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OPEN Experimental investigation on spray morphology in dual pitch spiral nozzle

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This study investigates dual-spiral-pitch nozzles, which are essential for high-discharge applications like deluge fire suppression systems (5–4000 L/min). Such nozzles produce multi-sprays, which have received little attention in the past. In the present research, experiments quantified the relationship between inlet pressure (0.2–3.4 bar), mass flow rate, and spray characteristics. Results reveal three distinct spray morphologies linked to inlet pressure: a gradual mass flow rate increase across 0.2–1 bar inlet pressure, a dramatic surge exceeding 1000% between 1 and 3 bar, and an approach to hydraulic saturation (maximum achievable flow) at 3.4 bar, due to geometric constraints. In addition, the results indicated that at 0.2 bar inlet pressure, the nozzle produces single, coarse droplets. As pressure increases to 1.6 bar and above, the spray pattern evolves into two distinct, separate jets: an outer spray (Spray 1) and an inner spray (Spray 2). While increasing the inlet pressure from 1.6 to 3.4 bar causes the outer spray cone angle to expand significantly (from 64° to 121°), the inner spray cone angle remains remarkably stable at approximately 30°. These experimental findings can be used to rigorously verify the accuracy of the corresponding CFD simulations, providing necessary experimental validation for the models.

Keywords Spiral nozzle, Two spiral pitches, Experimental test, Mass flow rate, Spray cone angle

Atomization refers to the process of disintegrating liquid jets into sheets, ligaments, and droplets^{1,2}. The phenomenon of fluid spray and its fragmentation into minute droplets is recognized as one of the most intricate aspects of fluid mechanics³. The effectiveness of atomization is frequently assessed by the size of the droplets produced, with smaller droplets signifying superior atomization quality. Nevertheless, additional factors, such as the angle of the spray cone, are also vital for a comprehensive evaluation of spray characteristics^{4,5}. Various atomizers and nozzles are available for generating sprays, each designed for specific applications. Extensive research has been conducted to explore the spray behavior across numerous types of atomizers, including air-assisted pressure swirl atomizers⁶, external-mixing atomizers⁷, rotary slinger atomizers⁸, hybrid air-blast-electrostatic atomizers⁹, and pressure swirl atomizers¹⁰. Among the nozzles that have received comparatively less attention from researchers is the spiral nozzle, which features a spiral section at its outlet, as illustrated in Fig. 1.

The spray distribution produced by spiral nozzles is characterized by a lack of uniformity; however, when compared to direct pressure nozzles, they exhibit superior droplet size and atomization quality. Their straightforward and compact design facilitates easy installation across various piping systems. This category of nozzles is capable of achieving a broad spectrum of spray angles, ranging from 60 to 170 degrees for full cone nozzles and from 50 to 180 degrees for hollow cone nozzles. The spray pattern of spiral nozzles is illustrated in Fig. 2. Additionally, it is important to highlight that spiral nozzles demonstrate enhanced energy efficiency and effectiveness due to the impact on the spiral plate and the resultant formation of the output jet, surpassing that of other conical nozzles. These nozzles can operate at pressures of up to 25 bar. In the full cone variant of spiral nozzles, two umbrella spray cones are integrated: the outer cone features a larger angle, while the inner cone has a smaller angle, collectively producing the effect of a full cone¹¹.

Spiral nozzles have been utilized in various applications, including flue gas desulfurization, spray towers^{12–14}, spray drying¹⁵, distillation¹⁶, the petrochemical industry¹⁷, and fire suppression^{18,19}. The design of the spiral

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Fig. 1. A sample of spiral nozzles¹¹.

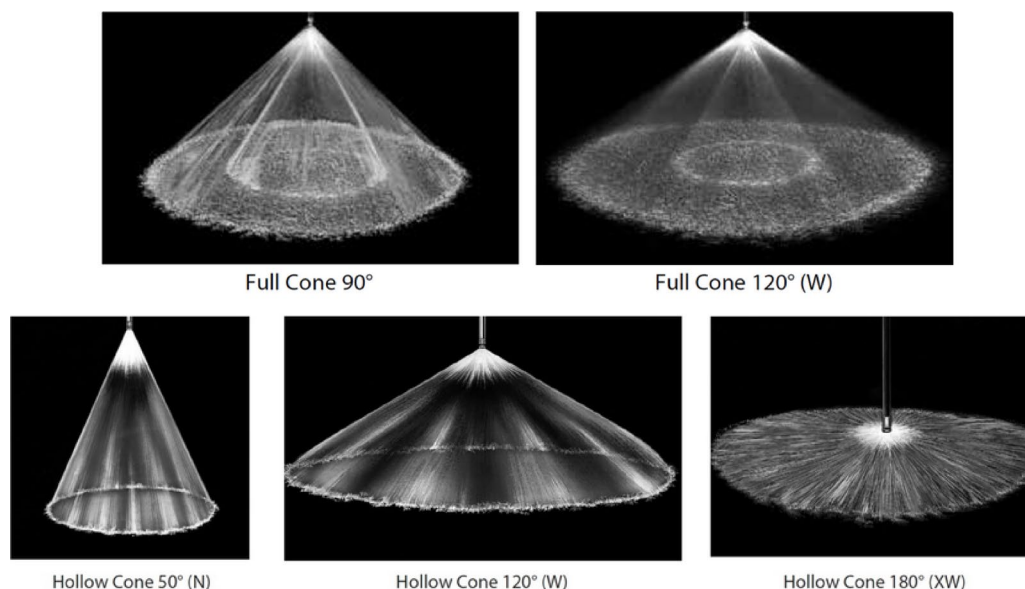


Fig. 2. Spray pattern variation in spiral nozzles¹¹.

nozzle is a single piece, lacking any internal components. The discharge rate of these nozzles can range significantly, from approximately 5 to 4000 L per minute. This capability makes them particularly effective in deluge fire extinguishing systems, which require the rapid release of large volumes of water. Additionally, spiral nozzles experience considerably less clogging, making them well-suited for use with hard water and solutions containing solutes. In summary, spiral nozzles are applicable for fire extinguishing, surface cooling, and creating fire-resistant barriers across various sectors, including cement, food processing, and pharmaceuticals. Depending on the required output pressure and the specific environment, spiral nozzles can be manufactured from materials such as steel, brass, plastic, polypropylene, nickel alloy, silicon carbide, phosphor, and bronze. While the spray pattern produced by spiral nozzles is not uniform, they excel in droplet size and atomization compared to other direct-pressure nozzles. Their straightforward and compact design allows for easy installation on most piping systems.

Research background

Although extensive studies have been conducted for pressure swirl nozzles with a spiral path^{20–22}, their geometries are conceptually different from the spiral nozzle investigated here and shown in Fig. 1 and they produce different spray patterns; they are also designed for different applications. For example, Kalata et al.²³ investigated air-assisted atomization in spiral-type nozzles for varying mass fractions of water and air flow. Drop size and its distribution throughout the range of operation conditions were measured using Phase Doppler Interferometry (PDI) and Laser Sheet Imaging (LSI). The findings showed a slight decrease in drop size with an increase in air mass flow rate. Furthermore, the increase in airflow led to a displacement of the spray plume from the predetermined center axis. The Volume of Fluid (VOF) model was used to simulate the internal and external two-phase flow of the nozzle under the same flow conditions. The investigation focused on the velocity of the fluids at the orifice of the nozzle. It was observed that the velocity of the liquid exiting from the nozzle's orifice increased as the mass fraction decreased, due to the increased total volume flow rate of both fluids. Cong et al.²⁴ studied a commercial spiral nozzle tray (SNT). They evaluated its hydrodynamics (pressure drop, weeping, liquid height, entrainment) with air–water and its mass transfer efficiency separating cyclohexane/n-heptane. Bubble visualization helped explain its high efficiency. Results show the SNT is a promising distillation tray, suggesting spiral nozzles integrated into trays represent a new direction for column internals development. Křištof et al.²⁵ did an experimental study on spray breakup in turbulent atomization using a spiral nozzle. Their research outcome was two key points: droplet diameters were larger than air-assisted atomizers, and the max radial velocity was lower than effervescent atomizers.

Li et al.²⁶ conducted a study on the spray characteristics of spiral nozzles utilized in flue gas desulfurization. Their findings indicated that the flow rate exhibited a linear relationship with the square root of pressure, while the droplet diameter was determined to be a power function of pressure. The variations in droplet diameter with respect to pressure were consistent across spiral nozzles with different orifice sizes, although the spray angle showed slight variations at pressures exceeding 40 kPa. Zhang et al.²⁷ examined the spray characteristics of spiral nozzles of varying diameters through particle image velocimetry at different spray pressures. They found that both the spray pressure and nozzle diameter significantly affected the spray angle, droplet diameter, droplet size uniformity, and the diameter of the sprayed area. In their biomass pyrolysis experiments, they identified a nozzle with a diameter of 5.6 mm and a liquid pressure of two bars as optimal for quenching pyrolysis vapors. In a separate investigation, Zhou et al.²⁸ performed experiments to assess the flow distribution characteristics of a low-pressure high-flux spiral nozzle using a flow distribution testing system. They evaluated the impact of nozzle size on flow distribution by manipulating various parameters, including the nozzle length-to-diameter ratio, radial flow rate, position of the sprayed surface, and spraying angle. The results revealed that an increase in the nozzle length-to-diameter ratio led to a decrease in flow rate and an increase in spraying angle. Similar relationships were observed with increasing pressure, consistent with the findings of previous studies. Dong et al.¹³ compared the desulfurization efficiency of scrubbers equipped with spiral nozzles and Dynawave nozzles. Additionally, Li et al.²⁹ developed a spray surface geometry model for a spiral nozzle featuring involute atomization, which they subsequently simulated using MATLAB, thereby validating its effectiveness and establishing a theoretical foundation for the design and production of spiral nozzles. Wasik et al.³⁰ investigated the impact of nozzle type, including the TF6 spiral nozzle, on mass spray density^{31,32}.

Research by Salamonowicz et al.³³ measured the ammonia absorption rate constant in water using a test station equipped with spiral nozzles. Their results enabled the determination of the nozzle's pressure-flow characteristic ($p(Q)$), its spray intensity distribution (modeled in SUFER), the ammonia concentration profile over time, and the absorption rate constant. Lazim et al.³⁴ explored flame characteristics in a flameless combustor ignition system utilizing spiral nozzles. Their investigation focused on premixing parameters involving air pressure and Liquefied Petroleum Gas (LPG). Zhang et al.³⁵ experimentally studied the thermal performance of an ice slurry production system incorporating a direct contact heat exchanger and a spiral nozzle. They proposed a novel system design where a horizontal PVC pipe equipped with a spiral nozzle acts as the direct contact ice slurry generator, effectively preventing nozzle ice blockage. Liu and Zhang³⁶ showed experimentally that spiral nozzle flow rate increases and droplet diameter decreases with rising spray pressure, but the pressure's impact on droplet size has a critical limit. Ren et al.³⁷ conducted an experimental analysis on spiral pressure nozzles for spray dryer applications, specifically examining spray angle control. Their work revealed a correlation between pressure and spray angle, yielding successful results. Kim et al.³⁸ studied a spiral flow nozzle featuring an annular slit. Their research clarified the self-generation mechanism of the spiral flow and experimentally and numerically examined how the width of the annular slit affects spiral flow characteristics. The findings demonstrated the presence of a tangential velocity component even without forced rotation. Furthermore, the experimental results showed close agreement with numerical simulations, both quantitatively and in terms of flow patterns.

New aspects of the present study, its objectives and applications

New aspects

An examination of existing research reveals a significant knowledge gap concerning spiral nozzles. While these nozzles inherently produce multiple distinct spray patterns at their outlet, prior scientific inquiry has been narrow in scope. Specifically, studies have almost exclusively focused on analyzing only the outermost spray pattern, neglecting the behavior of inner sprays. This singular focus creates an incomplete picture of how spiral nozzles actually function during operation. To gain a truly comprehensive understanding of the complex spray dynamics within these nozzles, it is essential to undertake more detailed and extensive research that examines all the spray components.

Objectives

This research directly addresses this gap. We conduct a thorough experimental investigation of both the inner and outer sprays generated by a specific spiral nozzle design featuring two spiral pitches. A core objective is to quantify the influence of inlet pressure on key spray characteristics. We specifically measure how pressure variations affect the overall mass flow rate of liquid passing through the nozzle. Furthermore, we meticulously analyze the impact of pressure on the spray cone angles for both the outer spray (designated "Spray 1" in this study) and the inner spray (designated "Spray 2").

Applications

The insights gained from this detailed analysis are expected to significantly advance our fundamental understanding of the spray formation and breakup phenomena unique to spiral nozzles. Moreover, by providing robust, experimentally validated data on the behavior of both sprays under varying pressures, this study will serve as a valuable technical resource. It will equip engineers with the necessary knowledge to design and manufacture spiral nozzles that achieve superior performance in their intended applications.

Geometrical characteristics

The geometric characteristics of the spiral nozzle studied in this research are documented visually and quantitatively: Fig. 3 provides a visual image of the nozzle, while Table 1 details its specific geometric dimensions or characteristics. The exact details of these characteristics (such as diameter, pitch, length, or specific spiral features) are contained within the referenced Table 1 and Fig. 3.

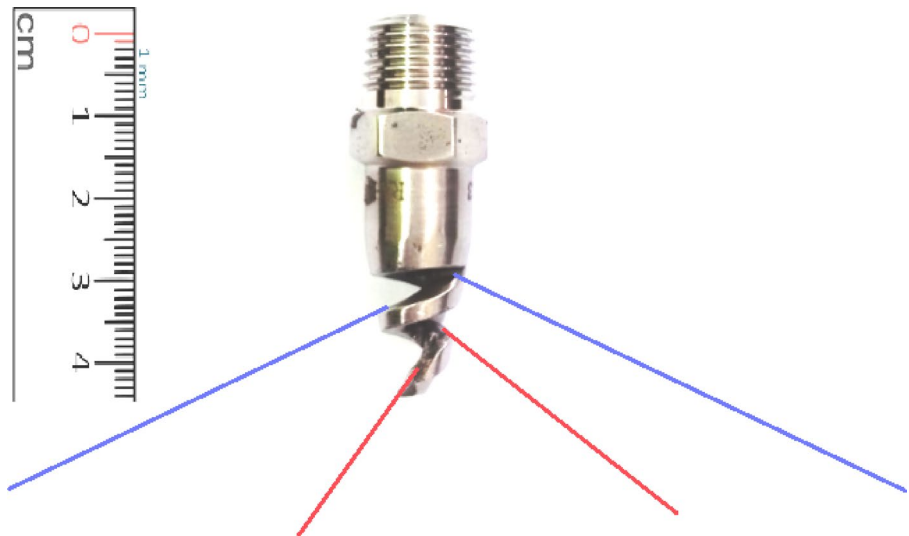


Fig. 3. Image of the studied nozzle and schematic lines of spray 1 (blue lines) and spray 2 (red lines).

Overall length	Inlet diameter	Outlet diameter	Number of spiral passage	Length of spiral passage	Cross-section of spiral passage
45 mm	8 mm	3 mm	2	15 mm	Rectangular: 2 mm × 3 mm

Table 1. Geometric characteristics of the studied spiral nozzle.

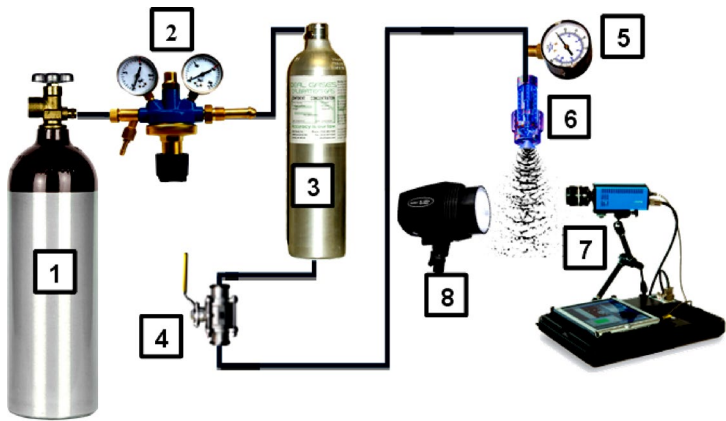


Fig. 4. View of the test equipment (1—Pressure Capsule, 2—Regulator, 3—Pressure Water Tank, 4—Discharge Valve, 5—Pressure Gauge, 6—Nozzle, 7—Camera, 8—Light Source).

The nozzle material, stainless steel grade 303, was chosen for its superior machinability and inherent resistance to corrosion, essential qualities for reliable performance in demanding service conditions.

Experimental test

The experimental apparatus closely follows the configuration depicted in Fig. 4, with one significant modification: the nitrogen pressurization system was replaced by a Pentax PM45 single-impeller centrifugal pump to generate the required water pressure. This specific pump model was selected from Pentax’s PM series due to its suitability for handling clean, non-corrosive fluids like water (both cold and hot). Key specifications relevant to the experiment included: single-phase electrical operation, 1-inch inlet/outlet diameters, a rated power of 0.5 horsepower, a maximum head capacity of 35 m, a maximum flow rate of 2.4 cubic meters per hour, and a temperature tolerance up to 90 °C. This range of capabilities ensured the pump could deliver the necessary pressure and flow conditions for the planned tests. To precisely monitor the input condition, a pressure gauge calibrated for a measurement range of 0 to 10 bar was installed specifically to record the inlet pressure delivered by the pump to the nozzle. The core experimental procedure involved systematically testing the atomizer (spiral nozzle) across a range of these controlled inlet pressures. Critically, for each pressure setting, the following key spray characteristics were

measured: the mass flow rate of water exiting the nozzle and the angles of both the outer (Spray 1) and inner (Spray 2) spray cones. Accurate measurement of the spray cone angles demanded clear visualization of the spray boundaries. To achieve this, a high-intensity, fixed-position light source was employed to backlight the spray plume. This illumination significantly enhanced the contrast between the spray droplets and the background, thereby improving the precision of the angle measurements. The specific light source utilized comprised an array of 800 LEDs with a total power output of 50 watts. An important feature was its adjustable light intensity, allowing optimization for different spray densities and measurement conditions. Capturing high-fidelity images of the dynamic spray patterns was essential for subsequent angle analysis. It is important to note that sprays are inherently unsteady in nature, even when ambient and feed conditions are static. At any instant in real time, droplet sizes and their trajectories are uniquely different from other times. This is especially true in atomizers with multiple co-flowing jets³⁹. Therefore, all data in this paper have been time-averaged to smooth these temporal instabilities. Additionally, any image herein should be taken as sufficiently similar to images taken at other times for the same feed conditions. This task was performed using a Canon EOS R6 digital camera, chosen for its advanced imaging capabilities suited to scientific documentation. Experimental testing indicated that the spray edges were dusty, especially at high inlet pressures, so identifying the spray boundary and edge for accurate spray angle measurement was a challenge. To overcome this challenge or minimize it, a black background was chosen for the test site, which, along with the use of a light source and light irradiation of the spray, provided better visibility of the spray edges. At each inlet pressure, the test was performed after ensuring the stability of the flow and also within a suitable and acceptable time interval. In addition, to further ensure the accuracy of the test results, the test was performed twice at each inlet pressure, and although the results were very close and only a very slight difference was observed, the average results were used for this study.

Potential error sources and equipment accuracy

Significant effort was dedicated throughout the experimental testing in this study to minimize measurement error and ensure data reliability. Despite these rigorous precautions, inherent limitations of the specific measurement instruments employed naturally introduced potential sources of error. The primary factors contributing to measurement uncertainty are detailed below:

Pressure measurement accuracy

The pressure gauge utilized had a measurement range of 0 to 10 bar, with a graduation (smallest marked increment) of 0.1 bar. Consequently, the fundamental accuracy limit for determining the inlet pressure in this study is ± 0.1 bar. This means the smallest detectable change or the precision of any single pressure reading is constrained by this graduation size. Theoretical Improvement: Employing a pressure gauge with finer graduations (e.g., 0.01 bar) would inherently provide a higher resolution measurement and reduce the uncertainty associated with reading the gauge.

Spray angle measurement precision

A multi-faceted approach was adopted to maximize the accuracy of spray cone angle determination: a high-intensity light source was used to illuminate the spray boundaries, a high-quality camera (Canon EOS R6) captured detailed images, and image processing techniques and using edge detection method (as illustrated in Fig. 5) were applied to precisely identify the edges of the spray cones. This methodology was designed to achieve the highest possible precision and clarity in defining the spray edges, thereby minimizing error in the calculated angles.

Within the image processing methodology employed in the present study, the Prewitt operator^{40,41} was utilized for edge detection. This algorithm provides efficacy in gradient identification across diverse applications, including computer vision and medical imaging. Comparative analysis had revealed that the Prewitt operator generally yielded sharper and more precise edge delineation than the Sobel operator, thereby enhancing the accuracy of spray edge identification within this investigation⁴². Furthermore, to mitigate image noise, Gaussian blur filtering^{43,44} was applied to enhance the images prior to edge detection. Also, the edge detection configuration was specifically set to normal mode.

Despite rigorous efforts to ensure accurate spray angle measurement—encompassing the acquisition of high-resolution images and the application of advanced image processing techniques—the error in angle measurement in the present study is estimated to be $\pm 0.5^\circ$, and this inaccuracy is due to the challenge of detecting the exact edge of the spray, especially at high pressures where the edges of the spray are dusty, not an error in the goniometer tool, which today's tools are high accurate. It must be acknowledged that precisely detecting the spray edge in spiral nozzles presents inherent challenges. This difficulty is particularly pronounced at elevated pressures where the spray periphery exhibits a nebulous or “dusty” characteristic, thereby complicating exact edge determination. Similar challenges have been documented in prior research concerning these nozzle types²⁵. Conversely, in numerous other nozzle and atomizer configurations, such as pressure swirl atomizers, precise spray edge detection is readily achievable using standard quality imagery without necessitating sophisticated image processing^{20,45}. Nevertheless, these identified challenges do not preclude further investigation into spiral nozzle phenomena.

Potential for Enhanced Accuracy: While the current setup represents a robust approach, utilizing even more advanced equipment could further reduce uncertainty. For instance, a dedicated high-speed camera would capture finer temporal details of the potentially fluctuating spray edges, and sophisticated image restoration algorithms could potentially correct for minor optical distortions or noise, yielding even sharper boundary definitions.

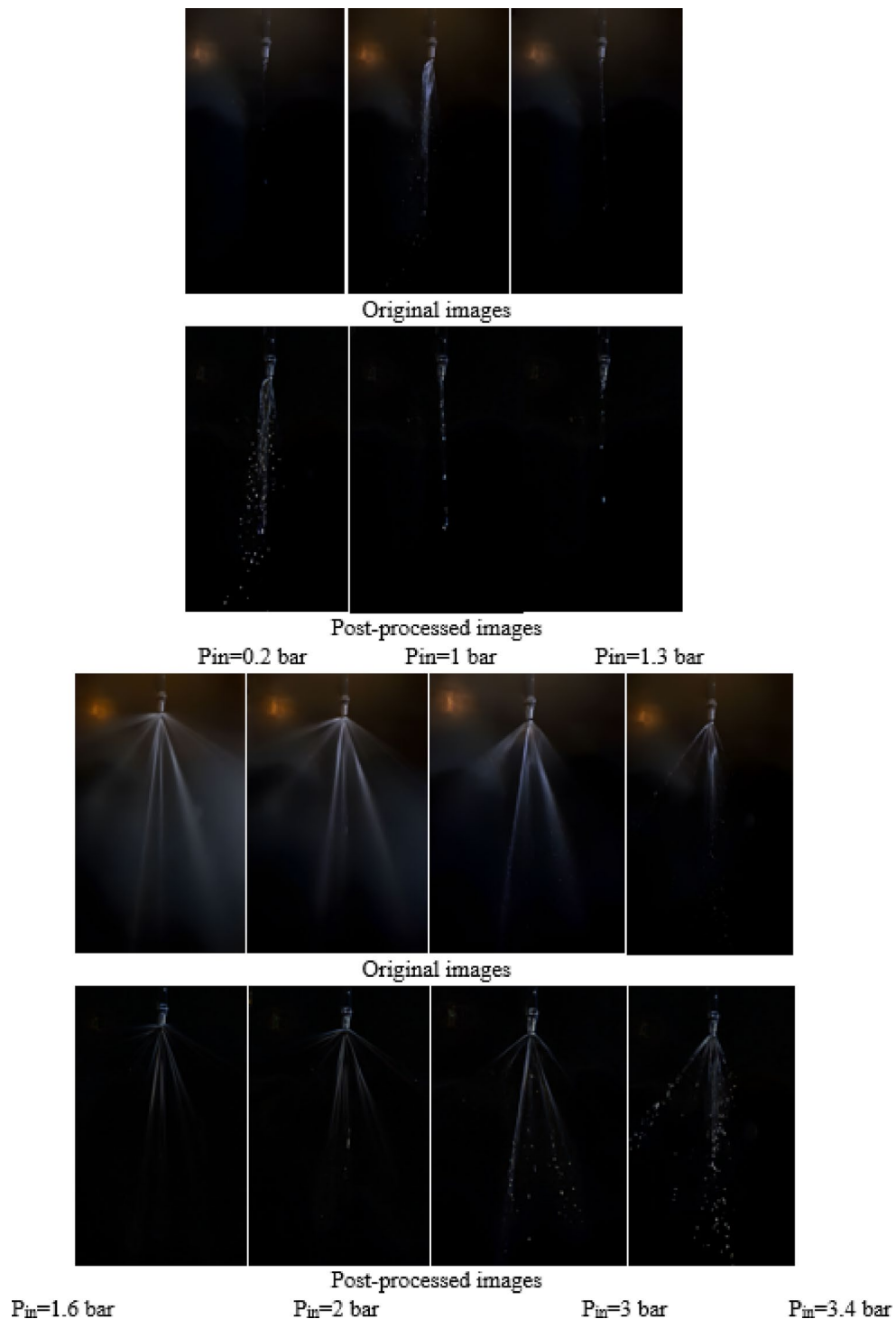


Fig. 5. Spiral nozzle test at different inlet pressures; different stages of spray formation as well as post-processing of spray images by using edge detection tools to find the exact boundary of spray edges: Pin = 0.2 bar (dripping), Pin = 1 bar (flowing), Pin = 1.3 bar (transition phase from flowing to initial spray formation), Pin = 1.6 bar (formation of the main sprays: outer spray (designated Spray 1 in this study) and the inner spray (designated Spray 2)), Pin = 2 bar (development of the Spray 1 and Spray 2), Pin = 3 bar (full development of the Spray 1 and Spray 2 and formation of secondary sprays next to spray 1 and spray 2 which are derived from spray 1 and 2), Pin = 3.4 bar (spray saturation and dusting of the edges of the main sprays as well as the derived sprays from the main sprays).

Average measurement of each step	Measurement accuracy	Parameter
2649.57 cc	2 cc (accuracy of the container used to measure the volume of the liquid in the test)	Volume
61.43 s	0.5 s (delay caused by human reaction in starting and stopping the test time)	Time

Table 2. Measurement of error in mass flow rate testing.

P _{in} (bar)	T (s)	V (lit)	$\dot{m}_{Ave}$ (kg/min)	Θ_1 (deg)	$\Theta_{1 Ave}$ (deg)	Θ_2 (deg)	$\Theta_{2 Ave}$ (deg)
0.2	280	0.224	0.048	Dripping	0	Dripping	0
0.2	155	0.124		Dripping		Dripping	
1	34	0.500	0.871	Flowing	0	Flowing	0
1	28	0.400		Flowing		Flowing	
1.3	26	0.754	1.738	Transition phase from flowing to initial spray formation	0	Transition phase from flowing to initial spray formation	0
1.3	32	0.926		Transition phase from flowing to initial spray formation		Transition phase from flowing to initial spray formation	
1.6	30	1.514	3.030	65	64	30	30
1.6	55	2.778		63		30	
2	30	2.400	4.782	70	70	32	31.5
2	60	4.774		70		31	
3	30	5.100	10.266	116	115.5	31	31
3	60	10.300		115		31	
3.4	10	1.800	10.950	120	121	30	30.5
3.4	30	5.500		122		31	

Table 3. Test results at different inlet pressure (1 L of water $\approx$ 1 kg).

Mass flow rate measurement uncertainty

Mass flow rate was determined indirectly using the gravimetric method: the total mass of liquid collected over a measured time interval.

Volume Measurement: An oversized collection vessel was positioned beneath the nozzle, ensuring its diameter exceeded the maximum spray dispersion. This configuration ensured all injected water was collected without loss, allowing for precise measurement of the injected volume. Then the volume of collected water was measured using a graduated cylinder with a 2 cc graduation. This graduation size dictates the precision limit for volume determination (± 2 cc).

Time Measurement: The duration of collection was timed using a stopwatch. A significant source of potential error here stems from human reaction time: the inherent delay between observing the start/stop condition and physically pressing the stopwatch button. This reaction time variability can introduce a small but measurable uncertainty into the time measurement, approximately ± 0.5 s.

Combined Effect: The uncertainties in both the volume measurement (± 2 cc) and the time measurement (due to reaction time) propagate into the final calculated mass flow rate value.

Table 2 presents the parameters that are effective in measuring the mass flow rate. Using the data in Table 2, the test error can be calculated as Eq. (1)⁴⁵:

$$\begin{aligned} \text{Mass flow rate error percentage} &= [(dV/V) + (dt/t)] \times 100 \\ &= [(2/2649.57) + (0.5/61.43)] \times 100 \approx 0.9\%. \end{aligned} \quad (1)$$

Results and discussion

The experimental results are presented in Table 3 and Figs. 5 and 6. They indicate that increasing the inlet pressure to approximately 1 bar yields a gradual increase in fluid mass flow rate. However, a further increase in inlet pressure from approximately 1 bar to 3 bar produces a substantial increase in mass flow rate at a constant slope, culminating in a 1078.65% increase over this pressure range. Beyond 3 bar, increasing the pressure to 3.4 bar results in a diminished slope for the mass flow rate increase, suggesting the nozzle is approaching saturation. Analysis of the relationship between inlet pressure and mass flow rate must consider that total pressure comprises static and dynamic pressure components. In the present study, static pressure remained constant; consequently, an increase in inlet pressure elevated the dynamic pressure. Given the constant density of the liquid (water), an increase in dynamic pressure corresponds directly to an increase in flow velocity, thereby increasing mass flow rate. Furthermore, due to geometric constraints imposed by the nozzle inlet and outlet diameters, increasing inlet pressure enhances mass flow rate only up to a specific threshold. Beyond this point, the influence of inlet pressure on mass flow rate diminishes as the nozzle approaches saturation, where further pressure increases yield negligible effects. Figure 6A illustrates this phenomenon, demonstrating that for inlet pressures exceeding 3 bar, the nozzle incrementally approaches saturation, and the sensitivity of mass flow rate to pressure decreases.

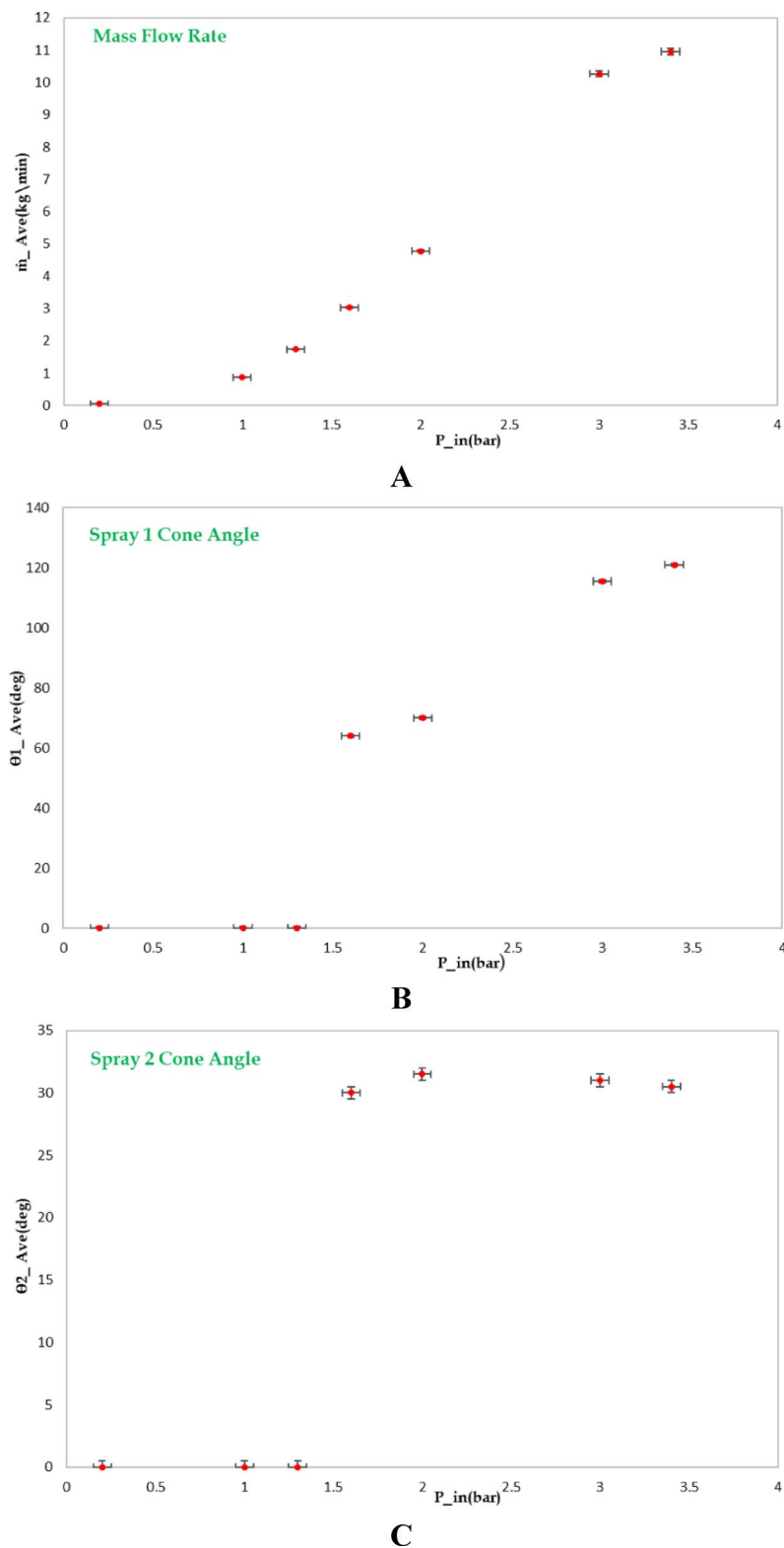


Fig. 6. Variation of mass flow rate (A), spray 1 cone angle (B), and spray 2 cone angle (C) at different inlet pressure (In this figure, the error bars are according to the error sources detailed in “Potential error sources and equipment accuracy” section, which may not be clearly distinguishable due to the low error and compression of the shapes).

Results presented in Fig. 5 reveal distinct flow regimes dependent on inlet pressure: droplet formation occurs at 0.2 bar, continuous flow at 1 bar, and a transition state immediately prior to spray formation at 1.3 bar (For these three cases, spray angle characterized by 0°). At 1.6 bar, primary sprays form, comprising an outer spray (Spray 1) and an inner spray (Spray 2), with measured angles of 64° and 30° , respectively. Increasing pressure to 2 bar expands both sprays, yielding angles of 70° (Spray 1) and 31.5° (Spray 2). At 3 bar, both sprays are fully developed, achieving angles of 115.5° (Spray 1) and 31° (Spray 2). Notably, secondary sprays adjacent to the primary sprays emerged at 3 bar. While the investigation of secondary sprays presents a potential avenue for future research, it falls outside the scope of this study. Figure 5 further indicates that increasing pressure from 3 to 3.4 bar has negligible impact on the angles of Spray 1 and Spray 2, signifying their approach to a saturated state. The primary observable effect at 3.4 bar is the development of diffuse edges on both sprays, complicating precise edge identification and necessitating high measurement accuracy.

Another significant observation within the 2 to 3.4 bar pressure range is the marked increase in Spray 1 angle (from 70° to 121°) concurrent with a subtle decrease in Spray 2 angle. This subtle decrease in Spray 2 angle can be attributed to the specific geometry of the spiral nozzle, especially its spiral section, as Spray 2 is more influenced by the spiral section than Spray 1. Regarding spray saturation at 3 and 3.4 bar, prior studies^{20–22,45–50} establish that spray cone angle depends on two critical parameters: pressure difference and geometric dimensions. Increasing inlet pressure enhances spray angle up to a limit dictated by nozzle geometry (including inlet and outlet diameters), beyond that, increasing the inlet pressure does not have a significant effect on increasing the spray angle.

The primary function of nozzles is to spray fuel into the combustion chamber; however, in this study, a spiral injector nozzle—commonly utilized in firefighting and industrial cooling applications—was employed to explore its performance through an experimental study, a precise and reliable approach well-established across various scientific and industrial fields⁵¹. The nozzle was fabricated from grade 303 stainless steel, known for its excellent machinability, and produced via machining rather than casting to ensure high dimensional accuracy and superior surface finish, supporting directly printing high-resolution, high-performance components⁵². For future research, advanced numerical simulation and computational methods, which have gained significant traction recently due to their cost-effectiveness and high accuracy, can be applied to further analyze nozzle performance, including deformation and breakage of droplets in air flow⁵³. Such studies could emphasize detailed characterization of droplet and particle size distributions generated by this spray type, while examining gas–liquid two-phase flow and mass transfer characteristics within the system⁵⁴. The influence of geometric parameters—particularly the spiral section dimensions—on spray behavior, including interfaces and wall slip effects, warrants comprehensive investigation⁵⁵. Furthermore, the effects of flow conditions such as temperature variations, turbulence intensity, and cavitation bubble dynamics on nozzle efficiency require extensive experimental and theoretical investigations, especially considering water as the working fluid^{56,57}. The nozzle's performance under high temperature and partial pressure conditions should also be evaluated to understand phase change phenomena and the role of nanofluids in enhancing thermal behavior and cooling efficiency^{58–62}. The activation effect of nanobubbles presents an innovative area for improving nozzle function and energy saving optimization, particularly in exhaust gas treatment^{63,64}. Optimization efforts are essential for enhancing nozzle design and performance, as optimization plays a critical role across all industrial sectors, including dual-fuel engines and marine low-speed engines employing valve controlled pumps and controlled injectors for precise fuel injection quantity management^{65–68}. Integrating experimental data with advanced numerical models enables real-time prediction of system behavior, accelerating design iterations and performance evaluation^{69,70}. By leveraging the latest research advances, it is possible to develop optimized spiral nozzles that maximize spray effectiveness while minimizing operational drawbacks, ultimately improving energy efficiency and operational reliability in diverse applications.

Conclusion

In this study, critical experimental insights into the hydraulic performance and spray morphology evolution of dual-spiral-pitch nozzles under varying inlet pressures (0.2–3.4 bar) were provided, with direct relevance to high-discharge applications such as deluge fire suppression systems. Three distinct operational regimes governing mass flow rate and spray formation were revealed. At low pressures (0.2–1 bar), flow was observed to increase gradually, characterized initially by the formation of single coarse droplets, which transitioned to a continuous jet. A dramatic surge in mass flow rate exceeding 1000% was observed between 1 and 3 bar, coinciding with the development of the defining dual-spray structure: a primary outer spray (Spray 1) and an inner spray (Spray 2). Beyond 3 bar, hydraulic saturation was approached by the nozzle, where geometric constraints (inlet/outlet diameters) significantly diminished the sensitivity of mass flow rate to further pressure increases, culminating in a near-saturated state at 3.4 bar. Crucially, asymmetric behavior was exhibited in the evolution of a dual-spray morphology. While remarkable angular stability ($\sim 30^\circ$) was maintained by Spray 2 across its operational pressure range (1.6–3.4 bar), substantial expansion was undergone by Spray 1, with its cone angle increasing from 64° at 1.6 bar to 121° at 3.4 bar. This divergence highlighted the distinct influence of the nozzle's spiral geometry on each spray component; Spray 2 was noted to be more constrained by the core spiral section. Furthermore, angular saturation was approached by both sprays above 3 bar, aligning with the mass flow rate plateau and confirming the dominance of geometric limits over pressure for enhancing spray angle beyond this threshold. The emergence of secondary sprays at 3 bar, although not explored in this study, was observed to indicate increasing spray complexity at higher pressures and highlighted a promising avenue for future research. Essential pressure-flow-morphology relationships were established by these comprehensive experimental results, and the rigorous validation data necessary for developing and verifying accurate CFD models of these complex nozzle systems were provided.

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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