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Investigation on Pressure Loss and Spray Angle on Different 3D-Printed Helical Swirl Injectors

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Abstract

The performance and stability of liquid rocket engines heavily rely on the behavior of the injector. Achieving an effective chemical reaction and highly efficient homogeneous fuel mixture within a minimal chamber length is a major challenge. This requirement extends to various modern combustion systems such as chemical industrial plants, heating systems, and engines, placing extreme demands on injection equipment.

This article presents a concept for a Swirler injector for the oxidizer that utilizes helical swirlers with different angles, lengths, and positions within the injector. The design of this system draws on the DLR Lampoldshausen's expertise in porous injection technologies, with potential future applications in the DLR LUMEN Technology Demonstrator.

To evaluate the performance of the system, tests were conducted at the Water Test Laboratory at DLR Lampoldshausen using water as a simulation of liquid oxygen (LOX) behavior at various pressures (ranging from 0 to 20 bar). High-speed cameras (Chronos CR21-1.0-16C) were employed for shadowgraphy imaging to visualize the spray angle at the injector post orifice and study atomization. Pressure measurements were taken using static pressure sensors at the LOX-Dome and directly before the swirler to assess the influence of pressure loss caused by the swirler in relation to the raw surface condition of the 3D-printed injector.

The helical swirlers were differentiated based on the swirler angle (15, 30, and 45 degrees), swirler length (full turn / 360 degrees or half turn / 180 degrees), and swirler position (entry, middle, and exit) within the injector.

1. Introduction

Liquid oxygen (LOX) and liquid hydrogen (LH2) have been extensively utilized as propellants in liquid propellant rocket engines (LPREs) in the USA and Europe, primarily due to their high specific impulse compared to other fuels. However, there is an increasing inclination towards exploring alternative fuels that are more cost-effective and easier to handle. Liquid methane (CH4) is emerging as one of the viable options, particularly in light of the goal of a Mars landing.

Injectors play a crucial role in LPREs as they directly influence flame anchoring, combustion stability, system pressure, and combustor length. Therefore, there is always an interest in finding improved injector types.

At the German Aerospace Center (DLR) in Lampoldshausen, Germany, a new type of porous injector called the Advanced Porous Injector (API) has been tested with LOX/LH2 and has shown good atomization, indicating the possibility of reducing the length of the combustor chamber.[3]

Using the API as an injector for CH4 could yield interesting results, although some modifications would be necessary for the LOX injectors to enhance atomization, considering the slower flame propagation velocity compared to LH2 and its higher density.

This work presents experiments conducted with eight small diameter swirl injectors using different helical swirler inserts, varying in swirler angle, length, and position. The setup was tested at the Water Test Laboratory at DLR Lampoldshausen, using water as a simulation of LOX behavior at different pressures ranging from 0 to 20 bar. High-speed imaging using shadowgraphy was employed to understand the atomization process.

The paper will begin by explaining the theory behind swirl injectors with fins. This will provide a background understanding of the principles involved in their operation and the benefits they offer.

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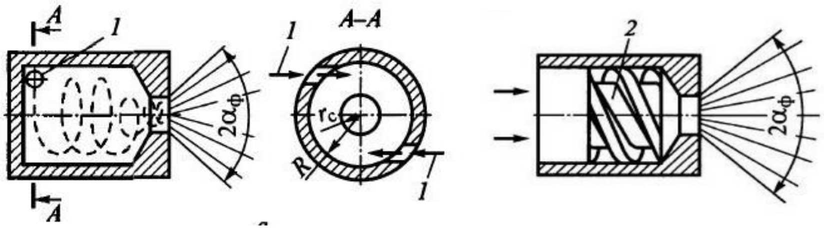
Following the theoretical explanation, the paper will proceed to describe the experimental setup used for the injectors and the accompanying test-bench. This section will outline the apparatus, instrumentation, and procedures employed to conduct the experiments and gather data.

Finally, the paper will present the results obtained from both conventional and optical data analysis. This will include the findings and observations derived from the experimental measurements, providing insights into the performance and characteristics of the injectors.

2. Theory

Swirl injectors are widely used in the aerospace industry due to their effective mixture capabilities for high-energy fuels.[4] There are two main types of swirl injectors. The first type utilizes tangential holes at the base of the injector to create a vortex, while the second type incorporates swirler inserts. The latter type is commonly used for gas fluids in turbines , as shown in figure 1.



(a) Swirler with radial entry holes (b) Swirler with insert

Figure 1: Schematics of different swirler injectors

In this particular case, a insert swirler type was chosen for the injector due to its small diameter size, length, and the complexity of manufacturing. A helical swirler was designed to generate angular momentum for the oxidizer, LOX.

For this type of injector, the final cone angle of the spray in the combustion chamber can be calculated using Equation 1.

$$\alpha = arctan(\frac{w}{u}) = arctan(\frac{3}{2}SN) \tag{1}$$

The Swirl Number (SN) is a dimensionless number that characterizes the rotating flows[1,2] and can be defined as seen in Equation 2.

$$SN = \frac{G_{tan}}{G_{ax}R} = \frac{\frac{2}{3}\pi R^3 uw}{R\pi\rho R^2 u^2} = \frac{2}{3}\frac{w}{u} = \frac{2}{3}\left[\frac{1-(D_h/D_t)^3}{1-(D_h/D_t)^2}\right] tan(\beta) \tag{2}$$

For this research with swirlers, disregarding friction losses with the injector wall, the final angle of the spray (α) is the same angle as the swirler fin angle itself (β). This can be obtained correlating equation 1 with equation 2, in this concept $\beta = 45°$. []

$$\alpha = \beta \tag{3}$$

However the Equation 3 can only be used in swirlers with a constant fin-angle (β) along the radius. Due to the nature of the helix form, it is noted that at the center of the swirler ($r_0 = 0$) no angular momentum is achieved, $\beta = 0°$ and only at the extremities of the insert (r_1 = 0,75 in this concept) a maximum in momentum can be obtained, in this case $\beta = 45°$. For this reason to achieve a equivalent value for β an interpolation is needed as seen in equation 4

$$\alpha = \beta_{eq} = \frac{\int_{r_0}^{r_1} 2\pi r^2 sin(\beta)}{\pi R^2} \tag{4}$$

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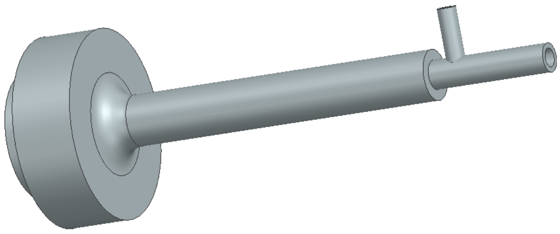
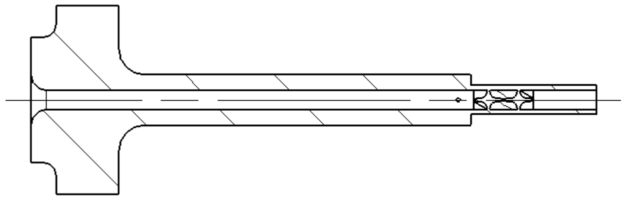
3. Experimental Setup

3.1 Injectors

Figure 2 shows a 3D schematic and a 2D cutaway view of the injectors used in this study. Specifically, it depicts an injector with a 45° swirler positioned 5 mm away from the injector tip. This particular injector is one of the eight injectors tested during the campaign. All injectors were manufactured using Additive Layering Manufacturing (ALM) due to the complexity of their design. The dimensions of the injectors are provided in Table 1.



(a) 3D view



(b) 2D cut view

Figure 2: Design of a 45° swirler injector tested

Table 1: Swirler injector dimensions

	15	15 Short	30	30 Short	45	45 Short	45 Inlet	45 Middle
Swirler Angle, β (°)	15	15	30	30	45	45	45	45
Fin thickness (mm)	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2
Swirler length (mm)	17,8	8,9	8,3	4,15	4,8	2,4	4,8	4,8
Distance swirler to tip (mm)	5	5	5	5	5	5	37	20
Total injector length (mm)	45	45	45	45	45	45	45	45

3.2 Test-bench

Figure 3 provides a schematic overview of the experimental setup employed for the test. In this setup, water was pressurized to 70 bar and transported through the designated lines until it reached the dome and injector.

To visualize the spray angle at the injector post orifice, a high-speed camera (Chronos CR21-1.0-16C) with a frame rate of 1000 frames per second (fps) was employed for Shadowgraphy imaging. This technique enabled the study of the spray angle by capturing and analyzing the shadows produced by the spray.

Pressure measurements were conducted using static pressure sensors. These sensors were positioned at the LOX-Dome and directly before the swirler in the injectors. It is important to note that for the injector with the swirler insert at the beginning (45°-Inner), no separate measurement for the swirler was made, as the measurement would have been taken at the same location. However, a pressure measurement for the swirler was conducted to assess the influence of pressure loss caused by the swirler's raw surface condition resulting from the ALM manufacturing process.

4. Results

4.1 Conventional Data

Figure 4 illustrates the pressure loss observed for all eight tested injectors. As anticipated, the injectors equipped with a 45° swirler exhibited the highest pressure loss among the different injector designs. Additionally, the position of the swirler insert also played a significant role in determining the pressure loss. A comparison of the three different positions for the 45° swirler (Inlet, Middle, and Normal/Tip) revealed distinct variations in pressure loss.

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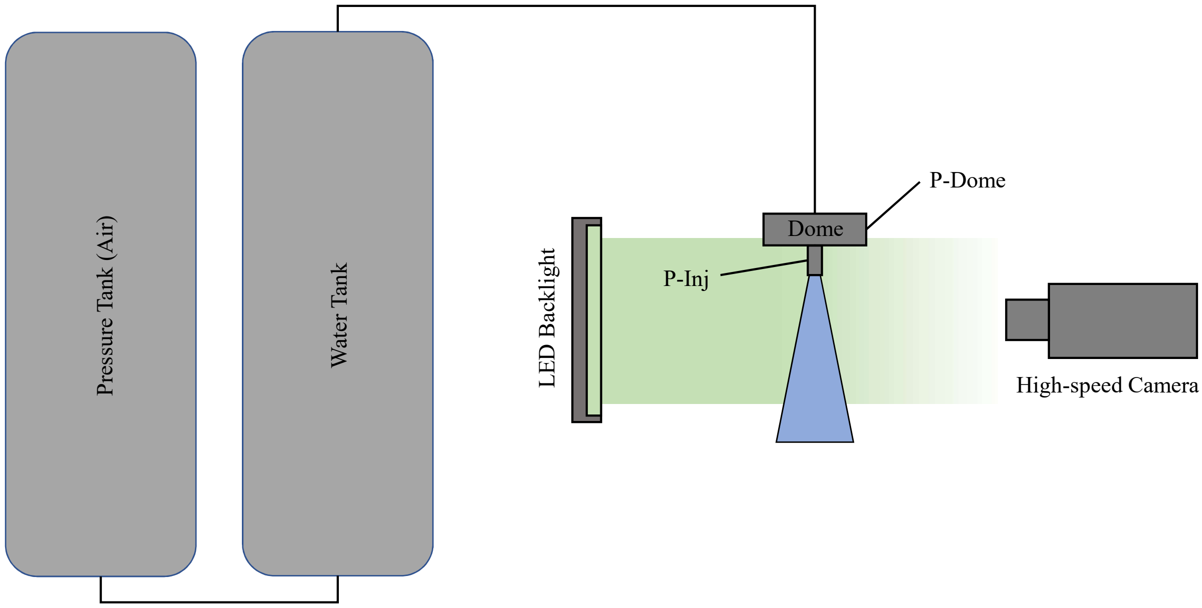

Figure 3: Schematic overview of experimental setup at the water test-bench

Interestingly, it is worth noting that the 15° and 30° injectors displayed almost identical pressure loss curves. A similar behavior was observed for the 15° Short and 30° Short injectors, further emphasizing the consistency in the pressure loss patterns for these designs.

In Figure 5, the pressure loss generated by the swirler itself for all eight tested injectors is depicted. It is important to note that for the injector with a 45° swirler at the inlet, no separate measurement for the swirler was taken. This is because the pressure loss of the swirler itself is equivalent to the measurement taken at the dome. Consequently, the values for this injector are consistently zero in the graphic.

As anticipated in the previous figure, the 45° swirlers produced the highest pressure loss among all the designs. However, an interesting observation is that both the 15° short and 30° short swirlers generated nearly identical pressure losses. This can be attributed to the longer length of the 15° short swirler compared to the 30° short swirler. The increased friction caused by the raw surface of the fins compensates for the lower pressure loss resulting from the lower angle β of the swirler. The swirler dimentions can be seen at Table1.

A similar effect can be seen in the case of the 15° and 30° swirlers, where the 15° swirler generated a higher pressure loss than expected. This further emphasizes the significant role played by the friction between the swirler angle β and the inner walls in determining the pressure loss.

4.2 Optical Data

To determine the cone angle of the liquid spray (α), shadowgraphy imaging was utilized. Figure 6 presents the optical data in this paper, with the images shown corresponding to the main load point at a mass flow rate of 0.035 kg/s. This specific operating condition was chosen as the reference for analyzing and studying the cone angle of the liquid spray.

As observed in Figure 6, there is minimal variation in the spray cone angle (2α) between the swirlers and their corresponding short variants. However, it is crucial to note that for 30° and 45° swirlers the short variants did not

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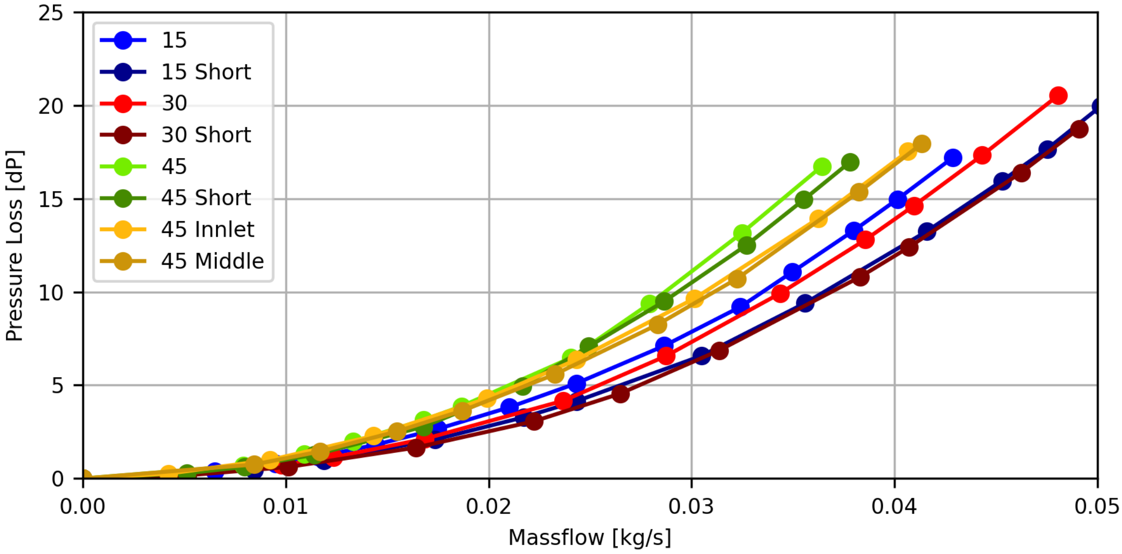

Figure 4: Injector pressure loss

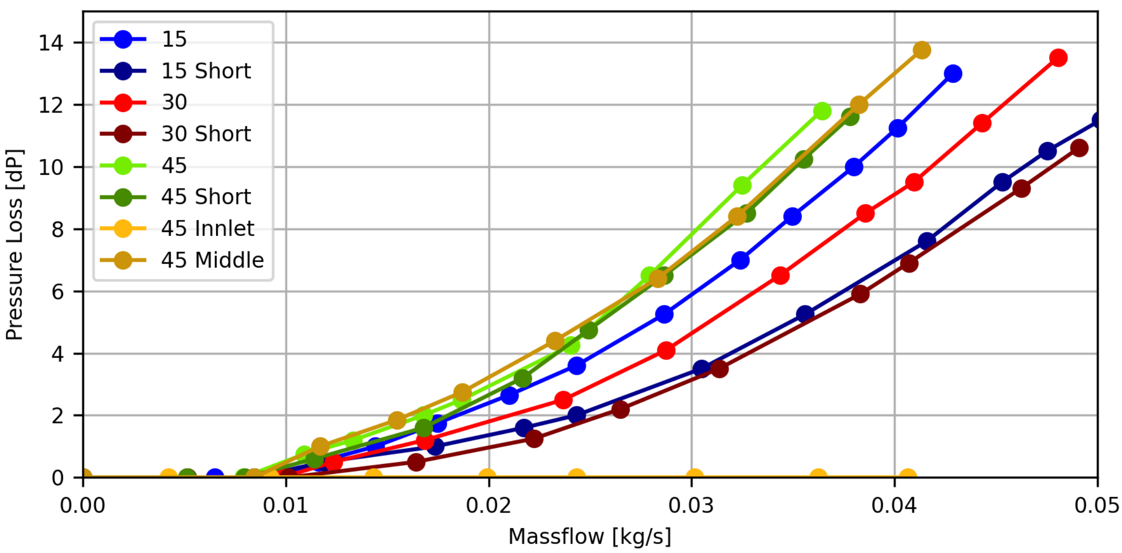

Figure 5: Swirler pressure loss

Table 2: Spray angle 2α

	15	**15 Short**	**30**	**30 Short**	**45**	**45 Short**	**45 Inlet**	**45 Middle**
Spray Angle, 2α (°)	15	15	35	38	45	52	10	24

produce the same level of atomization as their original counterparts, as depicted in Figures 6(d), and 6(f). A comparison can be made with the atomization achieved by the original swirlers, as shown in Figures 6(c), and 6(e), respectively.

For the 15° swirlers, the same level of atomization can also be observed in its short variant, as seen in Figure 6(a) and 6(b). This could be attributed to the longer length of the swirler compared to the lengths of the other short swirlers. The fluid has a longer path to acquire angular momentum compared to the 30° short and 45° short swirlers.

For the 45° inner swirler, almost no cone angle could be observed, as shown in Figure 6(g). This effect can be explained by the long distance that the fluid has to travel before reaching the injector exit. The rough surface of the injector reduces the angular velocity of the fluid due to friction. As a result, most of the angular momentum is lost, and

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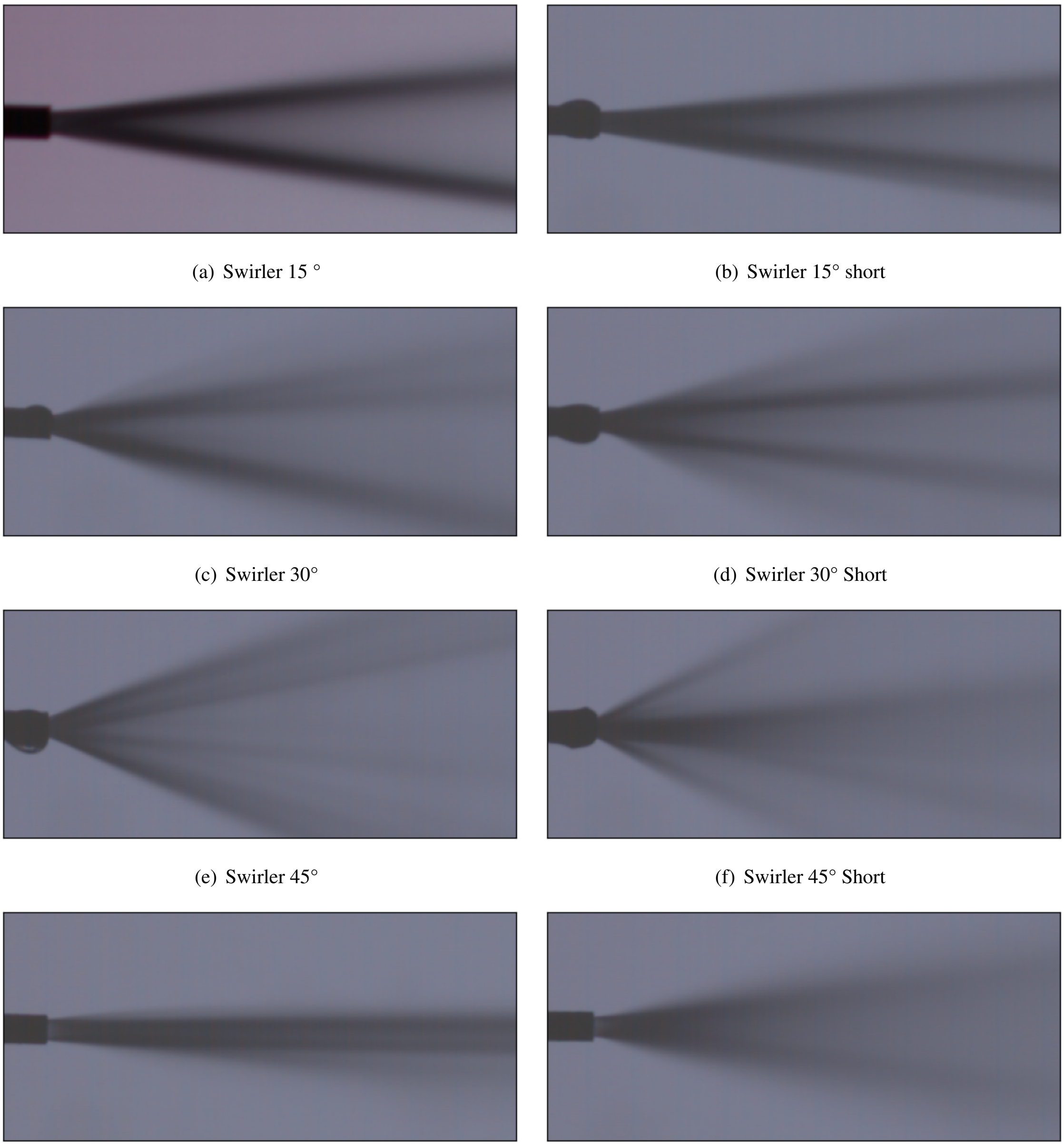

(a) Swirler 15 °

(b) Swirler 15° short

(c) Swirler 30°

(d) Swirler 30° Short

(e) Swirler 45°

(f) Swirler 45° Short

(g) Swirler 45° Inlet

(h) Swirler 45° Middle

Figure 6: Image of injectors spray

the spray resembles that of a conventional axial injector.

For the 45° middle swirler, a similar effect can be observed, as shown in Figure 6(h). The spray cone angle is significantly reduced, around 50% as seen in Table 2, due to friction between the fluid and the inner wall of the injector. An interesting effect to note is that the atomization of this injector is the best among all variants of the 45° swirlers. This can be explained by the fact that a certain length is needed to minimize the impact of the fin thickness on the fluid, resulting in a smoother spray.

5. Conclusion and Outlook

This manuscript presents an experimental study conducted at the water test laboratory at the Institute of Space Propulsion in Lampoldshausen, Germany. The objective of this test campaign was to analyze the pressure loss and spray angle of the fluid (2α) at the exit of the injectors using sensor and optical analysis. As anticipated, the 45° swirler exhibited the highest spray cone angle, but also demonstrated the highest pressure loss when compared to the other injectors. This study serves as the initial stage in the development of an 80mm porous injector head for LOX/CH4. Currently,

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the injector head is undergoing testing for a deep throttling liquid rocket engine, which will be utilized in the future LUMEN Project at the German Aerospace Center in Lampoldshausen.

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