

A Review of Studies Conducted on Pressure Swirl Atomizer (PSA)

Ali Kamranpey*

Department of Mathematics, University of Guilan, Iran

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*Corresponding author: Ali Kamranpey, Department of Mathematics, University of Guilan, Rasht, Iran

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Abstract

Pressure Swirl Atomizers (PSAs) are indispensable devices in various industries due to their ability to generate fine sprays that enhance atomization efficiency, fuel-air mixing, and combustion processes. Their widespread use in aerospace propulsion, power generation and agricultural spraying underscores the importance of understanding and optimizing their performance. This review comprehensively examines the extensive body of research on PSAs, focusing on key aspects including design innovations, experimental characterizations, numerical simulations, the influence of geometric and fuel properties on spray characteristics, and the role of high-velocity airflow in improving atomization. By synthesizing findings from both foundational and recent studies, this review identifies critical advancements and outlines gaps where further research is necessary to advance PSA technology.

Keywords: Pressure swirl atomizer; Design; Experimental; Simulation; Geometric parameters; Fuel; High-velocity air flow

Introduction

Pressure Swirl Atomizers (PSAs) are vital components in systems where efficient fuel atomization and spray generation are critical to performance. In schematic Figure 1, two main types of this type of atomizer can be seen. Their applications are particularly prominent in aerospace and aviation engines, where precise fuel delivery and fine atomization directly influence combustion efficiency, thrust generation and emissions control [1,2]. In gas turbine engines, PSAs enable effective fuel-air mixing, which is essential for achieving stable combustion and optimizing thermal efficiency [3,4]. Furthermore, PSAs are integral in advanced propulsion systems such as turbofan and turbojet engines, where atomizer design impacts thrust and specific fuel consumption [5,6]. The working principle of a PSA involves injecting liquid fuel tangentially or through a spiral path into a swirl chamber, generating a rapidly rotating flow. This swirl creates centrifugal forces that propel the liquid outward against the chamber wall, forming a thin, conical liquid sheet which subsequently breaks up into fine droplets [7,8]. The resulting hollow cone spray pattern, characterized by a large spray angle, promotes enhanced fuel-air mixing, critical for efficient combustion in aerospace applications [9]. A distinctive feature of PSAs is the central air core within the swirl chamber, which influences droplet breakup dynamics and spray dispersion, affecting flame stability and emissions [10]. Research efforts have focused on characterizing and optimizing PSA designs for aviation and gas turbine applications to maximize atomization efficiency and minimize pollutants [11,12]. Numerical simulations and experimental studies have provided insights into internal flow structures and near-nozzle spray behavior, informing improvements in atomizer geometry and operating conditions to meet the stringent performance demands of modern aerospace propulsion [2,8].

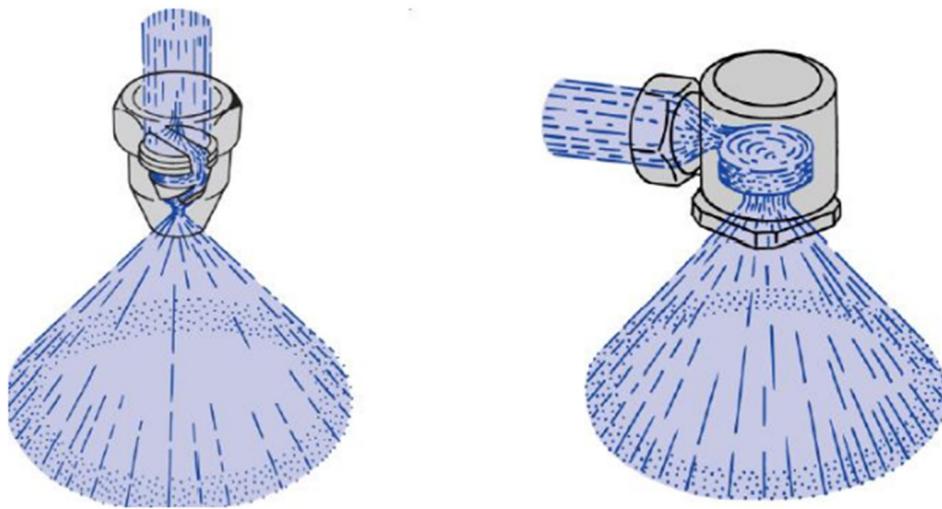


Figure 1: Pressure swirl atomizers, (a): with spiral paths, (b): with tangential inputs [1].

Objective of the Present Review

This review consolidates and synthesizes research on pressure swirl atomizers with several objectives. First, it evaluates design methodologies and innovations that have been instrumental in improving PSA performance. Second, it reviews experimental studies that provide empirical insights into internal flow structures and spray characteristics. Third, it analyzes numerical and simulation approaches that model PSA fluid dynamics and atomization processes. Fourth, it examines how geometric parameters and fuel properties influence spray behavior. Lastly, it explores how integrating high-velocity airflow enhances atomization. By organizing the literature into these thematic areas, the review aims to highlight trends, identify knowledge gaps and suggest pathways for future PSA development.

Classification of Studies on Pressure Swirl Atomizer (PSA)

In this section, the studies conducted on pressure swirl atomizers are systematically categorized and reviewed across several key areas. These include the design methodologies that influence atomizer performance, experimental investigations that provide empirical data on spray behavior and numerical simulation studies that offer detailed insights into the internal flow and atomization processes. Additionally, the review covers the effects of geometric parameters such as swirl chamber dimensions and orifice shape on spray characteristics, as well as the influence of fuel properties like viscosity and temperature. Finally, it examines how the addition of high-velocity airflow can enhance atomization quality. This structured and comprehensive review aims to serve as a valuable resource for researchers, facilitating a deeper understanding of pressure swirl atomizers and guiding future innovations in their design and application.

Design

Design optimization remains a primary focus in PSA research, as the device geometry directly impacts spray performance.

Dumouchel et al. [13] provided seminal work establishing the fundamental design principles of PSAs, emphasizing the critical role of swirl chamber shape and inlet configurations to control the internal flow and spray characteristics. Building on this foundation, Hu et al. [14] developed a multi-fluid swirling mixing atomizer tailored for agriculture, demonstrating that introducing multiple swirling fluid streams enhances the generation of ozonated droplets, improving disinfection efficiency in crop applications. Modarres-Razavi et al. [15] utilized the Volume of Fluid (VOF) numerical method to optimize PSA design, highlighting the importance of accurately capturing fluid interfaces to predict spray breakup and droplet formation. Mazaheri et al. [16] conducted a parametric study comparing pressure jet and swirl injector designs, identifying key geometric factors such as swirl chamber diameter and nozzle orifice size that influence spray pattern and atomization quality. Aminjan K et al. [17] integrated experimental measurements with numerical simulations to investigate the effects of inlet pressure and Reynolds number on flow stability in tangential input PSAs, showing that optimized flow parameters lead to enhanced spray uniformity. Earlier works by Aminjan K et al. [18,19] explored the impacts of tangential and spiral path designs on internal flow and spray performance, revealing that spiral paths can improve atomization by stabilizing the swirling flow and reducing droplet size. Lacava et al. [20] proposed a systematic design procedure combining theoretical modeling with experimental validation, which has been widely adopted in PSA engineering for achieving predictable spray characteristics.

Experimental studies

Experimental investigations provide essential validation of design concepts and insights into real-world PSA performance. Belhadeh et al. [21] combined numerical modeling and experiments to study atomization dynamics, particularly focusing on droplet size distribution and the breakup mechanisms within PSAs. Hansen et al. [22] utilized a combination of computational fluid dynamics and experimental flow visualization to uncover complex

internal vortical structures that influence spray formation. da Silva Couto et al. [23] experimentally evaluated a low-pressure swirl atomizer, confirming the reliability of engineering design procedures under practical operating conditions. Zhou et al. [24] investigated atomization processes and dust reduction capabilities of swirl pressure nozzles, demonstrating their efficacy in lowering particulate emissions in industrial applications. Bian et al. [25] focused on spray characteristics within nuclear power plant containment, emphasizing the importance of precise spray control for safety-critical environments. Laurila et al. [26] combined experiments and computations to study viscous fluid sprays, revealing that non-Newtonian fluid properties significantly affect atomization and flow patterns. Santangelo et al. [27] analyzed water-mist sprays generated by PSAs, integrating experimental data with modeling to understand discharge characteristics and spray distribution. Choudhury [28] performed theoretical and experimental work on cascading atomization, elucidating multi-stage droplet breakup and highlighting its effect on spray uniformity and droplet size distribution.

Numerical and simulation studies

Numerical simulations have become indispensable for investigating PSA internal flows and atomization phenomena, enabling detailed visualization and parametric studies. Nouri-Borujerdi et al. [29] simulated laminar and turbulent two-phase flows within PSAs, capturing complex interactions between liquid

and gas phases and providing insight into flow regimes that affect spray quality. Galbiati et al. [8] modeled internal flow dynamics specific to aircraft engine PSAs, contributing to design improvements for aviation fuel injectors. Aminjan et al. [6] conducted 3D simulations of flow in swirl injectors with spiral paths, showing that spiral configurations enhance flow uniformity and atomization efficiency. Salem et al. [30] utilized the InterFoam solver to simulate 2D axisymmetric flows, offering insights into flow stability and spray formation under various operating conditions. Han et al. [31] validated numerical models of pressure-swirl circuits for aviation atomizers, supporting their predictive capability for performance optimization. Gurakov et al. (2020) verified the applicability of the VOF method for simulating liquid spray processes, confirming its accuracy in predicting spray breakup and droplet size distributions. Chen et al. [32] applied large eddy simulation combined with VOF for multi-objective optimization of nozzle flow fields, advancing understanding of turbulent spray behavior. Shi et al. [33] integrated VOF and Discrete Phase Methods (DPM) to simulate atomization in gas-liquid pintle injectors under periodic flow conditions, providing detailed atomization mechanisms. Chen et al. [34] combined VOF-DPM simulations with experimental validation to study near-nozzle atomization in air-assisted spraying, improving the predictive capability of air-assisted spray models. In Figure 2, the spray angle obtained from the simulation with VOF method is compared with the experimental test, which indicates the high accuracy of the numerical solution methods.

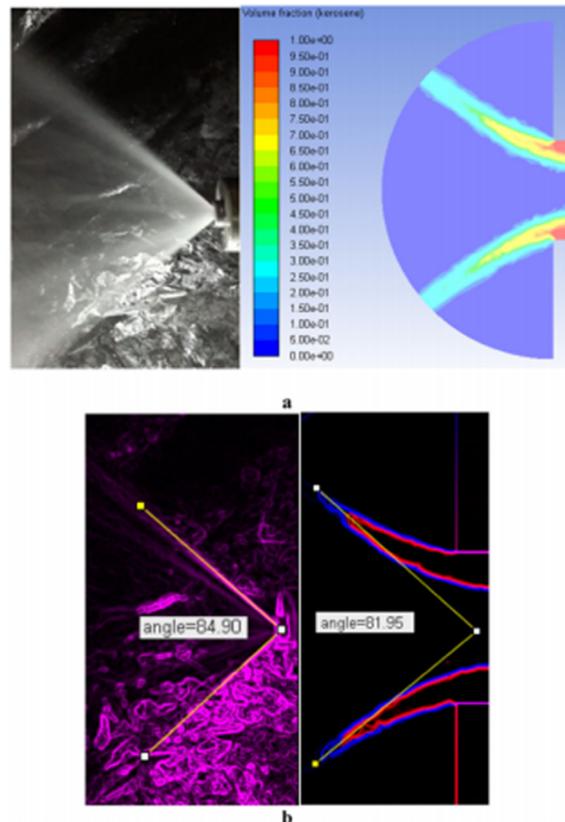


Figure 2: Comparing simulated spray angles with experimental tests (a) and using image processing techniques (b) to accurately locate edges [29].

Effect of atomizer geometric parameters on spray characteristics

The geometry of the atomizer strongly affects spray properties such as cone angle, droplet size and spray uniformity. Aminjan K et al. [19] analyzed the influence of spiral path angle in PSAs, showing how varying the angle modifies internal flow patterns, resulting in changes to spray dispersion and droplet size distribution. Rashad et al. [35] investigated multiple geometric parameters including orifice diameter and swirl chamber dimensions, finding that these have a direct impact on spray angle and atomization quality. Broniarz-Press et al. [36] studied orifice shape and injection pressure, concluding that optimized orifice geometry enhances atomization by promoting more efficient liquid sheet breakup. Xue et al. [37] examined simplex atomizer performance relative to geometric variations, contributing to design optimization for targeted spray characteristics. Ronceros et al. [38] compared open-end and closed-end PSAs, demonstrating how variations in geometry affect internal flow stability and spray pattern consistency. Dafsari et al. [39] highlighted the critical role of swirl chamber length, showing that longer chambers alter the centrifugal forces and thus the atomization behavior. Zheng et al. [40] found that orifice geometry significantly influences the breakup process and spray droplet sizes. Liu et al. [41] demonstrated that precise control of geometric parameters allows manipulation of spray cone angles, which is critical for effective spray coverage. Gurakov et al. (2021) studied three-way PSAs and revealed how geometric characteristics influence liquid fuel flow distribution, thus affecting atomization uniformity.

Effect of fuel and its characteristics on spray characteristics

Fuel properties such as viscosity, density and temperature substantially influence PSA atomization behavior. Laurila et al. [42] used large-eddy simulation to study viscous fluid flows inside PSAs, showing that increased viscosity dampens atomization and results in larger droplet sizes. Reddy KU et al. [43] examined spray behavior in the transition regime, noting that fuel properties significantly affect spray cone angle and droplet size distribution. Dafsari et al. [44] experimentally assessed aviation fuels with varying viscosities, confirming that higher viscosity fuels produce coarser sprays with larger droplet sizes. Aminjan K et al. [45] numerically studied the impact of fuel temperature on spray characteristics, demonstrating that temperature-induced viscosity changes alter spray breakup and droplet size. Further studies by Aminjan K et al. [46,47] explored the combined effects of inlet pressure, Reynolds number and acoustic dynamics on spray formation, providing a comprehensive understanding of fuel behavior in PSAs. Wimmer et al. [48] investigated viscous flow through swirl chambers, establishing that fluid properties affect internal flow stability and atomization efficiency. Dafsari et al. [49] also evaluated alternative aviation fuels, showing how viscosity variations influence atomization quality and spray characteristics.

Using high-velocity air flow to improve the atomization process

Incorporating high-velocity airflow into PSAs is a promising approach to enhance atomization by producing finer droplets and more uniform spray patterns. Zang et al. [50] conducted numerical investigations of internal mixing air interactions with different fluids, demonstrating that airflow significantly improves atomization efficiency by promoting liquid breakup. Liu et al. [51] studied the effects of internal mixing air mass flow rate and temperature, finding that increased airflow and temperature lead to better atomization and spray quality. Gad et al. [52] examined geometric parameters in air-assisted PSAs, confirming that optimized geometry combined with airflow enhances spray uniformity and coverage. Doustdar et al. [5] combined numerical and experimental methods to characterize air-blast atomizers, introducing a new non-dimensional number (K) to predict spray performance under various airflow conditions. Ma et al. [53,54] focused on biodiesel sprays in industrial furnaces, revealing how airflow rate and temperature influence droplet velocity and size, thus affecting combustion efficiency. Wang et al. [55] investigated air-assisted atomizers used in snow-makers, highlighting the sensitivity of atomization characteristics to operating conditions. Zhang et al. [56] studied air-assisted atomizer structures, showing improved ignition and flame propagation stability in combustion chambers [57-60].

Conclusion

This review has consolidated extensive research on pressure swirl atomizers, illustrating how optimized design supported by experimental and numerical studies significantly enhances atomization and spray performance. Geometric parameters and fuel properties are shown to critically influence spray characteristics, with precise control enabling targeted atomization outcomes. The integration of high-velocity airflow presents a compelling advancement for further improving spray quality, offering finer droplets and more uniform distribution. Continued interdisciplinary research and innovation in design, experimental methods, simulation techniques and airflow integration are essential for advancing PSA applications across aerospace, power generation, agriculture and other sectors.

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