table 4. Validation and Error Matrix of Selected Air-Assist Atomization Numerical Frameworks.

Author (Year)	Numerical Method	Validated Parameters	Experimental Diagnostics	Error Range	Key Findings & Limitations
M. Liu & Hung (2024) [26]	Segmented VOF-to-DPM + LSA (flat-fan nozzle)	Spray angle, spanwise SMD distribution	High-speed shadowgraph + Spraytec laser diffraction	SMD error: 5.7% at spray center, 11.7% at spray edge	Segmented conversion outperforms global averaging; VOF input data is mandatory
Ercolano et al. (2026) [18]	LES (RSM turbulence model) + KH-RT model (external-mixing SCR injector)	Radial droplet velocity, Rosin–Rammler distribution	SIV (near-field) + PDA (far-field)	Maximum velocity deviation $\approx$ 30% at 200 mm downstream	Two-phase simulation superior to single-phase model; grid convergence above 500,000 cells; ultra-fine grids underestimate droplet coalescence
Liu et al. (2025) [8]	LES-VOF (WALE subgrid model) + TAB model (internal-mixing mine nozzle)	Liquid core breakup length, SMD	High-speed camera + PDI	Breakup length error < 12%	Directly captures toroidal vortex breakup; computation domain limited to millimeter scale, cannot be extended to full industrial equipment
Tanner et al. (2016) [2]	CAB model + χ^2 distribution (food emulsion spray)	Volume-weighted droplet size distribution	Laser diffraction	Volume-averaged error < 14%	Breakup constants need calibration for non-Newtonian fluids ($k_2 = 13$ for internal mixing, $k_2 = 1$ for external mixing)

2.3.4. Numerical Uncertainty and Validation Challenges

A critical yet frequently understated challenge in multiphase flow modeling is the quantification of numerical uncertainties, which primarily stem from mesh dependence, turbulence-model selection, and the inherent difficulties of experimental validation in dense spray regimes. **Mesh Dependence and Coalescence Modeling:** In hybrid Eulerian–Lagrangian frameworks, grid resolution poses a paradoxical challenge. While fine meshes are necessary to resolve aerodynamic shear layers and continuous-phase gradients, overly refined grids can artificially distort Discrete Phase Model (DPM) calculations. As demonstrated by Ercolano et al., reducing the mesh size below a critical threshold decreases the statistical number of discrete droplet parcels per cell; this inadvertently compromises the collision–coalescence sub-models, leading to a severe underestimation of downstream droplet coalescence. Consequently, systematically addressing this mesh dependency requires advanced modeling interventions. Within the Lagrangian framework, standard models can be upgraded using stochastic collision algorithms equipped with adaptive sub-grid corrections, such as employing an independent, dynamically coarsened “collision mesh” that completely decouples the collision detection volume from the highly refined gas-phase aerodynamic grid. Alternatively, for ultra-dense near-field zones, a fundamentally different modeling approach is required. Implementing Probability Density Function (PDF) frameworks or Population Balance Models (PBM) within a fully Eulerian–Eulerian architecture completely circumvents the parcel-per-cell paradox. By treating the droplet size distribution as a continuous field rather than discrete entities, these methods decouple collision and coalescence physics entirely from the spatial constraints of the flow grid, yielding true mesh-independent predictions. **Turbulence-Model Selection:** The choice of turbulence model fundamentally dictates the predicted momentum transfer between the high-velocity gas and the discrete liquid phase. Standard RANS approaches, particularly the k – ϵ model, operate under the assumption of isotropic turbulence; this frequently results

in a significant underestimation of radial airflow dispersion, leading to narrower predicted spray widths and erroneously high centerline droplet velocities. To accurately capture the anisotropic turbulent fluctuations that drive lateral droplet diffusion, the Reynolds Stress Model (RSM) or Large Eddy Simulation (LES) is required. For example, LES with the WALE subgrid model has proven highly effective at capturing small-scale disturbances at the gas–liquid interface during primary breakup, though its computational cost largely restricts its application to near-field domains. Validation in Dense Spray Regions: The fidelity of numerical models is ultimately constrained by the quality of experimental validation data. In the dense near-field region immediately downstream of the nozzle (<15–35 mm), traditional Phase Doppler Anemometry (PDA) often fails completely due to multiple light reflections and extreme droplet number densities. This creates a critical “validation blind spot” for primary breakup simulations. To overcome this uncertainty, near-field simulations must be validated using specialized diagnostics such as Structural Image Velocimetry (SIV) or high-speed shadowgraphy, which can resolve dense liquid ligaments and core velocities prior to the transition into the dilute far-field regime where PDA becomes reliable.

2.3.5. Model-Selection Recommendations for Practical Simulations

From a practical modeling perspective, the selection of a numerical framework should depend on the target physical process, computational scale, and required accuracy. For near-nozzle primary breakup, where liquid-film deformation, ligament formation, perforation, and vortex-induced interface instability must be resolved, VOF or LES–VOF is recommended, especially for studies focused on nozzle internal geometry and primary atomization mechanisms. However, because of its high mesh-resolution requirement and computational cost, VOF is not suitable for meter-scale spray transport. For downstream dilute spray transport, deposition, evaporation, and secondary breakup, DPM or Eulerian–Lagrangian coupling is more appropriate, provided that reliable initial droplet size and velocity distributions are available from experiments, empirical correlations, or near-field VOF simulations. For flat-fan nozzles or sprays with strong spatial non-uniformity, segmented VOF-to-DPM transition methods are recommended because they can better preserve spanwise variations in liquid-film thickness, velocity, and initial droplet size. For simulations requiring unsteady turbulent structures and vortex-induced breakup, LES is preferable to RANS, whereas RANS-DPM remains more practical for large industrial domains such as SCR reactors, mine tunnels, and orchard canopies. Therefore, a hierarchical strategy is recommended for engineering applications: LES–VOF or VOF in the near-nozzle breakup region, followed by RANS-DPM or Eulerian–Lagrangian modeling in the far-field spray transport region.

In short, high-fidelity interface-resolved methods should be used when breakup mechanisms are the primary concern, whereas Lagrangian particle-tracking methods are preferable when the objective is spray transport, deposition, or application-scale performance prediction.

2.4. Experimental Diagnostics and Characterization

Empirical investigations of air-assist atomization rely on high-speed, high-resolution optical techniques [84–86]. These diagnostics are broadly categorized into macroscopic morphology characterization, droplet velocity field mapping, and droplet size distribution measurement [87]. Table 5 evaluates five primary optical diagnostic techniques, highlighting their operating principles, resolved capabilities, and technical limitations.

Table 5. Methodological Comparison of Primary Spray Diagnostic Techniques.

Technique Name	Measurement Principle	Measurable Parameters	Typical Spatial Resolution	Applicable Region	Advantages	Main Limitations
High-Speed Shadowgraphy	Backlight illumination + grayscale threshold segmentation	Spray angle, breakup length, liquid ligament morphology	10–20 $\mu\text{m}/\text{px}$	Near-field (<50 mm downstream)	Intuitive visualization, low cost, high frame rate	Subjective binarization threshold, no velocity data
Structural Image Velocimetry (SIV)	Cross-correlation analysis of dual-pulse shadow images	2D velocity field (dense near-field spray)	Medium (depends on cross-correlation window)	Near-field (<20 mm downstream)	Capable of measuring ultra-high droplet number density zones	Cannot measure droplet size; requires dual-pulse laser trigger
Phase Doppler Anemometry (PDA/PDPA)	Doppler frequency shift + phase difference in scattered laser signals	Simultaneous droplet diameter & velocity (single point)	Point measurement ($\sim 0.1 \text{ mm}^3$ probe volume)	Mid/far-field (>15–35 mm downstream)	Highest measurement accuracy, obtains coupled size-velocity distribution	Multiple light scattering causes failure in dense near-field; point-by-point scanning is time-consuming
Particle Image Velocimetry (PIV)	Dual-pulse laser sheet + cross-correlation of tracer scattering signals	Full-field 2D/3D velocity vector distribution	Millimeter scale (depends on cross-correlation window)	Mid/far-field	Non-intrusive full-field velocity measurement	Requires tracer particles; limited by optical window layout
Laser Diffraction Particle Sizing	Inversion algorithm based on angular distribution of laser scattering signals	Volume frequency distribution, SMD, span parameter	Line/area average over entire spray beam	Steady full spray plume	Fast measurement, stable repeatability, insensitive to droplet density	No velocity information; cannot distinguish radial size gradients without spatial slicing setup

2.4.1. High-Speed Shadowgraphy and Structural Image Velocimetry (SIV)

High-speed shadowgraphy employs parallel backlight illumination of a spray and records shadow images of droplets and liquid filaments using a high-speed camera [88]. This technique provides visual representations of spray morphology, droplet breakup length, spray angle, and the spatial distribution of liquid filaments and droplets [89]. Ercolano et al. utilized an LED light source with a pulse width of 300 ns and a Phantom v711 camera to achieve a spatial resolution of $16.4 \mu\text{m}/\text{pixel}$ at 1280×800 pixel resolution, successfully capturing detailed breakup phenomena across a 2–20 mm region downstream of the air-assisted nozzle [18]. Through image binarization, the spray angle (using the mean image method) and the core region of spray activity (using the standard deviation image method) can be determined; the difference between these two estimates may range from 5 to 10 degrees.

Structural Image Velocimetry (SIV) is an extension of shadow imaging technique that records dual-pulse images (with a $2 \mu\text{s}$ interval) and performs cross-correlation analysis on the droplet/filament textures in the images to obtain a two-dimensional velocity field [90–92]. SIV is particularly suitable for high-density regions near nozzles, where severe droplet overlap makes traditional Particle Image Velocimetry (PIV) difficult to apply [93,94]. Dageforde et al. employed SIV to measure the velocity distribution within 20 mm downstream of an air-assisted nozzle outlet and found that core velocities exceeded 250 m/s, while velocities rapidly declined at the edges [18].

The spatial resolution of shadow imaging typically ranges from $10\text{--}20 \mu\text{m}/\text{px}$; for microscopic droplets with particle sizes smaller than 3–5 pixels, measurement errors increase significantly [95,96]. Liu et al. reported that their system achieved an identification rate of less than 50% for droplets smaller than $15 \mu\text{m}$, necessitating cautious interpretation of

particle size distribution data at this scale [8]. Additionally, PDA fails to function properly in the high-density region near the nozzle (typically within 15–35 mm from the outlet) due to multiple scattering effects, and velocity information in this region can be supplemented by SIV or LES-VOF methods [97,98].

2.4.2. Phase Doppler Velocimetry and PIV

Phase Doppler Velocimetry (Phase Doppler Anemometry, PDA/PDPA) is currently the most accurate method for simultaneous measurement of droplet diameter and velocity [99–101]. Its principle involves: when a droplet passes through the interference fringes of two laser beams, the scattered light exhibits a Doppler frequency shift, from which droplet velocity can be derived; simultaneously, phase differences exist between the scattered light signals received by detectors at different angles, with these differences being proportional to the droplet diameter [102–104]. The point-measurement capability of PDA enables it to obtain combined diameter-velocity distributions at various radial positions across the spray cross-section [105,106]. However, PDA's effective measurement range is limited by droplet density, and it fails to operate properly in dense nozzle regions (<15–35 mm) due to multiple reflections [107,108]. Liu et al. used an Artium PDA system to measure droplet parameters 65 cm downstream of a mine gas-assisted nozzle and found that as gas pressure increased, the droplet velocity distribution gradually converged toward the center, indicating that high-speed airflow enhances droplet concentration [8].

Particle Image Velocimetry (PIV) is employed to measure the overall velocity distribution in a spray flow field [109,110]. Tracer particles are dispersed into the spray (or droplets are directly used as scattering bodies), and the measurement plane is illuminated with a dual-pulse laser; the two-dimensional velocity vector field is obtained through cross-correlation analysis [111–114]. PIV complements PDA: PIV provides the full-field velocity structure, while PDA offers high-precision particle size–velocity correlations at individual points.

2.4.3. Laser Diffraction Particle Size Analysis

Laser diffraction is a rapid method for measuring droplet size distribution. The principle involves droplet clusters diffracting and scattering laser beams; the angular distribution of scattered light correlates with droplet size distribution, enabling determination of volume frequency distribution through inversion algorithms [115–117]. Compared to particle size distribution analysis (PDA), laser diffraction offers faster measurement speeds, is insensitive to droplet density, and provides average particle size distribution across the entire spray cross-section, though it cannot yield velocity information or distinguish size variations at different spatial positions (unless spatial resolution measurements are employed). M. Liu and Hung utilized the Spraytec laser diffraction system to measure particle size distributions at various radial positions 52 mm downstream of a flat sector nozzle at 10-mm intervals, revealing that Dv50 increased from approximately 150 μm to over 250 μm from spray center to edge, indicating longitudinal size variation [26]. Vankeswaram et al. also employed laser diffraction to investigate atomization characteristics of aviation biofuels, obtaining trends in Sauter mean diameter (SMD) versus axial air-to-liquid ratio (ALR) [28]. Figure 3 illustrates general variation of droplet SMD under different ALR in typical fluid sprays.

Each of the three experimental methods has its own advantages and limitations; only their combined application can fully characterize the multi-scale characteristics of airflow-assisted atomization: shadow imaging and SIV reveal the morphology and velocity of primary particle breakup in the near field, PDA provides precise pointwise particle size-velocity data in the far field, laser diffraction yields the overall average par-

ticle size distribution, while PIV supplements the spatial velocity structure [118–120]. This integrated multi-method approach has become the gold standard in airflow-assisted atomization research.

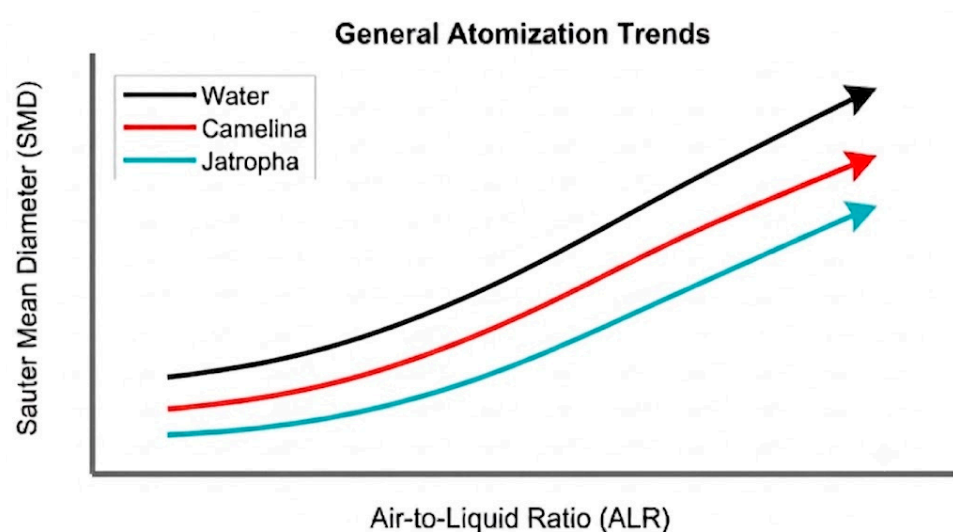


Figure 3. The general variation of droplet SMD under different ALR in typical fluid sprays.

3. Cross-Disciplinary Applications: Tailored Droplet Customization

The core advantage of airflow-assisted atomization lies in its flexibility: by adjusting the air-to-liquid ratio, pressure, nozzle geometry, and auxiliary methods (such as electrostatic effects, heating, or air curtains), droplet size, velocity, spatial distribution, and even charge state can be precisely tailored to target specifications across various applications [121,122]. This chapter examines four typical fields—agricultural plant protection, food processing, disinfection, and combustion atomization—to demonstrate how the same atomization mechanism can evolve into tailored design and control strategies for distinct objectives. Table 6 summarizes recommended droplet sizes, control strategies, and performance improvement outcomes for each application scenario.

Table 6. Comparison of optimal droplet parameter windows and control strategies for four typical application scenarios.

Application Field	Representative Author (Year)	Typical Liquid Medium	Recommended Dv50/SMD (μm)	Core Regulation Methods	Key Performance Improvements
Orchard Precision Agriculture	Ou et al. (2026) [107]	Aqueous pesticide solution	35 (VMD)	Electrostatic induction (3 kV) + lateral auxiliary air jet	Abaxial leaf deposition increased by 203–1350%
Milk Powder Spray Drying (Food Processing)	Qamar et al. (2025) [15]	Oil–water food emulsion	100–200 (SMD)	Solar air preheating + closed-loop hot air circulation	Electrical heating power reduced from 2.68 kW to 1.69 kW (30% energy saving)
Underground Mine PM10 Dust Suppression	Nie et al. (2024) [13]	Water	27.6 (D_{32})	Wind-assisted misting + 8 MPa liquid supply pressure	PM10 capture efficiency > 90%, residual PM10 concentration $\leq 0.99 \text{ mg}/\text{m}^3$
Surface & Space Disinfection	Chauhan et al. (2023) [17]	Sodium hypochlorite disinfectant	49.7 (VMD)	Electrostatic induction (2 kV, 4 bar air pressure)	Disinfectant consumption reduced by 87%, microbial inactivation > 4 log reduction
Aviation Kerosene Combustion (AADI)	Hu et al. (2022) [11]	RP-3 aviation kerosene	<6.5 (SMD) ¹	Asymmetric pre-chamber + excess air ratio $\lambda = 0.7$	Engine power increased by 16.7%, combustion duration shortened by 18%

3.1. Precision Agricultural Spraying: Achieving Targeted Deposition and Minimizing Drift

Pest and disease control in orchards, field crops, and greenhouse crops requires that spray droplets effectively penetrate complex canopy structures while minimizing wind-driven drift and evaporation loss [123–125]. Air-assisted spraying technology is widely employed in this field, with the core challenge being how to control the drift of fine droplets (typically $<50\ \mu\text{m}$) while ensuring adequate deposition on leaves, particularly their undersides.

The crop canopy exhibits multi-layered, non-uniform, and dynamically changing structural characteristics. The core principle of air-assisted spraying lies in utilizing airflow to transport droplets into the canopy interior, though airflow parameters must be precisely balanced between penetration depth and droplet loss: excessive airflow causes direct penetration into the canopy leading to ground-level droplet loss, while insufficient airflow fails to reach mid-to-lower leaf layers [126]. To address this issue, Lin et al. found that in long-distance air-assisted spraying for greenhouse tomatoes, structural errors in fan configuration combined with horizontal movement-induced drag angles naturally caused a spray axis deflection of approximately 2° [28]. By applying the angle-time cumulative balance (b-CAD) method to adjust the nozzle angle from 0° to $1.2\text{--}2.3^\circ$, the coverage gap between left and right canopy sides decreased from 8.6–11.7% to $-2.3\text{--}4.0\%$, while the overall sample coefficient of variation dropped from $\sim 71\%$ to 55%. Hołownicki et al. developed a variable air volume assistance system (VAA) for dwarf and semi-dwarf orchards, employing two independent axial fans with real-time airflow regulation via frequency conversion or pitch adjustment. This system reduced airflow volume from traditional $30,000\ \text{m}^3/\text{h}$ to $20,000\ \text{m}^3/\text{h}$ and power consumption from $\sim 28\ \text{kW}$ to below $10\ \text{kW}$, while achieving a more rectangular vertical wind velocity distribution for uniform coverage. Under crosswind conditions, independent adjustment of airflow rates on the windward and leeward sides compensates for wind interference: increased wind speed on the windward side shifts the spray nozzle backward, while reduced wind speed on the leeward side minimizes canopy penetration drift. Coordinated optimization of nozzle installation angles further enhances the overall efficiency of both the wind curtain and air-assisted spraying systems.

Intelligent agricultural machinery integration for variable-rate spraying systems. Precise pesticide application requires real-time adjustment of spray volume based on canopy density and travel speed. Traditional orchard sprayers predominantly employ manual adjustments, lacking capability to modify air flow or chemical dosage during operation [127,128]. The EDAS (Environment-Dependent Application System) sprayer developed by Doruchowski et al. utilizes ultrasonic sensors to detect canopy volume and density, with a microprocessor-controlled diaphragm-type airflow regulator at the fan inlet enabling independent, continuous adjustment of bilateral airflow [129]. Ou et al. designed an air-assisted electrostatic nozzle operating on a lateral jet atomization principle, employing annular induction electrodes to charge droplets, producing charged droplets with a VMD of $35\ \mu\text{m}$ under 0.5 bar air pressure and 0.7 bar liquid pressure, achieving a charge-to-mass ratio of approximately $2.7\ \text{mC/kg}$ [107]. Field trials demonstrated that at a charging voltage of 3 kV, droplet coverage on leaf undersides increased by 200–1350%. However, excessive spray distance ($>1.2\ \text{m}$) diminishes electrostatic adsorption efficacy and reduces penetration capacity (SP value decreases from 0.48 to 0.16). Therefore, in practical applications, the relative positioning between the nozzle and canopy should be optimized according to crop row spacing (typically 0.6–1.0 m).

Control of Fine Mist Droplet Evaporation and Drift: Small mist droplets ($<100\ \mu\text{m}$) are prone to drift due to airflow disturbances and evaporate rapidly in high-temperature, low-humidity environments, leading to reduced effective deposition [130,131]. Ou et al. found

that when the spray distance increased from 0.6 m to 0.9 m, even with a maintained 3 kV electrostatic voltage, mist droplet coverage within the canopy (at sampling points S3/S4) decreased by approximately 20–30%, indicating that electrostatic adsorption cannot fully compensate for momentum loss during long-distance transport [107]. Another approach to mitigate drift is the use of air-induced (AI) nozzles, which introduce air into the nozzle to form bubbles within the droplets, increasing droplet size while preserving optimal impact fragmentation characteristics. Kasbi et al. demonstrated that AI nozzles exhibit a 30–50% larger specific mean diameter (SMD) compared to conventional sector nozzles, yet reduce drift by over 60% [132]. For UAV-based agricultural spraying, the downwash flow field beneath the rotor critically influences droplet trajectories: this airflow creates complex vortex structures above crop canopies, entrapping fine droplets in vortex cores and preventing their sedimentation. Coombes et al.'s CFD-DPM simulations revealed significant reductions in effective deposition rates when $Dv50 < 100 \mu\text{m}$, recommending a particle size range of 50–150 μm for UAV applications [133]. The downwash flow field under the rotor plays a decisive role in determining droplet trajectories during UAV agricultural spraying. Using CFD-DPM simulations, Coombes et al. demonstrated that when $Dv50 < 100 \mu\text{m}$, the downward flow vortex entrains most droplets into its core, preventing their sedimentation; they therefore recommend employing a particle size range of 50–150 μm for UAV spraying systems.

While electrostatic adsorption efficacy is distance-dependent, this 0.6–1.0 m range serves as an optimal design target rather than a restrictive operational limit. In modern variable-rate systems, this constraint is reconciled through two integration strategies: (1) Dynamic positioning, where ultrasonic or LiDAR sensors inform real-time actuators to adjust boom orientation, maintaining the optimal nozzle-to-canopy distance; and (2) Adaptive electronic modulation, where induction voltage and air-assist jet momentum are dynamically tuned based on detected canopy density and distance, compensating for potential electrostatic deposition loss in more distant or dense foliage.

3.2. Food Drying and Spray Processing: Achieving Uniform Phase Transition and Preserving Activity

Spray drying is the core unit operation for producing milk powder, juice powder, and microcapsules. The feed liquid is typically a high-viscosity non-Newtonian fluid; conventional pressure nozzles are prone to clogging, whereas air-assisted nozzles achieve efficient atomization at lower pressures, making them more suitable for drying heat-sensitive materials [134].

The mixing mechanism between droplets and high-temperature airflow within the drying tower determines both the drying rate and particle morphology [135]. Qamar et al. conducted an energy and exergy analysis of a solar-assisted milk powder spray drying system, demonstrating that the use of a solar air preheater (SAH) reduced power consumption from 2.68 kW to 1.69 kW, with solar energy accounting for approximately 30% of total energy input [15]. The greatest improvement potential was observed in the condenser and drying chamber, indicating that heat recovery and particle size control are critical for enhancing efficiency. Langrish et al.'s study revealed that for SMD sizes between 100–200 μm , optimal drying time corresponds to the optimal hot-air residence time; droplets smaller than 50 μm rapidly form coatings that hinder internal moisture evaporation (leading to burst), while those larger than 300 μm often impact the tower walls before complete drying [15]. Precise control of the particle size range is essential for ensuring drying efficiency and product quality [136]. Figure 4 illustrates the structural configuration of this closed-loop solar-assisted milk powder spray drying system, comprising a solar air preheater, electric heater, drying chamber, cyclone separator, and condenser.

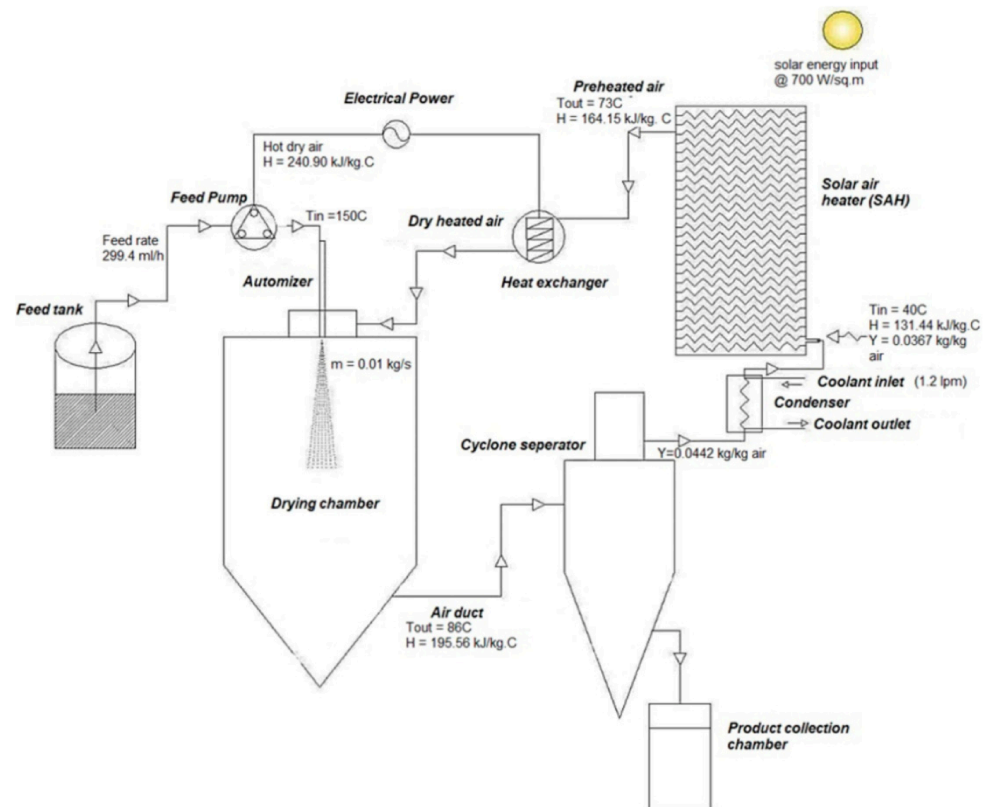


Figure 4. Schematic diagram of a closed-loop solar-assisted milk powder spray drying system. The system comprises a solar air preheater, an electric heater, a drying chamber, a cyclone separator, and a condenser. Reprinted from Ref. [15].

Food liquid formulations, as well as many biopharmaceuticals, typically exhibit complex non-Newtonian behaviors such as shear-thinning, yield stress, or viscoelasticity [137–139]. The atomization characteristics of these complex fluids differ markedly from those of standard Newtonian fluids. Modeling the atomization of non-Newtonian fluids introduces significant complexity, as their rheology-dependent behaviors fundamentally alter both primary and secondary breakup dynamics, often prolonging ligament lifetimes and delaying droplet pinch-off. As highlighted by recent advancements in rheology-dependent CFD modeling, traditional Newtonian constitutive equations are insufficient for these applications. It is critical to incorporate advanced rheological models into CFD frameworks to accurately predict complex-fluid breakup and non-Newtonian thermal-fluid transport mechanisms [140,141].

Addressing these numerical challenges, Tanner et al. employed an improved Cascade Atomization and Drop Breakup (CAB) model to simulate the atomization of non-Newtonian oil–water emulsions (viscosity 0.1799 Pa·s) in gas-assisted nozzles [2]. Their rheology-inclusive simulations revealed that a χ^2 distribution more closely approximates the experimentally measured droplet size distribution than a standard uniform distribution. Furthermore, they demonstrated that for internal mixing nozzles, due to intense gas–liquid pre-mixing, the breakage constant must be calibrated significantly higher than that of external mixing nozzles to accurately capture the particle sizes. When the gas pressure ratio equals 0.66, the initial Weber number enters the catastrophic breakage region ($We > 350$), reducing the median droplet diameter to approximately 25 μm . These studies underscore that integrating precise rheological parameters into multiphase flow simulations is indispensable for optimizing product quality in spray drying.

Crucially, food emulsions exhibit time-dependent rheology where viscosity evolves due to shear-induced structural breakdown. Incorporating this requires moving beyond

static non-Newtonian models toward dynamic structure-based frameworks, where a state variable representing the material's internal structural integrity evolves based on local shear history. For common food materials, validated constitutive models are increasingly derived from high-shear experimental rheometry, allowing researchers to calibrate empirical constants within advanced fragmentation frameworks like the CAB model. Future modeling efforts should focus on integrating these shear-history-dependent viscosity functions directly into the Eulerian–Lagrangian transition interface to accurately capture the evolution of complex food liquids during atomization.

Particle aggregation and loss of heat-sensitive substances represent another critical challenge in spray drying, closely related to droplet size distribution and drying rate. Studies by Dubey et al. demonstrate that during oil–water emulsion spray drying, an excessively high oil-to-droplet size ratio leads to oil droplet migration to the surface, resulting in oxidation and degradation; increasing the air-to-liquid ratio (ALR) above 0.8 reduces the standard deviation of droplet size (SMD) below 50 μm , effectively minimizing surface exposure of oil droplets [6]. Spray freeze drying, as a novel approach for processing heat-sensitive materials, requires rapid droplet freezing under low-temperature conditions. Tanner et al. found that droplets with an initial diameter < 100 μm exhibit greater subcooling and shorter freezing times, which facilitates spherical particle formation and mitigates ice crystal-induced damage to cellular structures [2]. These findings underscore that precise control of the particle size range is essential for achieving optimal encapsulation efficiency and retention of active pharmaceutical ingredients.

3.3. Disinfection and Sterilization: Achieving Spatial Dispersion and Adhesion

In environments such as livestock sheds, hospitals, public transportation systems, and cold chain facilities, disinfectants must diffuse throughout the space in aerosol form and adhere to object surfaces—including hard-to-reach areas like backsides and crevices [142,143]. Traditional high-pressure sprayers produce large droplets that settle rapidly, making spatial dispersion challenging; while ultrasonic atomization generates extremely fine droplets (VMD < 10 μm), its low mist flux and limited directional delivery capabilities limit effectiveness. Air-assisted electrostatic spraying combines the fine particle size and high momentum of pneumatic atomization with electrostatic-induced enhanced adhesion properties, emerging as a cutting-edge technology in disinfection applications [144].

Aerosol-level ultrafine atomization refers to the suspension and diffusion of particles within enclosed spaces. Wood et al. (2021) evaluated six commercially available electrostatic sprayers and found that most devices exhibited a particle size distribution (VMD) $\geq 40 \mu\text{m}$, with four models achieving a charge-to-mass ratio of 0.1–0.3 mC/kg, demonstrating fundamental “encapsulation effects” [143]. Chauhan et al. (2023) further optimized an air-induced electrostatic nozzle using sodium hypochlorite disinfectant solution (concentration: 1000 mg/L) under 2.0 kV voltage and 4 bar pressure, achieving a charge-to-mass ratio of 2.43 mC/kg and reducing the VMD from 230 μm in conventional handheld sprayers to 49.7 μm [17]. The inactivation rates for *Pseudomonas aeruginosa* and bacteriophage MS2 exceeded 4 log reductions, while disinfectant consumption was reduced by 87% compared to traditional methods (2.62 L/h vs. 33.7 L/h). When droplet diameters were below 50 μm , the settling velocity could decrease to below 0.1 m/s, allowing particles to remain suspended for minutes to tens of minutes under non-convection conditions—enhancing collision opportunities with airborne aerosol particles (e.g., viral droplet nuclei) for inactivation. Figure 5 illustrates the variation of the charge-to-mass ratio of the liquid in the air-assisted electrostatic nozzle with the applied voltage under different air pressures.

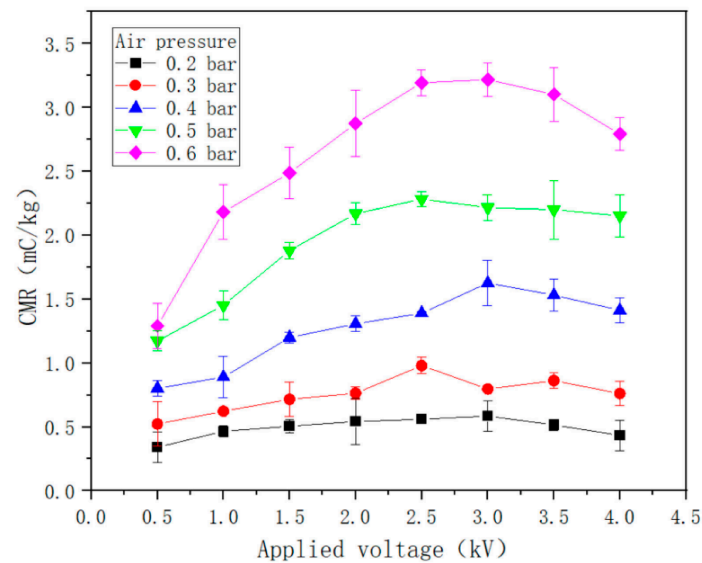


Figure 5. CMR variation with the applied voltage. Reprinted from Ref. [145].

The coupling between electrostatic fields and pneumatic assistance enhances adhesion. The electrostatic effect rapidly diminishes with increasing spray distance [146]. Ou et al. (2026) found that when the distance increased from 0.6 m to 1.2 m, the charge-to-mass ratio decreased from 4.2 mC/kg to 2.7 mC/kg, and the deposition increment on leaf undersides dropped from >1000% to <200% [107]. Chauhan et al. (2023) also reported that under optimal operating conditions (voltage 2 kV, air pressure 4 bar, distance 10 cm), the charge-to-mass ratio reached 2.43 mC/kg, achieving a significant “flow-around encapsulation” effect [17]. Therefore, in practical channel disinfection, it is recommended to maintain the nozzle-target distance at 0.6–1.0 m and employ low-speed movement (<0.5 m/s) to ensure effective charge transfer. In high-humidity environments, charge leakage accelerates; thus, appropriately increasing the voltage or shortening the treatment intervals is advised [147,148].

The efficacy of electrostatic deposition is highly sensitive to ambient humidity. Quantitatively, charge leakage follows an exponential decay relative to increasing relative humidity (RH), with rapid acceleration observed when RH exceeds 70–75%. Electrostatic performance is generally compromised above a threshold of 80–85% RH due to elevated surface conductivity. In such high-humidity environments, we recommend either shifting the technical reliance toward enhanced air-assist aerodynamic penetration or employing advanced dielectric media and real-time, humidity-compensated voltage modulation to mitigate charge loss.

3.4. Combustion Atomization: Achieving Instantaneous Mixing and Complete Reaction

Combustion equipment such as gas turbines, boilers, kilns, and diesel engines requires fuel to mix with air and combust within milliseconds to reduce pollutant emissions (NO_x, soot, CO) and enhance combustion efficiency. Gas-assisted atomization is particularly suitable for high-viscosity or low-volatility liquid fuels like heavy oil, biodiesel, and kerosene. Its primary objective is to achieve the smallest Sauter Mean Diameter (SMD) and the narrowest particle size distribution at a given fuel flow rate, thereby increasing the evaporation area and reducing ignition delay [149,150].

The micro-explosion fragmentation of high-viscosity fuels under high-pressure airflow conditions. For heavy oils or biodiesel, high viscosity inhibits the initial growth of liquid film disturbances; simply increasing fuel pressure is limited by pump power and nozzle wear [151]. Gas-assisted atomization applies stronger aerodynamic shear forces through

high-speed airflow, effectively reducing SMD (Sauter Mean Diameter). Vankeswaram et al. compared the performance of Jet A-1 aviation kerosene with two camel thorn/bitternut-derived HRJ biofuels (with blending ratios ranging from 20% to 70%) in hybrid pneumatic atomizing nozzles [28]. Under identical ALR (Air-Liquid Ratio) conditions, the SMD difference between biofuels and Jet A-1 was less than 10%, demonstrating the feasibility of “drop-in” compatibility. However, samples with higher biofuel proportions (70%) exhibited slightly lower viscosity (1.11 mPa·s) but achieved slightly smaller SMD values. Chouaieb et al. introduced a central micro-jet (diameter 1 mm, velocity 0–25 m/s) into methane-air turbulent flames to enhance mixing [12]. Even when the micro-jet mass flow rate accounted for only 0.16% of total fuel flow, it reduced methane concentration at the core region by 62% and decreased soot volume fraction at the outlet by 94%. The mechanism involves creating localized recirculation zones near the nozzle exit, promoting pre-mixing of fuel and air and thereby enabling low-temperature flameless combustion (MILD combustion).

The quantitative relationship between SMD and ignition delay, combustion efficiency, and pollutant emissions. In aviation piston engines, the atomization quality of kerosene (e.g., RP-3) directly determines ignition reliability and combustion completeness. Hu et al. applied an asymmetric pre-combustion chamber to an air-assisted direct injection (AADI) kerosene engine, with a pre-combustion chamber volume of 5.38 cm³ (approximately 9.8% of the clearance volume), injecting jet flames into the main combustion chamber through five nozzles (three in Zone A and two in Zone B) [11]. Simulations demonstrated that the asymmetric pre-combustion chamber accelerated the combustion process in the main chamber by 7%, increased cumulative heat release by 17%, and shortened combustion duration by 16%. When nozzle diameter increased from 1.5 mm to 2.0 mm, jet velocity reached $Ma \approx 1.0$ (approximately 340 m/s), achieving maximum peak cylinder pressure and heat release; further enlargement to 2.25 mm resulted in excessive flame penetration due to high jet momentum, thereby reducing efficiency. With an excess air coefficient $\lambda = 0.7$, the rich mixture in the pre-combustion chamber released higher ignition energy, advancing CA50 by approximately 19% and increasing engine power by 16.7%. These findings indicate that for fuels with slow evaporation rates like kerosene, gas-assisted atomization must be optimized in synergy with pre-combustion chamber jet ignition rather than solely pursuing minimal SMD.

In SCR (Selective Catalytic Reduction) systems, gas-assisted atomization of urea aqueous solutions directly impacts the uniformity of ammonia distribution. Ercolano et al. conducted systematic optical diagnostics and CFD modeling on ten industrial external-mixing gas-assisted nozzles from the same batch. Within air flow rates of 8–20 L/min and liquid flow rates of 0.5–1.5 kg/h, the spray droplet diameter (SMD) decreases with increasing air-to-liquid ratio, reaching a minimum of approximately 25 μm [18]. They observed that spray angle variations between nozzles ranged from 19° to 28°, primarily attributed to manufacturing tolerances in nozzle annular gaps (local deviations of 100 μm). CFD simulations demonstrated that the two-phase method (simulating both airflow and droplets simultaneously) more accurately reproduces radial droplet velocity distributions compared to the single-phase method (simulating only droplets), and exhibits greater sensitivity to turbulence models: the Reynolds Stress Model (RSM) outperforms the $k-\varepsilon$ model in predicting spray width and central velocity attenuation [152–154]. After grid refinement exceeding 509,803 elements, particle size distribution converged; however, overly fine grids may underestimate coalescence effects due to reduced droplet numbers per element. These findings provide practical parameter sensitivity guidance for high-fidelity simulations.

Case analyses across the four domains demonstrate that the “customization” capability of airflow-assisted atomization stems from multiple independently adjustable parameters:

gas–liquid ratio, gas/liquid pressure, nozzle geometry (mixing configuration, orifice size and angle), and auxiliary fields (electrostatic field, temperature, air curtain). In agriculture, moderate particle sizes (50–200 μm) and directional deposition are required; food drying demands uniform particle sizes (50–150 μm) while accounting for the shear-thinning properties of non-Newtonian fluids; disinfection applications necessitate ultrafine particles (<30–50 μm) combined with electrostatic coupling for effective dispersion and adhesion; whereas combustion processes require extremely small standard deviation of mean diameter (<50 μm) and narrow distribution to accelerate evaporation and mixing. The same physical mechanisms exhibit significant variations in parameter ranges depending on application objectives, requiring researchers and engineers to make informed trade-offs rather than mechanically pursuing “the finer, the better” or “the higher the pressure, the better.” Figure 6 compares instantaneous flame temperature fields under crosswind conditions for two nozzle geometries square nozzles exhibit broader, shorter flames due to corner vortex-enhanced mixing, resulting in higher combustion efficiency.

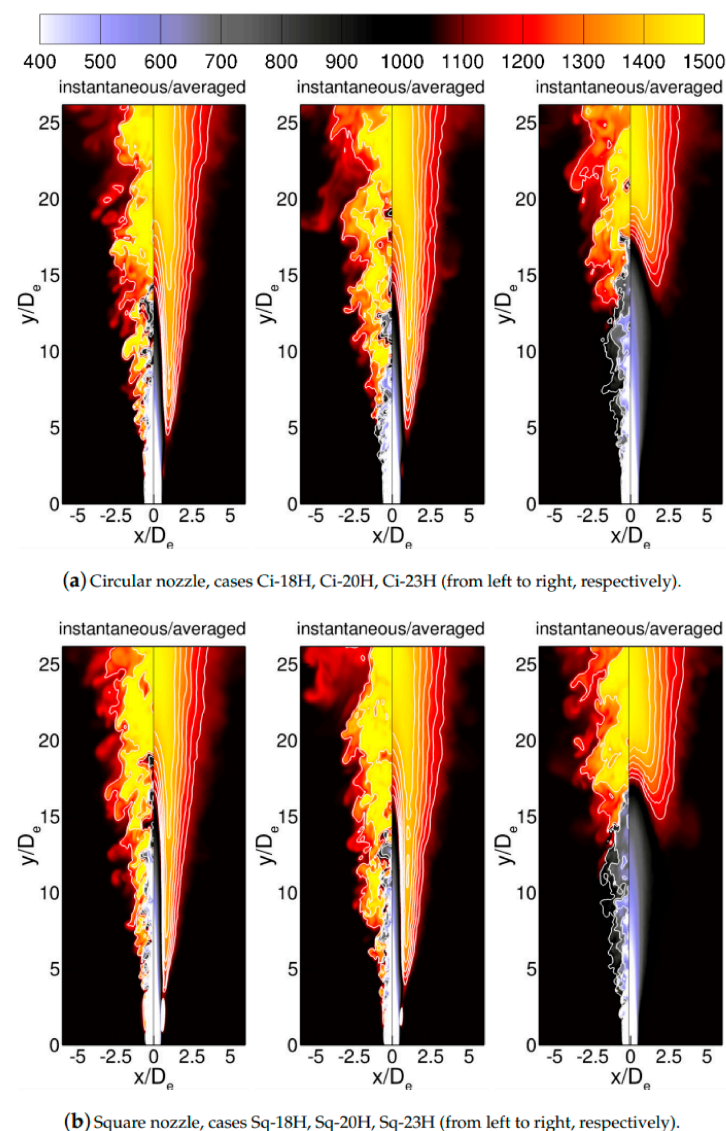


Figure 6. The instantaneous flame temperature fields under crosswind conditions for different nozzle geometries. Square nozzles exhibit broader and shorter flames due to corner vortex-induced enhanced mixing; in contrast, circular nozzles produce slender flames that are prone to lift-off. Reprinted from Ref. [155].

4. Challenges and Future Perspectives

Airflow-assisted atomization technology is undergoing a critical transformation from “experience-based design” to “data-driven design,” from “open-loop presetting” to “closed-loop intelligence,” and from “metalworking approaches” to “biomimetic materials.” At the multiphase flow modeling level, three major bottlenecks limit simulation accuracy: grid-dependent droplet collision behavior in dense regions, the lack of universal prediction models for single-stage breakup in non-circular nozzles, and inadequate constitutive relationships for non-Newtonian fluids. Developing reduced-order models coupled with PBM-CFD methods is urgently needed to achieve rapid, engineering-ready predictions. In system control, transitioning from open-loop presetting to closed-loop adaptation requires integrating low-cost MEMS sensor arrays with edge AI chips to optimize gas–liquid ratios online via MPC strategies, while balancing energy efficiency and reliability through tiered implementation of full closed-loop or simplified setpoint-adaptive strategies tailored to specific applications. Sensor survivability in industrial atomization environments—characterized by high shear, chemical exposure, and fouling—remains a major implementation challenge. To ensure robustness, we advocate a tiered ‘protection-isolation-virtualization’ strategy. In harsh combustion environments, we propose the use of virtual sensing (soft sensing) frameworks, where edge AI algorithms derive droplet metrics from downstream pressure and temperature signatures, eliminating the need for high-risk, direct-contact sensors. In agricultural and environmental scenarios, sensor longevity is maximized through the application of self-cleaning, hydrophobic nano-coatings and modular, field-swappable sensor housings. These strategies extend operational life toward practical maintenance cycles (e.g., 500–1000 h for agricultural systems), while non-contact sensing architectures provide extended durability for high-intensity industrial applications. Regarding hardware innovation, biomimetic liquid-guiding structures, ceramic/composite coatings, and light-curable 3D printing technologies offer new solutions for nozzle wear resistance, clogging prevention, and chemical compatibility; the introduction of green media such as magnetized water, superheated steam, and exhaust gas recirculation further expands decarbonization pathways. While non-circular nozzle geometries (square, diamond) offer significant advantages in combustion efficiency and emissions reduction due to corner vortex-enhanced mixing, they introduce challenges in manufacturing and maintenance. However, the ‘performance-to-penalty’ ratio increasingly favors non-circular designs in high-performance industrial scenarios. System-level savings—such as reduced combustion chamber size, lower exhaust after-treatment demands, and improved combustion stability—often offset the initial manufacturing premiums and potential maintenance costs. With the maturation of 3D printing and anti-fouling ceramic coatings, the reliability gap between non-circular and traditional circular nozzles is rapidly narrowing, positioning non-circular geometries as an effective pathway for next-generation, high-efficiency smart nozzles. The synergistic advancement of these three dimensions. The synergistic advancement of these three dimensions—using physical mechanisms to refine models, leveraging predictive models for closed-loop control, and employing advanced materials and green media for efficient operation—will serve as the core drivers for transformative progress in airflow-assisted atomization across combustion, environmental protection, agriculture, and food processing. Table 7 summarizes key future challenges and potential solutions.

Current research highlights the absence of robust atomization constitutive formulations for non-Newtonian fluids as a primary bottleneck. While a universal SMD correlation remains a theoretical ideal, its physical realization is hindered by the extreme diversity of complex fluid rheologies. Consequently, future efforts should shift toward developing application-specific databases and reduced-order models, which provide a more pragmatic

engineering solution for industrial-specific flow regimes than pursuing a single universal empirical correlation.

Table 7. Summary of Key Future Challenges and Potential Solutions.

Challenge Category	Specific Problems	Potential Solutions	Expected Benefits
Droplet collision & coalescence modeling in dense sprays	Mesh refinement reduces collision detection frequency, leading to large SMD prediction bias	PBM-CFD coupled framework, optimized coalescence kernel function	Eliminates mesh dependency; improves prediction accuracy for dense spray zones
General primary breakup model	Classical engineering models (LSA) fail for non-circular nozzles and turbulent inlet flow	Dimensionless reduced-order model based on momentum flux ratio & liquid film Reynolds number	Rapid prediction of spatial droplet size distribution; supports industrial nozzle selection
Atomization of non-Newtonian fluids	Lack of universal SMD correlation equations incorporating rheological parameters	Systematic multi-fluid experimental database + embed constitutive equations into CFD solvers	Extend applicable scenarios to food, cosmetics and biopharmaceutical manufacturing
Intelligent closed-loop regulation	Sensor signal delay, limited edge computing performance	Lightweight CNN algorithm + Model Predictive Control (MPC)	Real-time adaptive spray adjustment; reduces pesticide/fuel consumption
Material & sustainability bottlenecks	Severe nozzle abrasion & clogging, high energy consumption of compressed air	Biomimetic liquid-guiding inner surface, ceramic/composite coating, green atomization media (magnetized water, superheated steam)	Extend nozzle service life, cut energy use, lower carbon emissions

5. Summary

Airflow-assisted atomization achieves efficient atomization through gas–liquid momentum exchange. This paper provides a systematic review of its mechanisms, cross-domain customization strategies, and future directions. The atomization mechanism exhibits scale-independent consistency, though the fragmentation path is governed by nozzle geometry and gas–liquid ratio: internal mixing is dominated by annular vortices, while flat sectors exhibit spatial variations; the KH-RT model ($We > 350$) and TAB model ($12 < We < 350$) are suitable for high, medium, and low Weber numbers, respectively; LES-VOF offers high accuracy but requires computationally intensive simulations, whereas the piecewise Euler–Lagrange coupling approach is more practical for engineering applications.

The essence of cross-domain applications lies in balancing particle size, velocity, distribution, and adhesion characteristics: agricultural applications (50–200 μm) require resistance to drift; food drying demands avoidance of either excessive fineness leading to caking or excessive coarseness causing wall adhesion; sterilization relies on 30–50 μm aerosols coupled with electrostatic forces; combustion requires $SMD < 50 \mu\text{m}$ for accelerated mixing. There is no universal optimal design. Challenges include grid-dependent collision modeling in dense regions, the absence of a universal primary breakage model, and limitations in non-Newtonian constitutive models. Future trends include transitioning from open-loop to closed-loop adaptive control, shifting from metal processing to biomimetic and additive manufacturing, and replacing compressed air with green propellants. Key recommendations involve prioritizing the development of PBM-CFD coupling models,

intelligent nozzle prototypes, and non-Newtonian atomization databases, with expansion into precision manufacturing and biopharmaceutical applications. More importantly, intelligent spray control has broader environmental significance beyond atomization efficiency. By dynamically regulating droplet size, airflow assistance, spray direction, and application rate according to target characteristics and ambient conditions, closed-loop spraying systems can reduce off-target atmospheric emissions, including both particulate matter such as mine dust and liquid aerosols such as pesticide droplets. This reduction in drift, airborne residue, and unnecessary chemical or water consumption directly supports cleaner production, safer occupational environments, and more sustainable agricultural and industrial practices. Therefore, the optimization of air-assist atomization and intelligent spraying processes is closely aligned with global sustainable development goals related to environmental protection, resource efficiency, climate action, and human health.

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