CP301

DEVELOPEMENT ENGINEERING PROJECT

End-Semester Report

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1 Title of Project

Hybrid Atomizer for shear-thinning fluids

2 Abstract

This experimental study explores the atomization characteristics of water and aqueous Carbopol gels with concentrations of 0.10 wt.%, and 0.35 wt.% using a pressure-swirl atomizer. The performance of these non-Newtonian fluids is compared against water under atmospheric conditions across an injection pressure range of 1–8 bar. The investigation focuses on key spray parameters including liquid sheet breakup length, spray cone angle, discharge coefficient, mass flow rate, and droplet size distribution. Results show that water produces a well-defined hollow-cone spray with early breakup and fine droplet formation. In contrast, Carbopol gels exhibit delayed atomization, longer breakup lengths, and reduced spray angles—especially at higher concentrations due to increased viscosity and yield stress. The mass flow rate for all fluids increases with pressure, though gels initially resist flow and only exhibit improved discharge behavior at higher pressures due to shear-thinning effects. Droplet size measurements indicate that higher gel concentration and lower pressure produce coarser droplets, with the smallest sizes occurring at the spray center. Overall, the study highlights the challenges of atomizing shear-thinning gels and emphasizes the influence of rheology and pressure on spray formation in pressure-swirl systems.

3 Aim and Objectives

To design and analyse the performance of a Hybrid Atomizer for the efficient atomization of shear-thinning liquids, optimizing spray characteristics.

1. Design and Fabrication: Develop a novel hybrid atomizer integrating the benefits of pressure swirl atomization for non-Newtonian shear-thinning fluids.
2. Spray Characterization: Analyze the spray breakup process by capturing spray images at different injection pressures and mass flow rates.
3. Rheological Characterization: Measure the flow behavior index (n) and consistency index (K) of the shear-thinning fluid .
4. Discharge Coefficient Analysis: Evaluate the discharge coefficient vs. pressure drop to understand flow efficiency.

4 Introduction

Atomization of bulk quantity of any substance, whether liquid or solid is widely observed in nature, for example, rain water, breakup of waves in oceans [Villermaux E (Fragmentation and Cohesion, J. Fluid Mech., 2020][1], and various industrial process like, agriculture, pharmacy, paint industry, and propulsion. The process of atomization is very crucial as it determines the size distribution of droplets or fragments from the bulk material. For instance, finer droplet sizes produced from the atomization of liquid fuels and propellants allow efficient combustion, however, finer droplet sizes are undesirable in agricultural spray as wind carries away smaller droplet before reaching the desired crops [Lefebvre A H (Atomization and Spray)][2].

Droplet sizes formed from the atomization of higher viscosity liquids are reported to be larger than those of less viscous liquids. In the field of rocket propulsion, recent studies explored the possibilities of gel propellants, which is superior in terms of safety and handling, at the same time gives a challenge of atomization because of its non-Newtonian nature. Various injector or atomizers currently used to atomize gel propellants are impinging jets, pressure swirl atomization, air-blast atomization etc.

5 Background and literature review

5.1 Atomization and Pressure-Swirl Atomizers

Atomization is the process of disintegrating a bulk liquid into fine droplets, enhancing surface area and promoting efficient mixing in applications such as fuel injection, spray drying, and medical nebulization. Various atomization techniques exist, including pressure-swirl, airblast, ultrasonic, and electrostatic methods, each leveraging different mechanisms to achieve droplet formation.

In this project, we focus on a pressure-swirl atomizer, which imparts angular momentum to the liquid, forming a hollow cone spray. This mechanism is particularly effective for atomizing complex fluids like shear-thinning liquids.

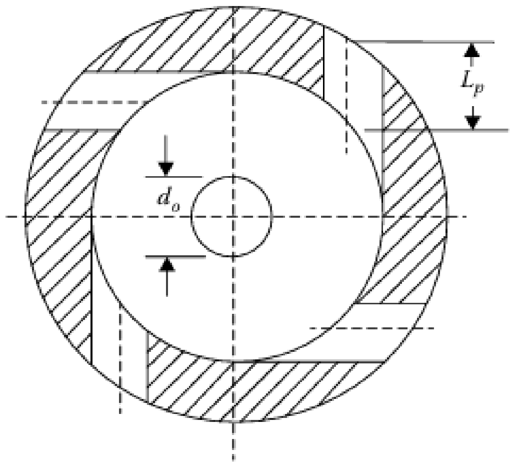


Figure 1. Schematic view of a simplex swirl atomizer [2]

5.2 Evolution of Atomization Technology

The concept of atomization has evolved over centuries, with early applications in perfumery and medicine. The 19th century marked the advent of mechanical atomizers, notably in internal combustion engines. The 20th century witnessed significant advancements with the development of pressure-swirl injectors in aerospace and automotive industries. In the 21st century, the demand for precise atomization in fields like pharmaceuticals and additive manufacturing has led to the emergence of advanced atomizers capable of handling complex fluids such as gels and suspensions.

5.3 Spray Dynamics and Measurement Technique

The atomization process encompasses several stages: initial liquid sheet formation, breakup into ligaments, and subsequent droplet formation. These stages are influenced by fluid properties, injection pressure, nozzle geometry, and ambient conditions. Understanding spray behaviour is crucial for optimizing atomizer design and performance.

To characterize sprays, experimental techniques such as high-speed imaging, laser diagnostics, and computational fluid dynamics (CFD) simulations are employed. High-speed cameras capture transient phenomena like ligament breakup and spray angle variations. In this project, we utilize high-speed imaging and large-distance microscopy (LDM) to analyse both macroscopic spray patterns and microscopic droplet behaviours, providing insights into primary and secondary atomization stages.

5.4 Shear Thinning Fluids and Rheology

Shear-thinning fluids, such as Carbopol gel, exhibit a decrease in viscosity with increasing shear rate. At rest, these fluids maintain high viscosity due to entangled molecular structures. Under shear, these structures align, reducing internal resistance and facilitating flow. This non-Newtonian behaviour is advantageous in spray systems, allowing for easy ejection at high shear rates without compromising structural integrity during storage.

Rheological characterization is conducted using a rotational rheometer, focusing on parameters such as:

- Flow Behaviour Index (n): Determines the degree of shear-thinning; $n < 1$ indicates shear-thinning behaviour.
- Consistency Index (K): Represents the fluid's viscosity at a reference shear rate.
- Shear Stress vs. Shear Rate Curves: Classify fluids and understand their response to varying deformation rates.

5.5 Discharge Coefficinet in Atomizers

The discharge coefficient (Cd) is a dimensionless parameter evaluating the efficiency of fluid flow through an orifice, accounting for real-world losses due to friction, contraction, and turbulence [3]. It is calculated as:

$$C_d = \frac{Q_{actual}}{Q_{ideal}}$$

where Q_{actual} is the measured flow rates and Q_{ideal} is the theoretical flow based on Bernoulli’s equation. A higher Cd indicates more efficient flow, which is desirable in atomizer design.

In our setup, Cd is evaluated at different injection pressures using mass flow rate and pressure drop data. These measurements allow us to correlate pressure-swirl efficiency with the behaviour of non-Newtonian liquids.

6 Experimental apparatus

6.1 Experimental Setup

The test liquid is stored in a cylindrical tube of inner diameter 72 mm. Compressed nitrogen gas is supplied to cylinder to push the liquid through the atomizer. The compressed gas and liquid are separated by a piston in between them. The movement of the piston due to force exerted by nitrogen drives the liquid out through the nozzle. A piston position sensor attached to the piston measures the movement of piston with time, which is utilized to estimate the mass flow rate of the liquid. A pressure sensor attached to the inlet of the nozzle measures the injection pressure. The piston traverse a length of 300 mm before emptying the cylinder. Both piston sensor and pressure sensor are connected to data acquisition system (NI), and there the voltage input signal are finally converted bar and kg/s. A valve is used to stop and start the flow through the atomizer. The spray formed from the atomizer is collected using a plastic tray and disposed. Fig 1. shows the schematic of experimental setup used in this study.

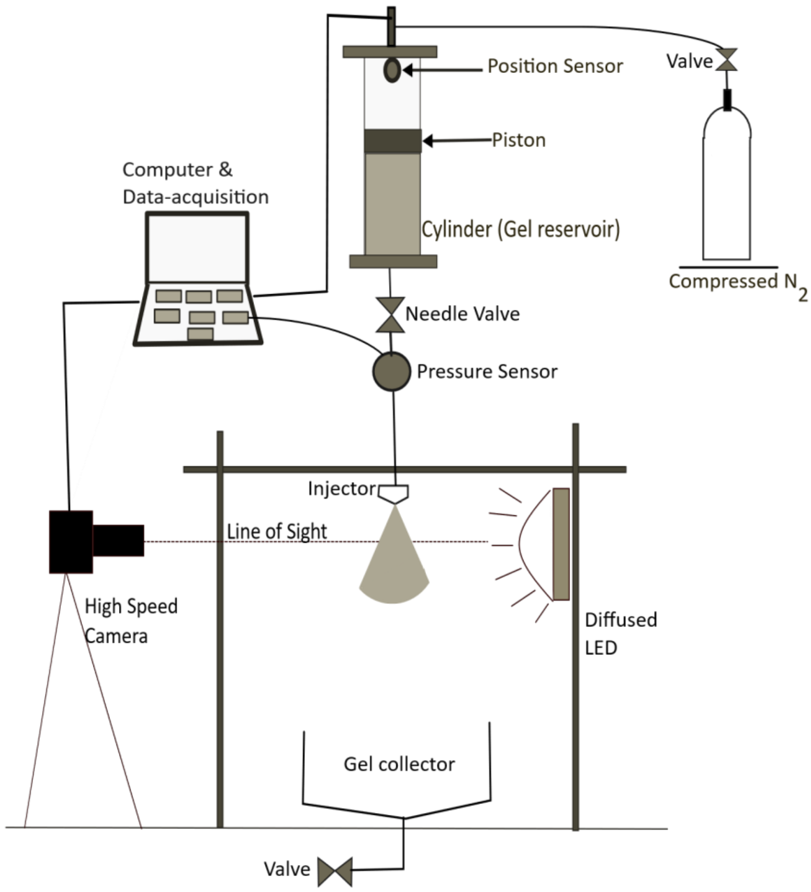


Figure 2. Atomization test rig.

The atomizer used in this study is pressure-swirl atomizer. The front view CAD drawing is shown in the Fig.2. The atomizer comprises two tangential inlets, a swirl chamber and a orifice. The tangential inlets are of circular shapes. The cylindrical shaped swirl chamber has a height if 5 mm and a diameter of 7 mm. The chamber tapers at an angle of 45° to meet the 2 mm diameter orifice.

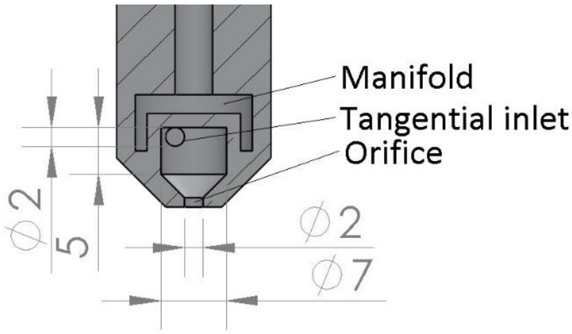


Figure 3. CAD drawing of front view of the pressure-swirl nozzle

6.2 Gel composition

The test liquids used in this study for atomization are aqueous carbopol gels. Preparation of carbopol gel involves dilution of measured quantity of carbopol powder (Himedia) in de-ionized water with the help of a mechanical stirrer at 800 rpm followed by the addition of triethanolamine (Emplura). The addition of triethanolamine in carbopol-water solution results in the formation of gel. The sample is stored for 24 hours in a sealed container before conducting atomization studies. The gel composition prepared and tested in the study are given in the Table. 1. A detailed description of carbopol gel preparation is provided in the paper[4] .

Sample	De-ionized Water (wt.%)	Carbopol powder (wt.%)	Triethanolamine (TEA) (wt.%)
1	100	0	0
2	99.8	0.10	0.1
3	99.55	0.35	0.1

Table 1. Liquid sample composition used in study

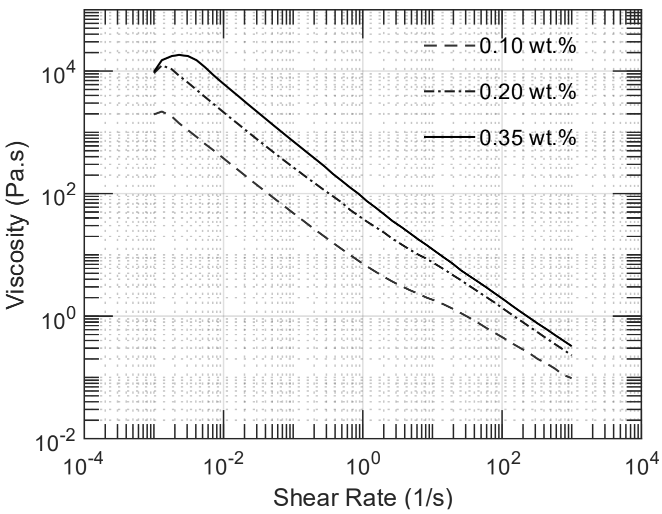


Figure 4. Rheometer measurements of gel viscosity shear rate for the Carbopol 0.10 wt.% and Carbopol 0.35 wt.%.

Various studies have reported the yield-stress and shear thinning behavior of Carbopol gels [5]. To estimate the effect of shear rate on the viscosity of carbopol gel, a flow curve measurement is performed using Anton Paar MCR 101 rheometer. A parallel plate geometry with 50 mm plate and a gap of 1 mm is kept while performing the measurements. Surface tension of the samples is measured by pendant drop method. Fig. 4 shows the shear rheology of the gel simulant. It can be seen that the shear viscosity of the gel simulant decreased with the shear rate increased.

We consider important fluid properties that influence atomization, particularly for shear-thinning and yield-stress fluids.

- *Surface tension (σ)*: Surface tension is the force that acts on the surface of a liquid, causing it to behave like a stretched elastic sheet. It plays a critical role during atomization by resisting the breakup of the liquid into droplets. A lower surface tension generally leads to easier droplet formation and finer sprays.
- *Yield stress (τ_0)*: This is the minimum stress required to initiate flow in a fluid. For yield-stress fluids like Carbopol gel, the fluid behaves like a solid until the applied stress exceeds this value. In the Herschel–Bulkley model, τ_0 represents this yield limit.
- *Shear rate ($\dot{\gamma}$):* Shear rate is a measure of how fast layers of fluid move relative to each other. It is a key parameter in defining the flow behaviour of non-Newtonian fluids. During atomization, higher shear rates help in breaking down the liquid into smaller droplets.

  Herschel-Bulkley model[5]is used to fit the gel rheology data.

$$\tau_s = \tau_o + K\dot{\gamma}^n$$

Where τ_s is shear stress, K is the consistency factor, and n is the power-law exponent. Parameters of the Herschel-Bulkley model (Eq [4]) fit to rheology data are shown in Table 2.

Sample	Water wt.%	Carbopol gel wt.%	Triethanolamine (TEA) wt.%	σ (mN m^{-1})	τ_o (Pa s^n)	n (-)	K(-)
1	100	0	0	72	-	-	-
2	99.8	0.10	0.1	64	3.0	0.47	5.0
3	99.55	0.35	0.1	32	25.3	0.33	37.1

Table 2. Rheological properties of test gels used.

6.3 Spray Diagnostics

High-speed instances of the swirl spray are captured by Photron fastcam Mini AX100 at 4000 fps and 5 μs exposure time. Shadowgraph method is used to take pictures of spray with the help of a 150W LED. A spatial resolution of 70 μm per px allowed to study the cone angle of spray, sheet breakup length, and identify the locations of fine atomization for various injector pressures.

Droplet sizing measurements are conducted at locations that are separated at a distance of 10 mm, 20 mm, 30 mm, and 40 mm radially from the geometric axis of the nozzle at an axial location of 70 mm, as shown in Fig 8. These locations are identified from the high-speed images and ensure fine atomization of all four gel compositions studied at the highest injection pressure. Each measurement location is a square with a side of 3.68 mm. Using a long-distance microscope, a resolution of 5 μm is achieved. Droplets having a minimum diameter of 30 μm are included in the study. Long-distance microscope allowed the droplet sizing measurements at a working distance of 700 mm. Nozzle is mounted on a horizontal and vertical traverse to change the location of droplet sizing.

7 Results and discussion

7.1 Spray behavior

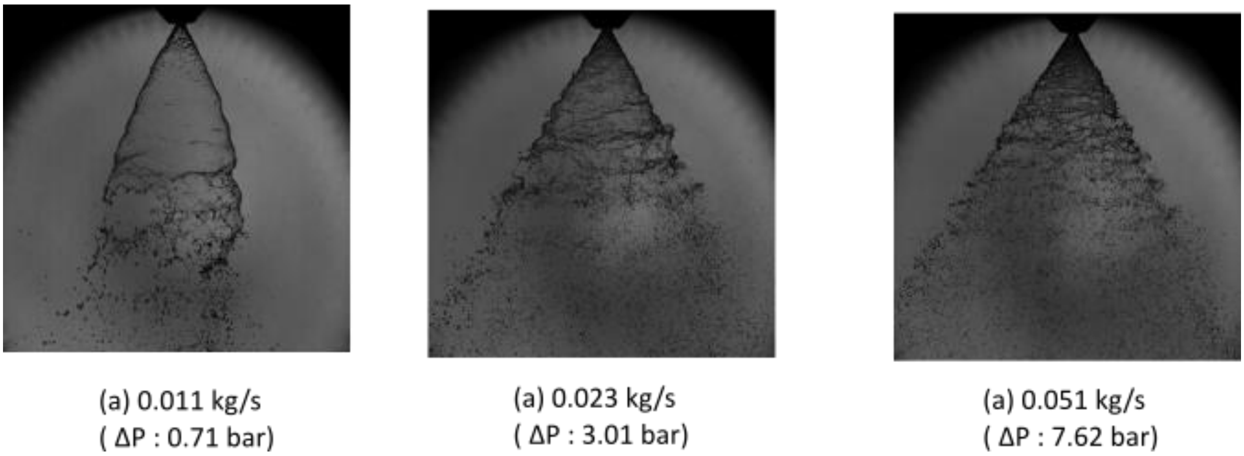
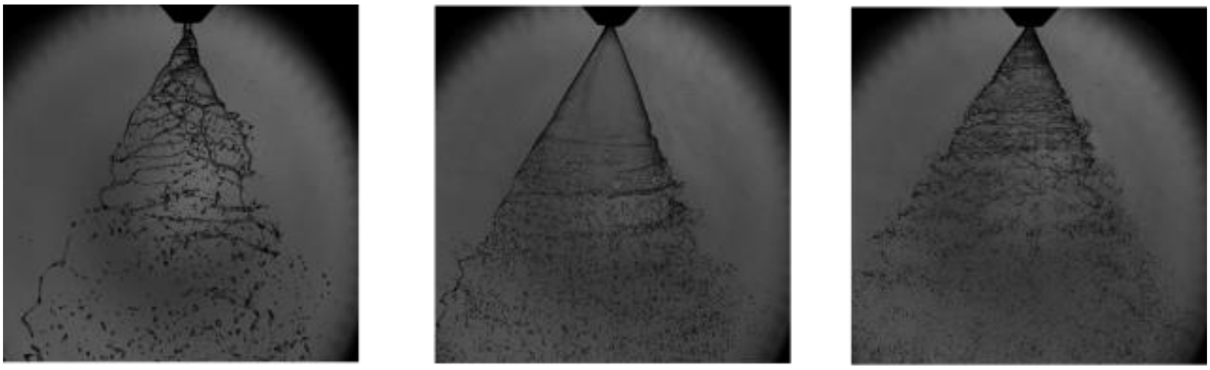


Figure 5. Spray images of water under different mass flow rates.

Figure 5 shows the spray patterns of liquid water at different injection pressures. At low pressure, a stable hollow cone forms with smooth edges, and breakup occurs further downstream. As the pressure increases, the cone becomes more turbulent and the breakup happens closer to the nozzle, forming finer droplets. This behaviour matches typical Newtonian fluids and agrees with findings from Yang et al. (2012) [6] and Wang & Lefebvre (1987) [7], who showed that increasing pressure leads to shorter breakup lengths and better atomization efficiency



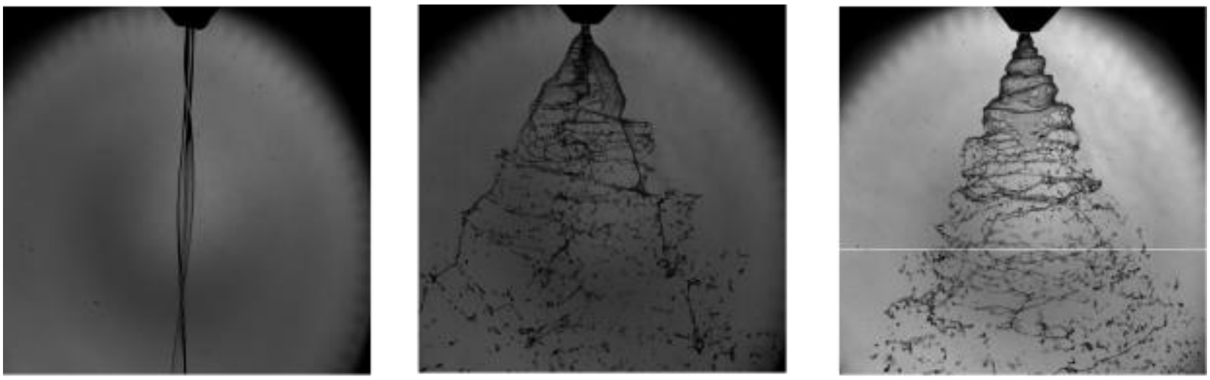
(a) 0.021 kg/s
(ΔP : 1.53 bar)

(a) 0.0373 kg/s
(ΔP : 6.21 bar)

(a) 0.0419 kg/s
(ΔP : 8.62 bar)

Figure 6. Spray images of Carbopol gel 0.10% wt. at different mass flow rates.

In Figure 6, the spray of Carbopol gel at 0.10 wt.% shows thicker liquid sheets and delayed breakup compared to water. At low pressure, twisted ribbons and long ligaments appear, indicating the gel’s resistance to atomization. As pressure increases, the spray becomes more developed but still retains a denser core and longer breakup length. This behavior reflects the non-Newtonian nature of Carbopol and supports observations from Kim et al. (2017) [8] and Yang et al. (2012) [6], where shear-thinning fluids showed poorer spray formation at low shear rates



(a) 0.025 kg/s
(ΔP : 4.04 bar)

(a) 0.033 kg/s
(ΔP : 5.64 bar)

(a) 0.038 kg/s
(ΔP : 6.42 bar)

Figure 7. Spray images of Carbopol gel 0.35% wt. At different mass flow rates.

Figure 7 illustrates the spray for a higher Carbopol concentration (0.35 wt.%), where atomization is much more difficult. At low pressure, the gel doesn’t even form a spray cone but exits as a thin filament. At mid and high pressures, the sheet forms but is dominated by thick, web-like ligaments and layered structures, with poor breakup into droplets. The higher yield stress and viscosity greatly resist deformation, confirming findings by Kim et al. (2017) [8] that higher gel concentration reduces spray efficiency and increases breakup length

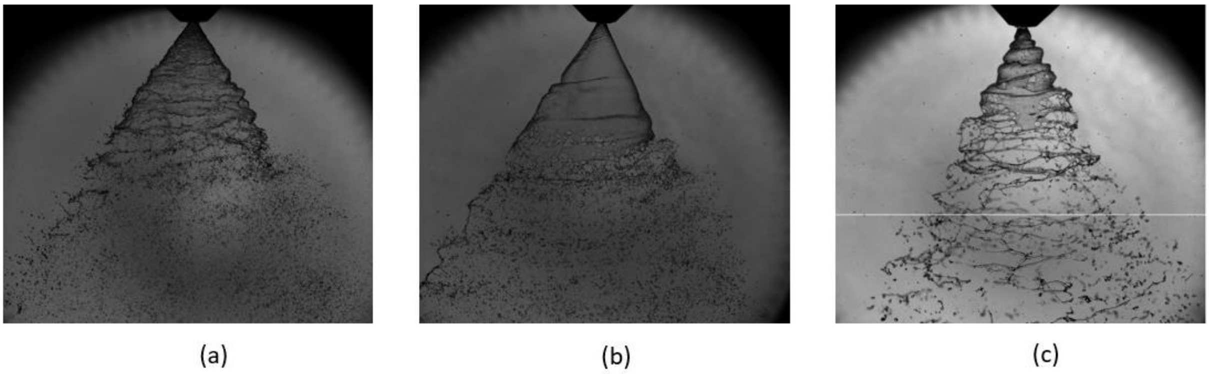


Figure 8. Spray formation of (a) water, (b) carbopol gel 0.10% and (c) carbopol gel 0.35% at injection pressure of 6.21-6.59 bar.

Figure 8 shows the spray morphology of (a) water, (b) 0.10 wt.% Carbopol gel, and (c) 0.35 wt.% Carbopol gel at an injection pressure of approximately 6.2–6.6 bar. Water, being a Newtonian fluid, forms a clean hollow-cone spray with early breakup and fine droplet dispersion. The 0.10% Carbopol gel, however, produces a thicker sheet that breaks up further downstream, forming stretched ligaments and showing signs of delayed atomization. In the 0.35% gel case, the spray becomes highly irregular — forming layered, coiled ligaments and failing to disperse effectively. This behaviour reflects the strong influence of increased viscosity and yield stress, which suppresses sheet destabilization.

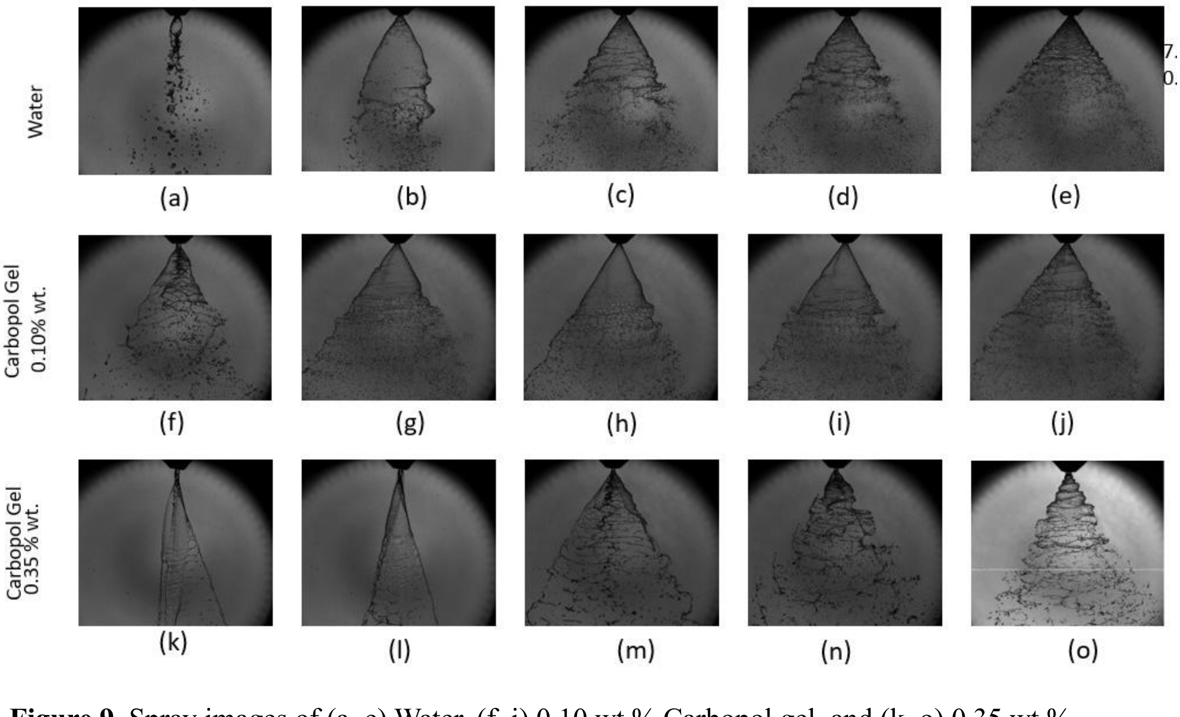


Figure 9. Spray images of (a–e) Water, (f–j) 0.10 wt.% Carbopol gel, and (k–o) 0.35 wt.% Carbopol gel at various injection pressures (ΔP) and mass flow rates.

This figure 9 highlights how spray behaviour changes with both fluid rheology and injection pressure. Water forms a stable, fine hollow-cone spray even at moderate pressures, while 0.10 wt.% Carbopol shows delayed breakup and thicker spray sheets. For 0.35 wt.% Carbopol, the spray remains jet-like at low pressures and forms distorted, web-like ligaments at higher pressures. Overall, increasing gel concentration significantly suppresses atomization, requiring higher pressure for breakup and resulting in longer breakup lengths and narrower spray cones.

Table 3. Injection pressure (ΔP) and mass flow rate data corresponding to the spray images shown in Fig. 7 for Water, 0.10 wt.% Carbopol gel, and 0.35 wt.% Carbopol gel.

		a	**b**	**c**	**d**	**e**
ΔP, bar	Water	0.25	0.71	1.53	3.01	7.62
Mass flow rate (kg/s)		0.006	0.011	0.016	0.023	0.051
		f	**g**	**h**	**i**	**j**
ΔP, bar	Carbopol gel 0.10 % wt.	1.53	3.41	5.57	7.08	8.62
Mass flow rate (kg/s)		0.021	0.0239	0.0368	0.0386	0.0419
		k	**l**	**m**	**n**	**o**
ΔP, bar	Carbopol gel 0.35% wt.	4.46	4.75	5.65	5.72	6.42
Mass flow rate kg/s		0.029	0.031	0.033	0.034	0.038

Figure 10 shows that the breakup length is the distance from the nozzle tip to the point where the web like ligaments appear. The spray angle is the full angle of the liquid filming forming the cone shape. The breakup length was determined using MATLAB by manually selecting the breakup point in each spray image. For every experimental condition, 50 images were captured to ensure consistency and accuracy. A similar manual process was followed to measure the spray angle, where points along the spray boundaries were clicked to estimate the angle formed by the spray cone.

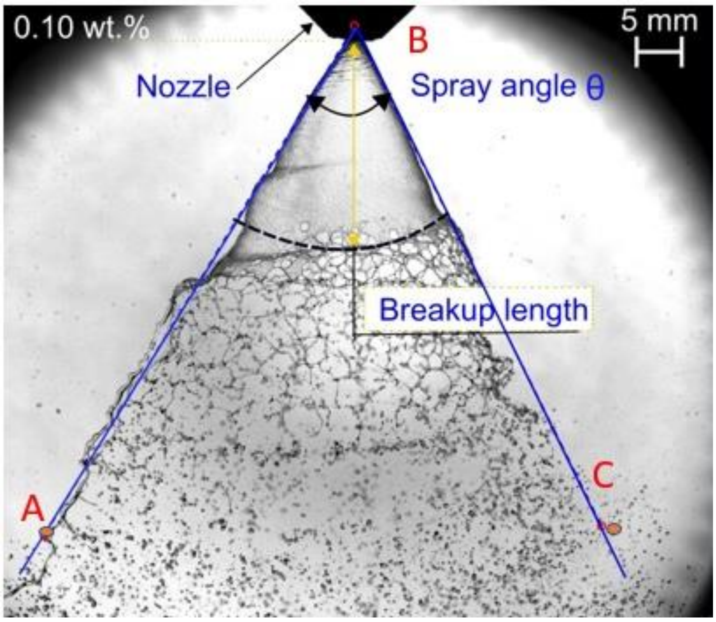


Figure 10. Definition of breakup length and spray angle

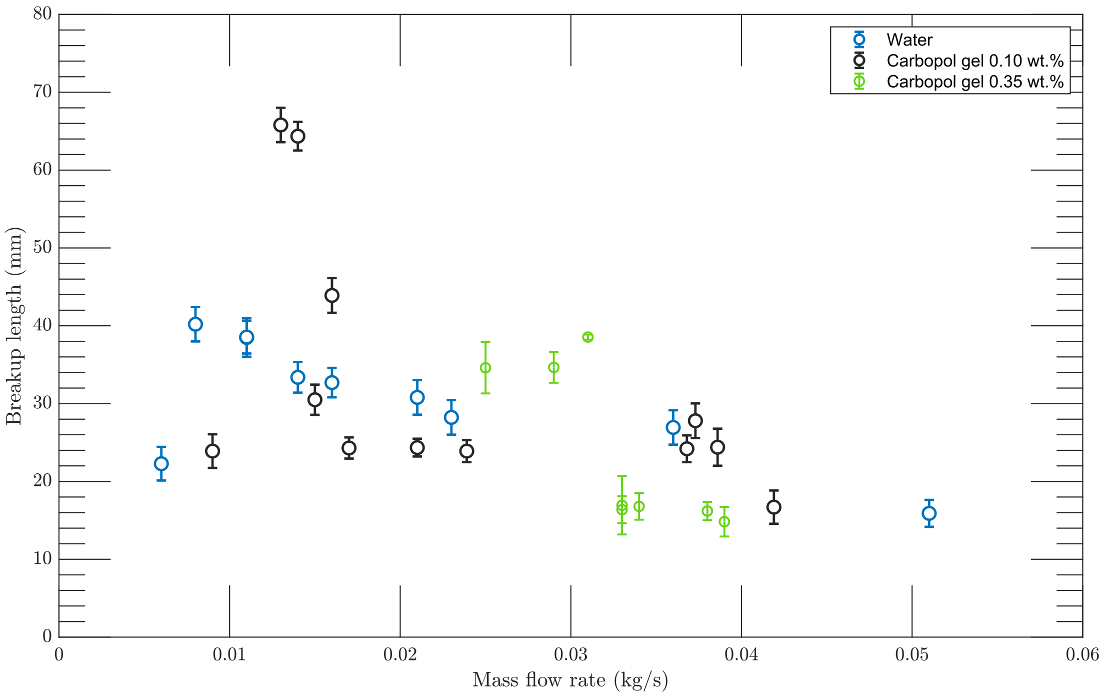


Figure 11. Breakup length with respect to mass flow rate

Figure 11 shows the variation of breakup length with mass flow rate for water and two Carbopol gel concentrations. For water, the breakup length generally decreases with increasing mass flow rate, consistent with classical atomization theory. In the case of 0.10 wt.% Carbopol gel, the breakup length is higher at low flow rates due to yield stress effects but gradually decreases as flow increases. The 0.35 wt.% gel exhibits the longest breakup lengths at low flow, with delayed atomization and persistent ligaments. As the mass flow rate rises, the breakup length shortens, indicating that higher shear forces overcome the gel's resistance. This behavior supports findings from gel spray studies like Fu et al. (2019), where higher viscosity and viscoelasticity delayed atomization onset.

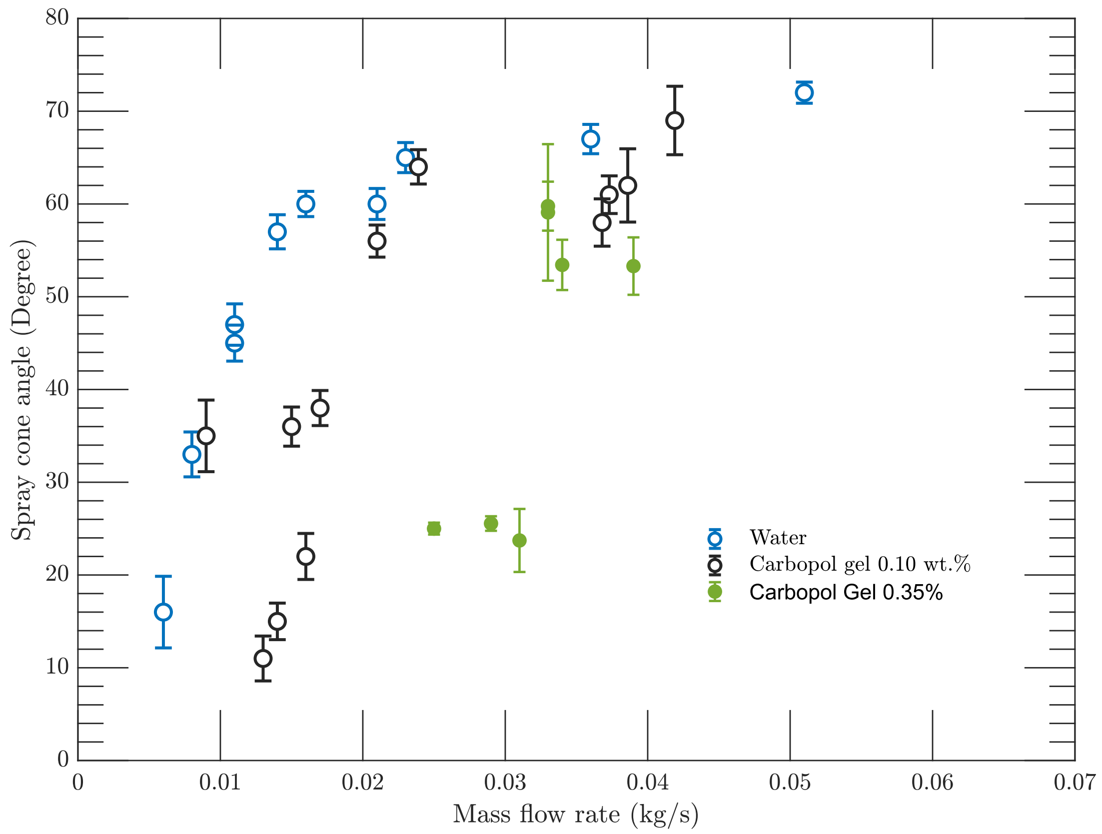


Figure 12. Spray cone angle as a function of the mass flow rate pf the liquid

Figure 12 illustrates how spray cone angle varies with mass flow rate for water and Carbopol gels. Water consistently shows larger cone angles, increasing steadily with flow rate due to its low viscosity and ease of sheet spreading. The 0.10 wt.% Carbopol gel follows a similar but slightly lower trend, reflecting mild resistance from shear-thinning properties. In contrast, the 0.35 wt.% gel displays significantly narrower cone angles, particularly at low flow rates, due to its high yield stress and viscoelastic structure which restricts lateral sheet expansion. As the flow rate increases, the cone angle improves slightly, indicating that higher shear helps overcome gel resistance. These trends align with prior observations that non-Newtonian fluids resist conical spray formation at lower shear rates

7.2 Effect of liquid composition on droplets

The performance of an atomizer is usually evaluated based on the average droplet size it generates under different working conditions. There are several ways to define this average in fuel atomization studies, but the Sauter Mean Diameter (SMD) is considered the most suitable as mentioned in [9]. This is because SMD best represents how quickly the droplets will evaporate and combust, which is especially important in applications like engines and burners. The SMD is defined as the ratio of the total volume to the total surface area of droplets, which is mathematically shown by Eq., where D_i stands for the size of all droplets passing each interested location

$$SMD = \frac{\sum D_i^3}{\sum D_i^2}$$

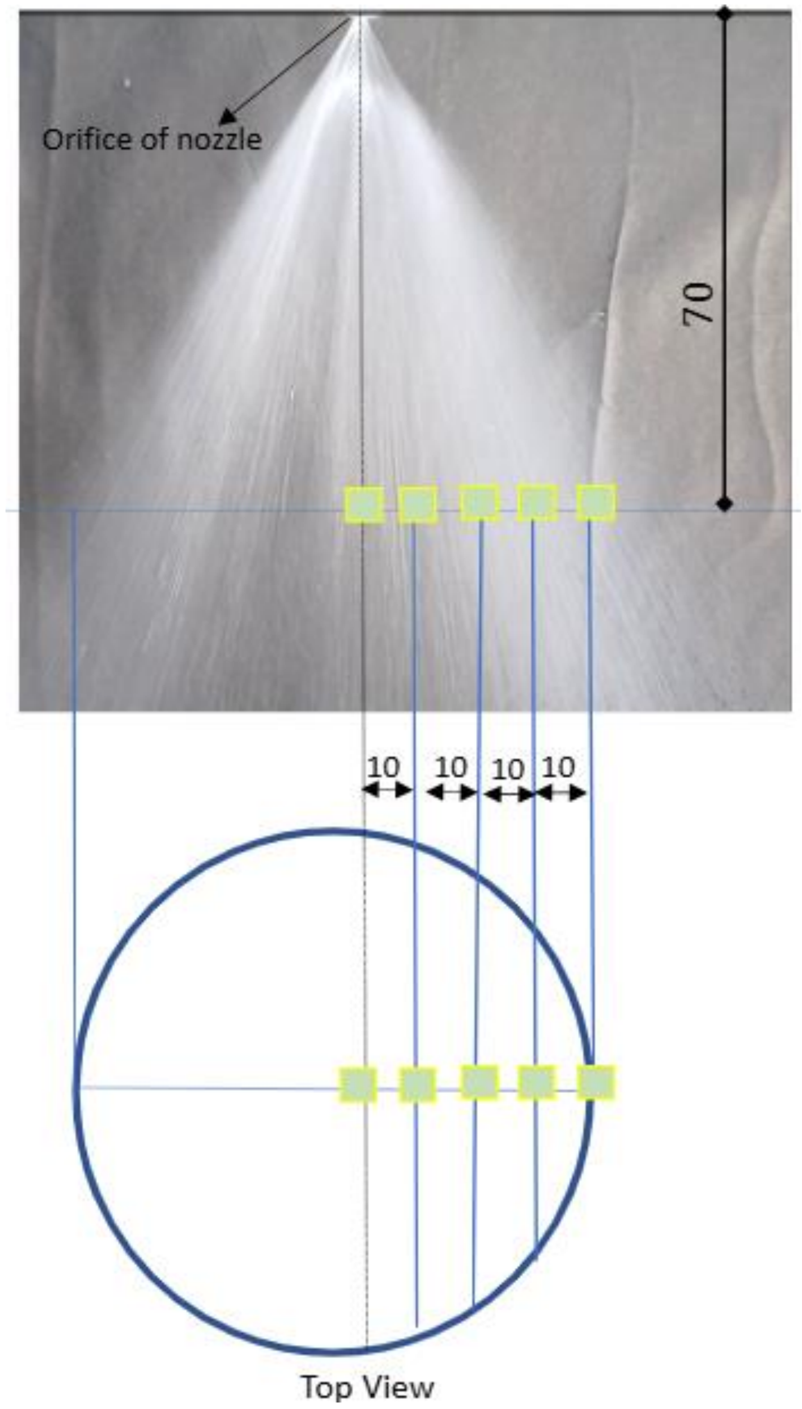
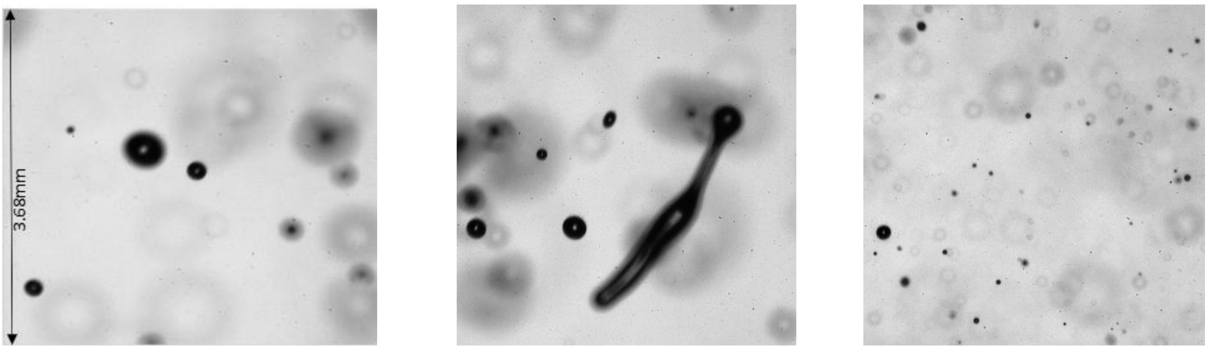


Figure 13. Radial locations of the interested region where the drop sizing was performed



(a) (b) (c)

Figure 14. Images of droplets region (3.68 mm × 3.68 mm) captured using high speed camera and LDM. (a) - Carbopol gel 0.10 wt.% at 6 bar injection pressure. (b)- Carbopol gel 0.10 wt.% at 4 bar injection pressure (c) - Water at 6 bar injection pressure.

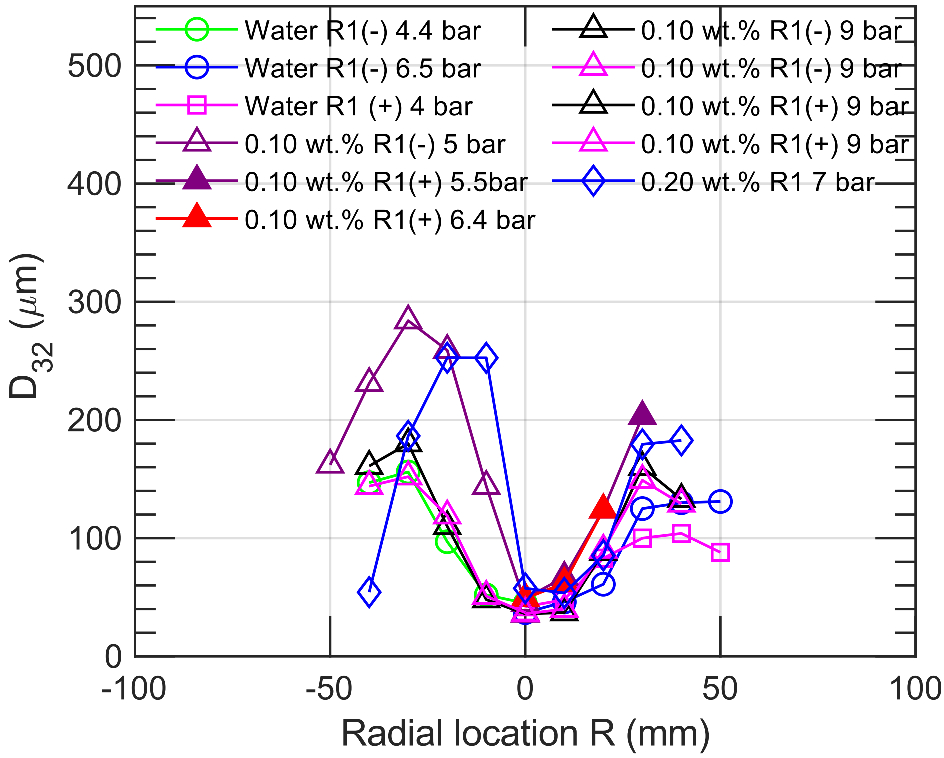


Figure 15. Drop sizing across the width of the spray for various flow rates locations for the spray

Figure 15 shows the radial variation of Sauter Mean Diameter (D_{32}) for water and different Carbopol gel concentrations at varying injection pressures. Across all cases, the droplet size is smallest at the spray center (R = 0 mm) and increases toward the edges. This is typical for pressure-swirl atomizers, where the core receives the highest shear, leading to finer atomization.

Water and low-concentration Carbopol (0.10 wt.%) generally show lower D_{32} values (~80–150 µm at the center), while higher gel concentration (e.g., 0.20 wt.%) and lower injection pressure result in coarser droplets (up to ~300–500 µm radially). At higher pressures (≥6 bar), D_{32} values tend to become more uniform across the spray, indicating more effective breakup.

These trends reflect the influence of both fluid rheology and shear: yield stress in gels inhibits droplet formation near the spray edges, where shear is lower, while high-pressure injection overcomes this resistance and narrows the size distribution.

7.3 Mass flow rate and Discharge Coefficient

In this experiment, mass flow rate was calculated indirectly using piston displacement data provided by a linear actuator. When the spray was turned on, the actuator recorded the movement of the piston, which was then used to determine the volumetric flow rate. This volumetric flow rate was then converted to mass flow rate ($\dot{m}$) using the fluid density. his approach allowed us to measure flow rate accurately even for non-Newtonian fluids like Carbopol gels, where traditional collection methods may be unreliable due to slow settling or stickiness.

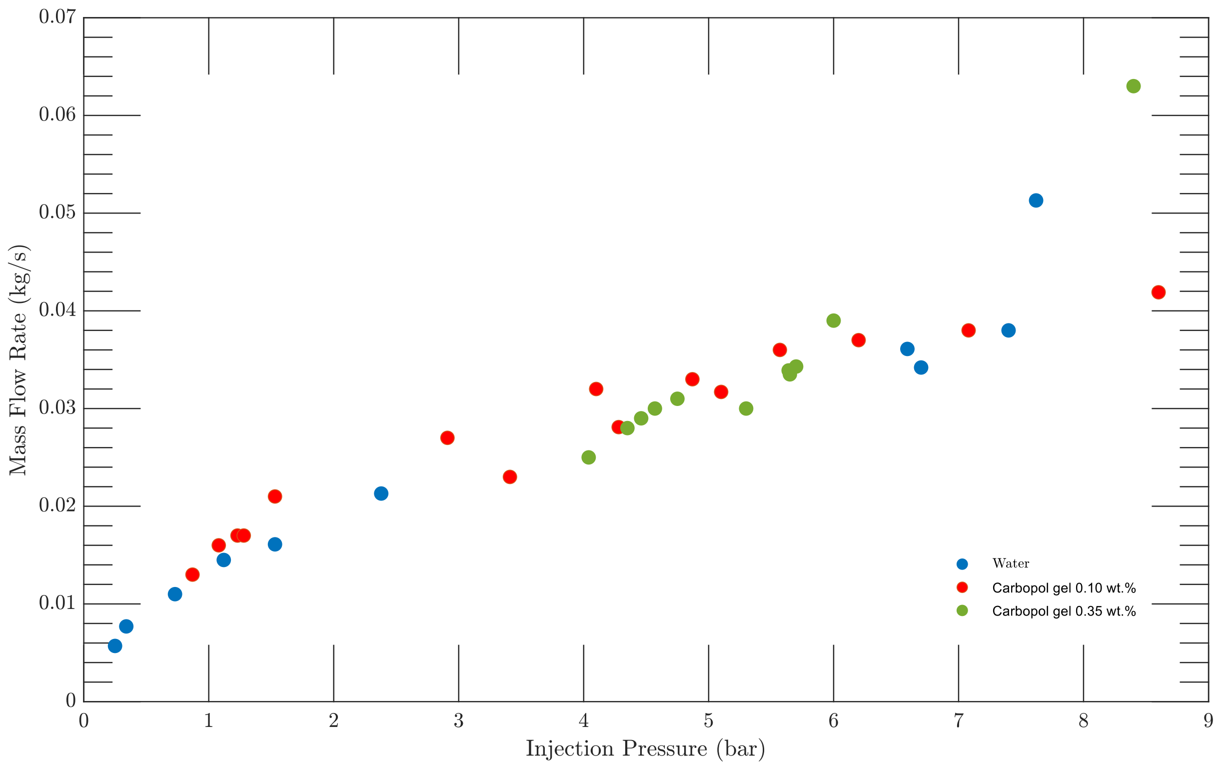


Figure 16. Mass flow rate of the sample liquid with respect to injection pressure

The fig. 16 shows that mass flow rate increases with injection pressure for all three fluids. Water exhibits a smooth, nearly linear rise due to its Newtonian nature. In contrast, both Carbopol gels, especially the 0.35 wt.%, show slower flow rate increase at low pressures due to yield stress. After a certain threshold, their flow rates rise more steadily as shear-thinning behavior takes over. At higher pressures, all three fluids show similar flow rates, indicating reduced influence of viscosity

The discharge coefficient (Cd) quantifies the efficiency of fluid flow through the nozzle by comparing actual to ideal flow rates. It was calculated using:

$$C_d = \frac{\dot{m}}{A_o(2\rho\Delta P)^{0.5}}$$

Here, C_d is the discharge coefficient, $\dot{m}$ is the mass flow rate, A_o is the orifice area, ρ is the density of the liquid, and ΔP is the injection pressure [8]

The fig. 17 shows how the discharge coefficient (C_d) varies with injection pressure for water and two Carbopol gel concentrations. Water maintains a relatively steady C_d around 0.3–0.35 across the pressure range. The 0.10 wt.% Carbopol gel also shows a similar trend but with slightly more fluctuation, likely due to its mild yield stress and shear-thinning behavior. In contrast, the 0.35 wt.% gel starts with a lower C_d at low pressures, indicating greater flow resistance, but shows a sharp increase at higher pressures as the gel structure breaks down and shear-dominated flow begins. This pressure-dependent improvement in C_d for higher concentration gels is consistent with literature on gel atomization behavior

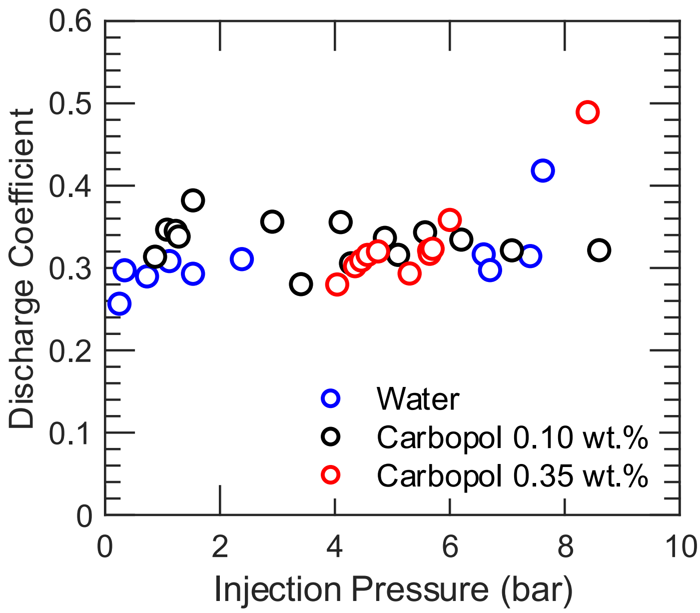


Figure 17. Discharge Coefficient of the sample liquid with respect to injectioin pressure

8 Applications

Pressure-swirl atomizers are integral components in numerous industries due to their ability to produce fine, uniform sprays. Their design, which imparts a swirling motion to the liquid, facilitates efficient atomization, making them suitable for a variety of applications:

1. Aerospace and Rocket Propulsion

   In aerospace engineering, pressure-swirl atomizers are employed in liquid-propellant rocket engines and gas generators. Their capability to generate a hollow cone spray ensures effective mixing of fuel and oxidizer, which is crucial for stable and efficient combustion as shown in fig. 18.

2. Gas Turbines and Power Generation

These atomizers are widely used in gas turbines for power generation. They facilitate the atomization of fuels, leading to improved combustion efficiency and reduced emissions.

3. Pharmaceutical Industry

   In pharmaceuticals, pressure-swirl atomizers are utilized in nasal spray devices and inhalers. They ensure the delivery of medications in fine droplets, enhancing absorption and efficacy.

4. Agriculture

   Agricultural sprayers use pressure-swirl atomizers to distribute pesticides and fertilizers evenly across crops. The fine mist produced ensures thorough coverage, optimizing crop protection and yield as shown in fig. 19.

5. Food Processing and Spray Drying

   In the food industry, these atomizers are essential for spray drying processes, such as producing powdered milk or coffee. They enable the formation of fine droplets that dry quickly, resulting in consistent powder products.

6. Fire Suppression Systems

   Pressure-swirl atomizers are integral to fire suppression systems, where they disperse water or fire retardants in fine sprays to quickly extinguish fires and prevent re-ignition.

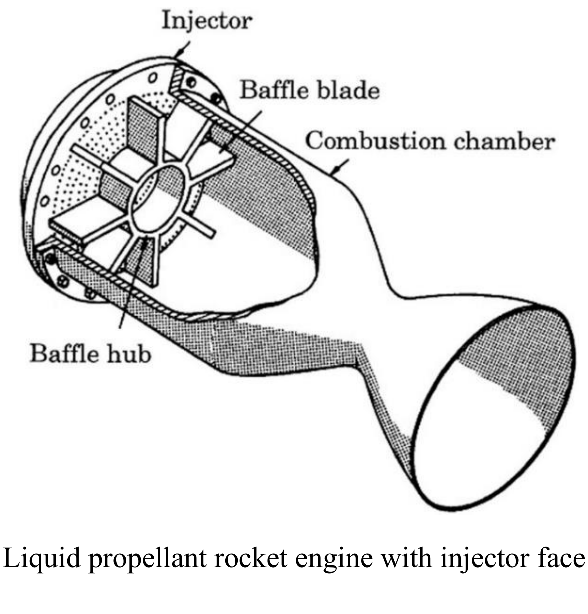


Figure 18. Liquid propellant rocket engine with injector face baffles.[10]

Figure 19. Pressure-swirl nozzles ensure fine droplet formation and even coverage, making them ideal for large-scale farming operations. (Credit: John Deere)

9 Conclusion

Experimental study on atomization of aqueous Carbopol gels—0.1 wt.%, 0.20 wt.% and 0.35 wt.% using a pressure-swirl atomizer is conducted and compared with atomization of water. The study presents atomization at an injection pressure range of 1—8 bars at atmospheric conditions. Liquid sheet breakup length, spray cone angle, coefficient of discharge, and droplet size distribution are measured and presented as a function of gel composition and injection pressure. The key conclusions are listed below:

1. Water forms a stable hollow-cone spray with fine droplets, showing early breakup.0.10 wt.% Carbopol gel forms a thicker spray sheet with longer ligaments and delayed breakup, while 0.35 wt.% Carbopol gel shows poor atomization at low pressures, forming narrow filament-like jets and coiled ligaments. With the increase in the injection pressure, gel sprays achieve conical shape, but still show delayed atomization compared to water. Gels concentrations 0.20 wt.% and 0.35 wt.% due to its higher viscosity and yield stress hinders atomization.

2. The water, Carbopol gel 0.10 wt.% and Carbopol gel 0.35 wt.% show increasing mass flow rate with pressure. Carbopol gels initially resist flow; shear-thinning behaviour improves flow at higher pressure. Water maintains a steady C_d, gels have lower $C_d$at low pressure. Higher pressures improve $C_d$for gels as internal resistance reduces.

3. Breakup length decreases with increasing flow for all fluids. Carbopol gels have longer breakup lengths at low flow, indicating resistance to atomization. Cone angle increases with flow rate; water achieves the widest angles.0.35% gel shows the narrowest angles due to high viscoelastic resistance. Droplet size is smallest at the spray centre and larger near the edges. Higher gel concentration and lower pressure result in coarser droplets overall.

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