

Evolution of Hydrogen Injection in Sub- and Super-critical Argon Environments

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ABSTRACT

An experimental investigation of hydrogen injection in an argon ambient was conducted within a constant volume combustion chamber (CVCC), with the ambient spanning both subcritical- and supercritical-Ar conditions. The test condition matrix comprised low-pressure low-temperature (LPLT) Ar (2–10 bar, 423 K) and high-pressure high-temperature (HPHT) Ar (22.8–53.5 bar, 1111–2520 K) environments. H₂ (150 bar, 423 K) was injected via an outward-opening hollow-cone injector under choked-flow conditions. Temporal evolution of the jet morphology was captured using Schlieren and quantified via axial penetration, jet width, jet area, and the width-to-penetration ratio as a metric for self-similarity. Under LPLT conditions, the jet transitioned from a near-field conical structure to an approximately cylindrical main body, with all spatial dimensions decreasing as chamber pressure increased; the penetration and width evolutions followed universal power-law correlations with time, while the width-to-penetration ratio evolution universally decreased with time, converging to ~0.5 after 1.5 ms after start of injection (ASI). Conversely, the HPHT jet morphology assumed a more globally conical structure in the late injection stages. At identical ambient densities, non-reacting injections under supercritical-Ar ambient conditions exhibited 20% shorter axial penetration, 10% smaller jet width and 20% smaller jet area compared to HPHT subcritical-Ar ambient conditions. Combustion in supercritical-Ar environments only increased the jet width by ~10% after ASI = 2.5 ms with negligible impacts on penetration or area; in contrast, it enhanced all structural parameters for injections with subcritical-Ar ambient. The width-to-penetration ratio was independent of combustion for all HPHT conditions; while its evolution for injections with subcritical-Ar ambient was identical to LPLT results, it exhibited higher values for injections with supercritical-Ar ambient with a converged value of ~0.6 at larger ASIs. Ultimately, the heightened complexity of jet evolution under HPHT conditions precludes description of penetration and width evolutions by simple power-law scaling, highlighting the significant impact of the near-critical ambient conditions.

1. Introduction

Hydrogen is expected to play a crucial role in the world's transition to a decarbonized future (Tingas, 2023). It has the potential to fuel future zero-emission gas turbines for power generation, which operate with oxy-combustion – therefore mitigating NO_x emissions – and uses supercritical

fluids (SCFs) as the working medium – hence significantly increasing the cycle efficiency and reducing system footprint (Oleś et al., 2025; Vesely et al., 2024). Both hydrogen and oxygen can be generated from water electrolysis using surplus green electricity, and the only product from oxy-combustion is water, which can be easily separated from the working fluid via condensation and recycled (Vesely et al., 2024).

A wide range of SCFs have been proposed for supercritical gas turbine systems, including CO₂, xenon (Xe) and argon (Ar) (Hodgson et al., 2021; Oleś et al., 2025; Sabatino et al., 2024; White et al., 2021). Although CO₂ has been selected as the working fluid in many supercritical power cycles, it poses potential corrosion issues (Coco Enríquez et al., 2016; Teeter et al., 2021) that can incur higher material costs. These challenges can be mitigated by utilizing inert noble gases, such as Xe and Ar. Furthermore, Oleś et al. (2025) demonstrated that Ar provides better cooling performance compared to Xe, thereby more effectively reducing peak temperatures within the power system and preventing potential overheating issues. An additional advantage of Ar over Xe is its substantially lower cost. Consequently, a gas turbine power system operating with H₂ oxy-combustion and supercritical Ar as the working fluids presents a promising low-cost, high-efficiency and zero-emission solution for future power generation.

A critical component of such supercritical gas turbine systems is the H₂ combustion process within SCF. Since H₂ exhibits substantially wider flammability limits and higher flame speeds than conventional hydrocarbon fuels (Zhou et al., 2024), it is typically introduced into the combustor separately from oxygen to eliminate the risk of flashback. Therefore, developing a fundamental understanding of H₂ injection and mixing dynamics within SCF is vital for the optimization of combustor design and operation.

Nevertheless, most of the existing literature on hydrogen injection only covers ambient conditions involving subcritical fluids. For example, Wang et al. (2020) examined the evolution of hydrogen injection via an outward-opening hollow-cone injector into nitrogen environments at pressures up to 4 bar. They underscored the dependence of jet morphology on the ratio of fuel pressure to ambient pressure, with higher pressure ratios enhancing both jet penetration and volume, and proposed a universal power-law trend for the correlation of axial jet penetration with time. Yeganeh et al. (2023) reported similar structural changes with pressure ratio for H₂ injection into nitrogen at pressures up to 20 bar, though they highlighted that the jet morphology is not solely governed by the pressure ratio but is also independently influenced by the injection and ambient pressures. Additionally, Deng et al. (2018) investigated H₂ injection via a single-hole injector into subcritical Ar environments at pressures up to 12 bar, noting that increasing the injection and ambient pressures enhanced the jet spread angle and the entrainment of ambient fluids.

Although these studies provide valuable insights into high pressure H_2 injection, the applicability of their findings to supercritical gas turbine power systems requires further validation, because the thermodynamic properties of the ambient fluid can change dramatically near the critical point, which, for argon, is $P_c = 49.0$ bar and $T_c = 150.9$ K (Linstrom & Mallard, 2025). To bridge this gap, this study established high-pressure high-temperature (HPHT) Ar environments – spanning both subcritical and supercritical Ar conditions – in a CVCC, into which H_2 was introduced through an outward-opening hollow cone injector. Highspeed Schlieren imaging was used to record the injection evolution, which was then quantified using metrics including axial penetration, jet width, jet area and width-to-penetration ratio. The HPHT injection evolution was compared to the results obtained within low-pressure low-temperature (LPLT) Ar environments, highlighting the impact of ambient conditions – especially the presence of supercritical Ar – and of the occurrence of hydrogen combustion on the injection evolution.

2. Experimental method

The experimental setup is schematically demonstrated in Fig. 1. The CVCC used in this study is a cuboidal chamber with an internal volume of approximately 1.5 L. Optical access to the chamber, from up to three different directions, is enabled by Fused Silica windows with a clear aperture of 100 mm. Four electrical heaters are integrated in the CVCC walls, enabling temperature control of the wall – and hence of the optical window – ranging from room temperature to about 200 °C. The wall temperature was maintained at 150 °C in this study, with the main purpose of preventing condensation of combustion-produced water on the window surface. The target high-pressure high-temperature (HPHT) argon environments for H_2 injection were created in the CVCC by the pre-burn of specific gas mixtures of $CH_4/O_2/Ar$, similar to the method used in (Skeen & Yasutomi, 2018; Yip et al., 2020). The partial pressure of Ar and the concentration of O_2 for the target injection condition can be accurately controlled by the composition of the gas mixture used for pre-burn. The composition of the pre-burn mixture is controlled during the CVCC charging process using the partial pressure method, enabled by mass flow controllers (MFCs) in the gas supply lines and a high precision pressure sensor (PWF-10MPa, Tokyo Measuring Instruments Lab) installed in the CVCC body. The pre-burn in this study was initiated using a glow plug.

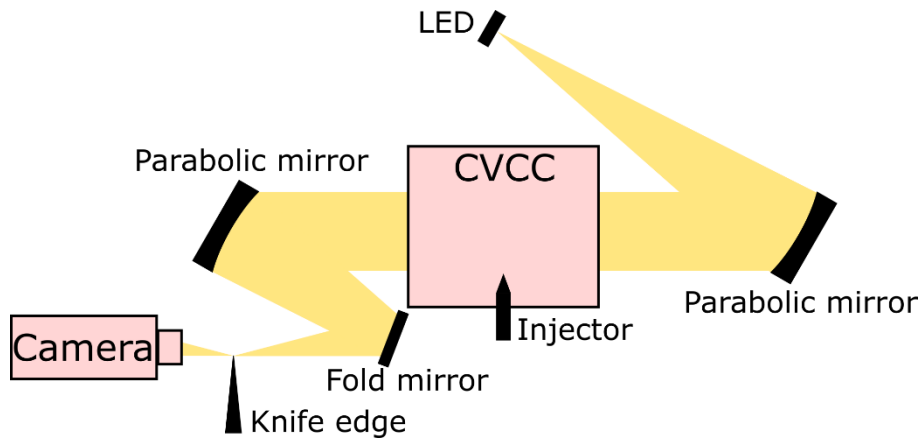


Fig. 1 Schematic of experimental setup for highspeed Schlieren imaging of hydrogen injection in the constant volume combustion chamber (CVCC)

Hydrogen was pressurized to the target injection pressure using piston accumulators and injected into the CVCC using an outward-opening hollow cone injector (HDEV-4-2, Bosch). Fig. 2 provides a cross-sectional view of the injector nozzle. The nozzle outlet is a conical annulus with a 90° cone angle. More technical details of the injector can be found in (Robert Bosch GmbH, 2022). The injector was installed with its axis in the horizontal direction, and it was driven by a direct injection module (NI9751, National Instruments) with a voltage of 135 V and a current within 7 – 8 A. The needle lift of the injector was 35 μm , measured using highspeed shadowgraph. Given that the chamber pressure gradually reduced with time after the pre-burn event, the initiation of H_2 injection at the target chamber pressure was enabled by monitoring the chamber pressure after pre-burn at 50 kHz with a piezo pressure transducer (6041AU20, Kistler). The injection duration was fixed at 5 ms.

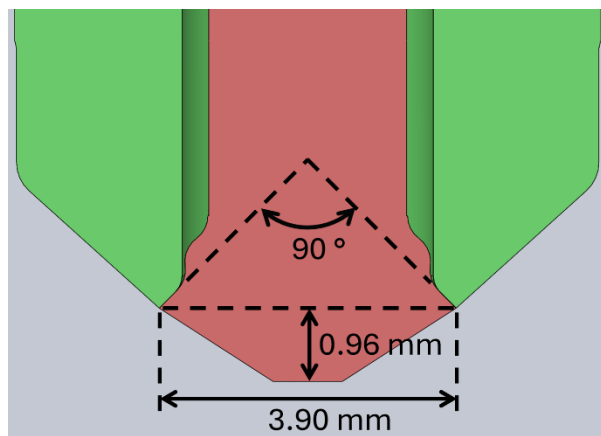


Fig. 2 Cross-sectional view of the injector nozzle with dimensions

Hydrogen injection was visualized using highspeed Schlieren imaging, which used the Z-type setup as shown in Fig. 1. More details about the theory of Schlieren imaging can be found in (Settles, 2001). The illumination source was a high-power green LED (PT-121-G-L11-MPN, Luminus Devices) with a single emitting element of 4 mm x 3 mm. The two f/8 parabolic mirrors have a diameter of 152 mm. The collimated light between the two mirrors travelled perpendicular to the injector axis. The converging light after the second parabolic mirror was directed, with the aid of a fold mirror, to a knife edge that was parallel to the injector axis. A highspeed camera (FASTCAM SA1.1, Photron), fit with a Nikon zoom lens (70 – 300 mm, f/4 – 5.6G), was used to record Schlieren images. It had a field of view of 104 x 69 mm² with a pixel resolution of 135 $\mu\text{m}/\text{pixel}$. The camera and the LED illumination were synchronized to a frequency of 15 kHz with the camera exposure being less than 2.5 μs for effective “freezing” of the flow.

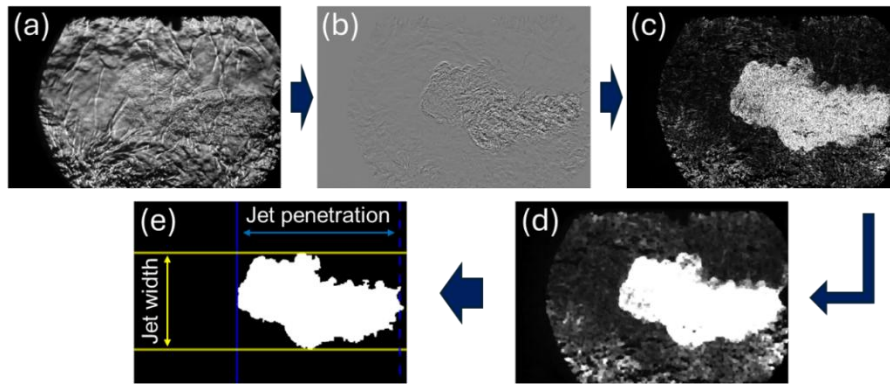


Fig. 3 Boundary detection procedure of instantaneous Schlieren images of the injected hydrogen jet: (a) original Schlieren image; (b) background corrected image; (c) intensity truncated image; (d) morphologically processed image; (e) binary image.

Instantaneous Schlieren images were processed using MATLAB to characterise the temporal and spatial evolution of the injected hydrogen, as demonstrated in Fig. 3 with an example of injection in HPHT environment. The original Schlieren images (Fig. 3a) demonstrated complex structures in the whole chamber, making it difficult to distinguish the boundary of the hydrogen jet. These structures were formed after the pre-burn due to the temperature gradient in the ambient gases and in the boundary layers near the optical windows. However, because of the slow movement of these structures and the high imaging frequency of the Schlieren measurements, there was little change in these structures between temporally adjacent images. Therefore, these structures can be effectively removed by subtracting the preceding image (Pickett et al., 2009), as shown in Fig. 3b. The resulting image was then truncated in intensity to emphasize the low-intensity regions (Fig. 3c) and morphologically processed with a series of morphological dilation and erosion (Fig. 3d).

Eventually, the image was binarized using a threshold determined with Otsu's method (Otsu, 1979), followed by object area filtering to extract the largest object (Fig. 3e). From the binary image, the hydrogen jet characteristics – such as jet penetration, jet width and jet area – can be evaluated. The jet penetration is defined as the maximum axial distance between the jet boundaries and the injector nozzle, the jet width represents the maximum radial distance between the jet boundaries, and the jet area is the area enclosed by the jet boundaries.

Table 1 lists the injection conditions tested in the present study. For Cases 1 – 3, the CVCC was charged with pure argon, and helium (He) was used as a safe surrogate for H₂. These conditions examine the effect of ambient pressure on the injection evolution in low-pressure low-temperature (LPLT) environments. The suitability of He as a surrogate for H₂ injection investigations has been evaluated by Coratella et al. (2025) and was found sensitive to the pressure ratio (PR, ratio of fuel pressure and ambient pressure). Nevertheless, for the injector used in this study, Rolke et al. (2022) and Fleischmann et al. (2025) compared the jet morphology of H₂ and He with PRs up to 100, and both studies reported insignificant differences in jet penetration and volume. For injections into HPHT environments (Cases 4 – 7), the pre-burn of CH₄/O₂/Ar mixtures was used with its composition specified using mole fractions in Table 1. Given that the critical pressure ratios for choked flows of H₂ and He are 1.899 and 2.049 respectively, the PRs listed in Table 1 indicate that the injection flow was choked at the injector nozzle for all test conditions examined in this study.

Table 1 Summary of test conditions. P_{charge} – CVCC charge pressure; Q_{charge} – density of charged mixture; mixture – composition of charged CH₄/O₂/Ar mixture, specified in mole fraction; P_{fuel} – fuel pressure; P_{inj} – chamber pressure at injection; PR – pressure ratio; T_{inj} – chamber temperature at injection; T_r – reduced temperature for Ar, $P_{\text{Ar, inj}}$ – partial pressure of Ar at injection; P_r – reduced pressure for Ar, $X_{\text{O}_2, \text{inj}}$ – mole fraction of O₂ at injection, evaluated based on assumption of complete reaction. *Bulk temperature derived from chamber pressure based on ideal gas law.

§Supercritical Ar condition.

Case	P _{charge} (bar)	Q _{charge} (kg/m ³)	Mixture			P _{fuel} (bar)	P _{inj} (bar)	PR	T _{inj} (K)	T _r	P _{Ar, inj} (bar)	P _r	X _{O2, inj}
			CH ₄	O ₂	Ar								
1	2.0	2.3	-	-	1.00	150 (He)	2.0	75	423	2.8	2.0	0.04	-
2	5.0	5.7	-	-	1.00	150 (He)	5.0	30	423	2.8	5.0	0.10	-
3	10.0	11.4	-	-	1.00	150 (He)	10.0	15	423	2.8	10.0	0.20	-
4	11.3	11.8	0.07	0.16	0.77	150 (H ₂)	67.0	2.2	2520*	16.7	51.4 [§]	1.05	0.03
5	11.3	12.0	0.07	0.13	0.80	150 (H ₂)	67.0	2.2	2509*	16.6	53.5 [§]	1.09	0
6	11.3	11.9	0.07	0.16	0.77	150 (H ₂)	30.0	5	1120*	7.4	22.8	0.47	0.03
7	11.4	12.1	0.07	0.13	0.80	150 (H ₂)	30.0	5	1111*	7.4	23.7	0.48	0

3. Results and discussion

In this section, we first present in subsection 3.1 the injection results in LPLT Ar environments, quantify the temporal evolution of jet morphological features and attempt to derive a universal correlation for evolutions of axial penetration and jet width across different injection conditions. Subsection 3.2 then presents the injection results in HPHT Ar environments in comparison to the LPLT results, demonstrating the influence of supercritical fluids and of hydrogen combustion.

3.1 Injections in low-pressure low-temperature Ar environments

Fig. 4 shows representative Schlieren images of He injection into pure argon, with a fixed ambient temperature of $T_{\text{inj}} = 423$ K. He was pressurised to $P_{\text{fuel}} = 150$ bar, whereas three different ambient pressures, $P_{\text{inj}} = 2, 5$ and 10 bar, were examined, leading to pressure ratios of $PR = 75, 30$ and 15 respectively. The timestamps on the images indicate the time after the start of injection (ASI). Red, blue and yellow lines mark the jet boundary, axial penetration and radial penetration, respectively. Note that these tests did not involve pre-burn in the CRU, so these Schlieren images do not have the strong background structures as indicated in Fig. 3.

Some common morphological features can be found for all three injection conditions. In the near field (i.e., near the injector outlet), the jet showed a conical appearance, which is a result of the conical annular geometry of the injector nozzle (Fig. 2). In the far field, the jet presented an approximately cylindrical shape. The cylindrical body was formed due to the jet collapsing towards the central axis, which has been reported for injections of various gases (including H_2 , He, CH_4) with a similar injector geometry (Fleischmann et al., 2025; Kuensch et al., 2014; Wang et al., 2020; Yeganeh et al., 2023). The cause for the collapsing was revealed in a numerical study by Kim et al. (2004) to be the pressure gradient, which was induced by the vortices in the near-field of the jet.

When the ambient pressure increased (or equivalently the PR reduced), the spatial extent of the conical structure in the near field reduced. Given that the initial momentum of the jet at the nozzle exit was the same for the three conditions due to the choked flow condition and the same injection pressure, this variation in the conical structure can be ascribed to the increased drag imposed by the ambient fluid, as a result of the increased ambient density at higher ambient pressures.

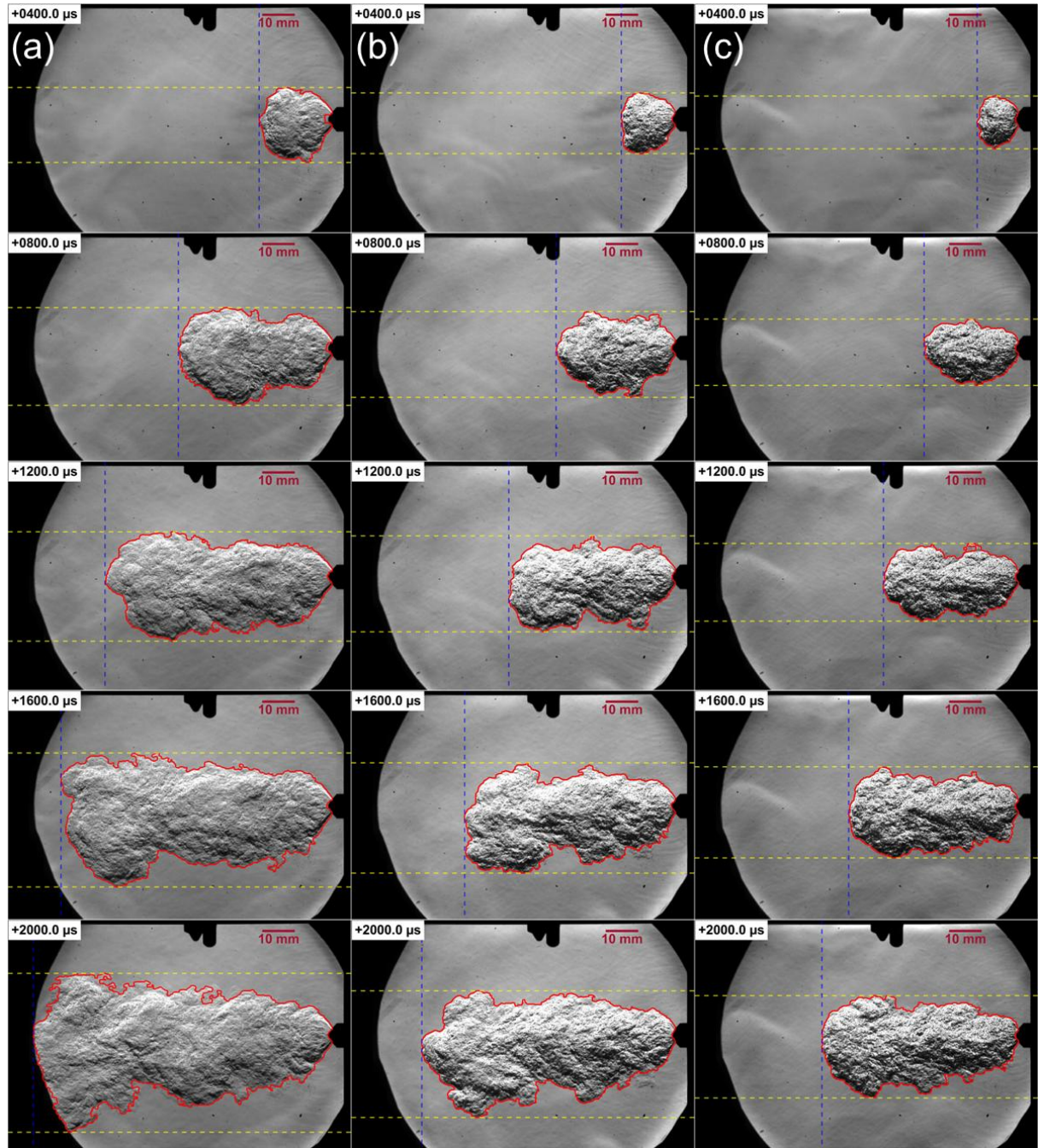


Fig. 4 Temporal and spatial evolution of helium jet in pure argon environment at different ambient pressures (a) $P_{inj} = 2$ bar; (b) $P_{inj} = 5$ bar; (c) $P_{inj} = 10$ bar. For all conditions, $T_{inj} = 423$ K, $P_{fuel} = 150$ bar, injection duration 5 ms. The conditions are those of Cases 1 – 3 in Table 1.

The increased drag by the ambient fluid at higher ambient pressures also hindered the jet penetration, both in the axial and radial directions, as shown qualitatively in Fig. 4 and quantitatively in Fig. 5. Note that the results in Fig. 5 only include penetration data before the jet axial penetration reached the edge of the field of view allowed by the optical window (see Fig. 4). Therefore, less data points are available for lower ambient pressures due to the faster axial

penetration. Compared to the jet for $P_{inj} = 2$ bar at the same ASI, the axial penetration of the jets for $P_{inj} = 5$ and 10 bar reduced by about 25% and 38% respectively, while the reductions in the jet width were about 20% and 35% respectively.

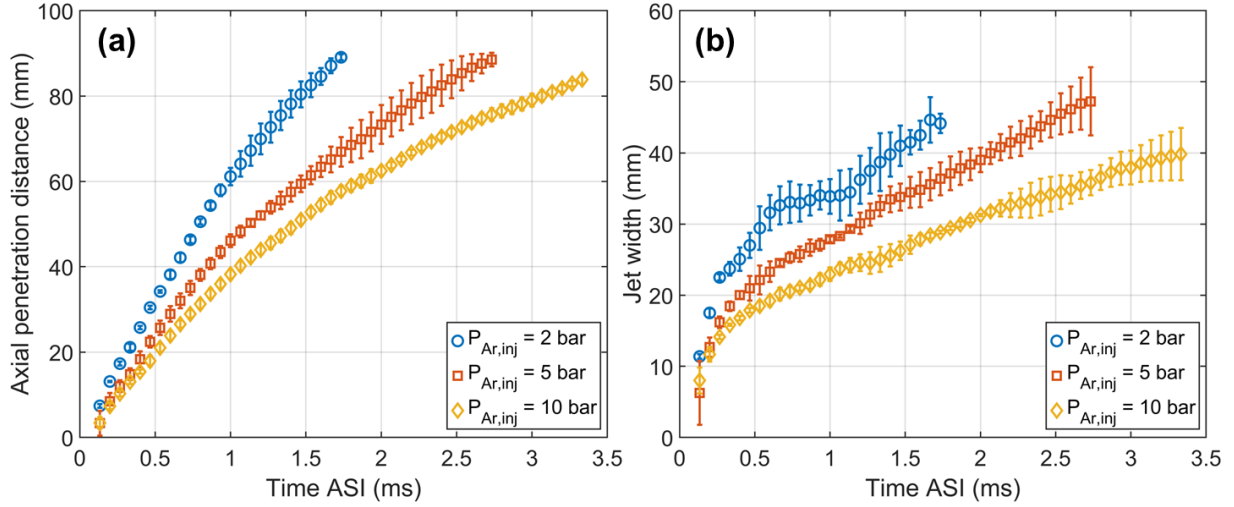


Fig. 5 Temporal variation of (a) axial penetration and (b) jet width for helium injection in pure argon environment with different ambient pressures. Symbols and error bars represent average and standard deviation of three repeated measurements. The conditions are those of Cases 1 – 3 in Table 1.

Nevertheless, the temporal profiles, of both axial penetration and jet width, for three injection conditions appear to share a similar shape, suggesting the potential existence of a universal scaling correlation between jet penetration and ASI. Such a scaling correlation for axial penetration has been proposed for gas injection with a similar injector geometry (Sankesh et al., 2018; Wang et al., 2020), which can be expressed as

$$z = \Gamma \left(\frac{\dot{M}_n}{\rho_c} \right)^{n1} ASI^{n2}, \quad (1)$$

where z is the axial penetration length, Γ the penetration constant, $\dot{M}_n$ the nozzle momentum injection rate, ρ_c the density of the ambient gas. The constants $n1$ and $n2$ were reported to be 0.25 and 0.5 respectively by Sankesh et al. (2018) for natural gas injection, and 0.18 and 0.83 respectively by Wang et al. (2020) for hydrogen injection. Although $\dot{M}_n$ was not measured here, its value should be the same for all three injection conditions given the choked flow at the nozzle exit and the same fuel injection pressure. Therefore, if Eq. (1) is valid for the conditions of this study, it would lead to the following linear correlation

$$z * \rho_c^{n1} \propto ASI^{n2}. \quad (2)$$

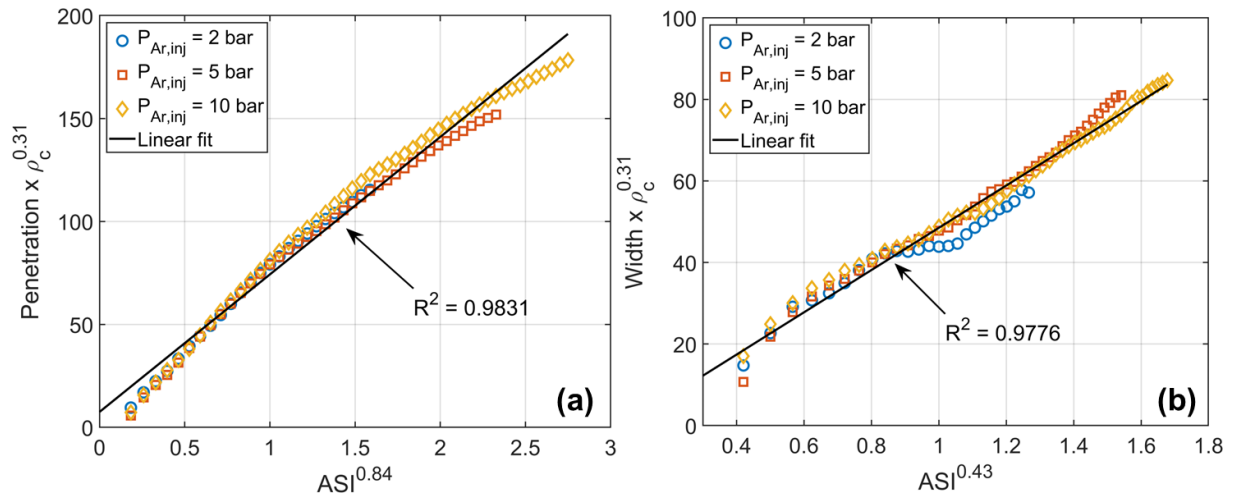


Fig. 6 Scaling relationship of (a) axial penetration and (b) jet width with respect to ASI for helium injection in pure argon environment at different ambient pressures. The conditions are those of Cases 1 – 3 in Table 1.

Such a linear correlation is found valid, with $n_1 = 0.31$ and $n_2 = 0.84$, for the axial penetration results of this study, as demonstrated in Fig. 6a. The value of n_2 is very close to the value proposed by Wang et al. (2020) for hydrogen injection, but the value of n_1 is much higher, which requires further investigation. In addition, $n_2 = 0.84$ is close to the 0.8-power-law dependence of axial penetration on ASI reported by Kuensch et al. (2014) for nitrogen injection into air. Fig. 6b shows the scaling of jet width following Eq. (2). The jet width temporal evolution for different injection conditions, with the same scaling parameter of $n_1 = 0.31$, also collapse into a single curve, but its dependence on ASI is described by $n_2 = 0.43$, which is larger than the 0.2-power-law reported by Kuensch et al. (2014).

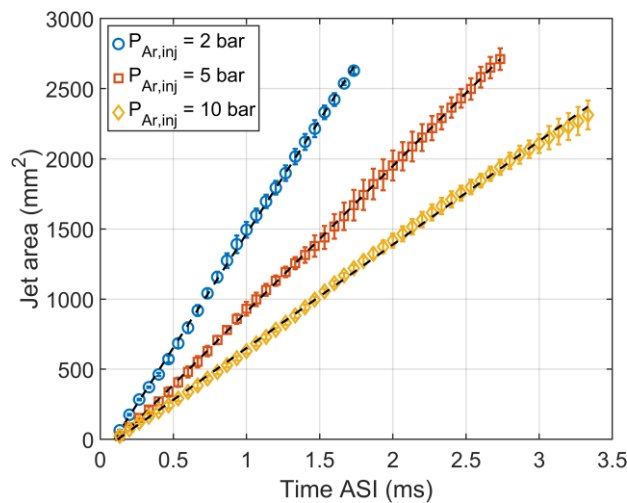


Fig. 7 Temporal variation of jet area for helium injection in pure argon environment at different ambient pressures. Symbols and error bars represent average and standard deviation of three repeated measurements. Black dashed lines represent linear fits with $R^2 > 0.99$. The conditions are those of Cases 1 – 3 in Table 1.

Fig. 7 presents the temporal evolution of the jet area for the three injection conditions. The jet area reduced with increasing ambient pressure, because of the reduced axial penetration and jet width demonstrated in Fig. 5. At the same ASI, the jet areas for $P_{inj} = 5$ and 10 bar were about 39% and 57% lower than that for $P_{inj} = 2$ bar. Given that the mass flow rate of injection was the same for different ambient pressures, if the entrainment rate of the jet is also assumed the same, the jet area reduction is expected to be 60% ($P_{inj} = 5$ bar) and 80% ($P_{inj} = 10$ bar), which is purely due to the increase in ambient pressure. The fact that the jet area reductions observed in Fig. 7 are smaller than these expected values implies that the higher ambient pressure (or equivalently, lower pressure ratio) enhances the entrainment of ambient fluids into the jet, which can be beneficial for combustion mixture preparation. Fig. 7 also shows that the jet area evolution followed a linear correlation with ASI, regardless of the ambient pressure, as demonstrated by the black dashed lines. Such a linear dependence on ASI is consistent with the results reported in (Coratella et al., 2025; Kuensch et al., 2014; Yeganeh et al., 2023).

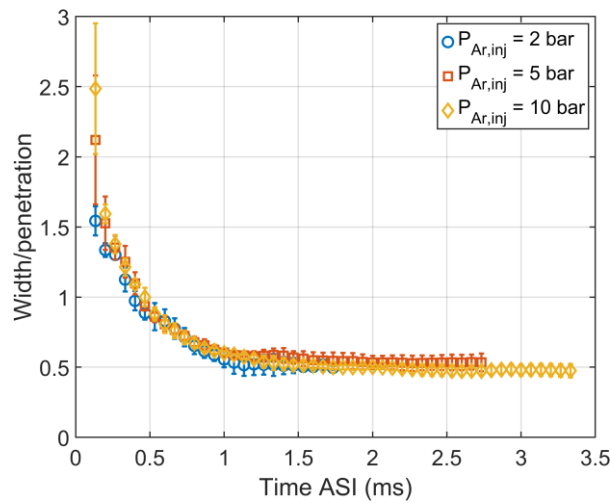


Fig. 8 Temporal variation of jet width-to-penetration ratio for helium injection in pure argon environment at different ambient pressures. Symbols and error bars represent average and standard deviation of three repeated measurements. The conditions are those of Cases 1 – 3 in Table 1.

Fig. 8 presents the temporal evolution of the ratio of jet width to axial penetration for the three injection conditions. This ratio is selected as an indicator of the self-similarity of the jet, as suggested in (Wang et al., 2020; Wu et al., 2025) for similar injection configurations. A higher self-similarity ratio indicates a more substantial jet development in the radial direction than in the axial direction. As ASI increased, the ratios for the three different conditions initially experienced a rapid drop, before gradually stabilize to a constant value at ASI = 1.5 ms, which indicates that the jet reached a self-similar state. In addition, the ratios for different conditions lied within the error

bar of each other for $ASI > 0.267$ ms, i.e., the data points for different conditions collapse into an identical trend. Therefore, the self-similar state of the jet is independent of the chamber pressure, and is characterised by a width-to-penetration ratio of 0.5, which is close to the results reported in (Wang et al., 2020; Wu et al., 2025).

3.2 Injection evolution in high-pressure high-temperature Ar environments

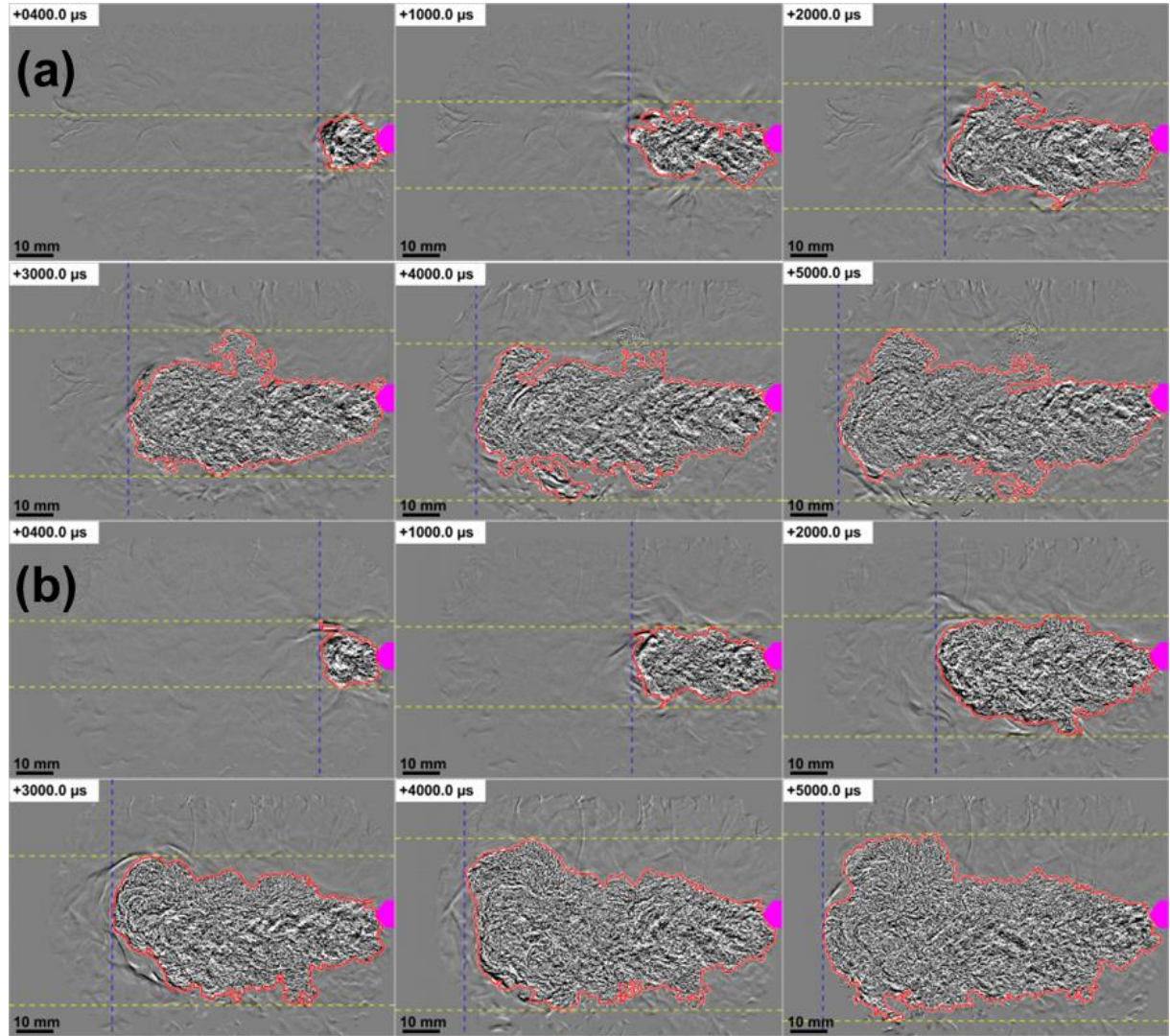


Fig. 9 Temporal and spatial evolution of hydrogen injection in HPHT argon environment of (a) $P_{Ar,inj} = 23.7$ bar, $T_{inj} = 1111$ K, $X_{O_2,inj} = 0$; (b) $P_{Ar,inj} = 22.8$ bar, $T_{inj} = 1120$ K, $X_{O_2,inj} = 0.03$; (c) $P_{Ar,inj} = 53.5$ bar, $T_{inj} = 2509$ K, $X_{O_2,inj} = 0$; (d) $P_{Ar,inj} = 51.4$ bar, $T_{inj} = 2520$ K, $X_{O_2,inj} = 0.03$. For all conditions: $P_{fuel} = 150$ bar, injection duration 5 ms. The conditions are those of Cases 4 – 7 in Table 1.

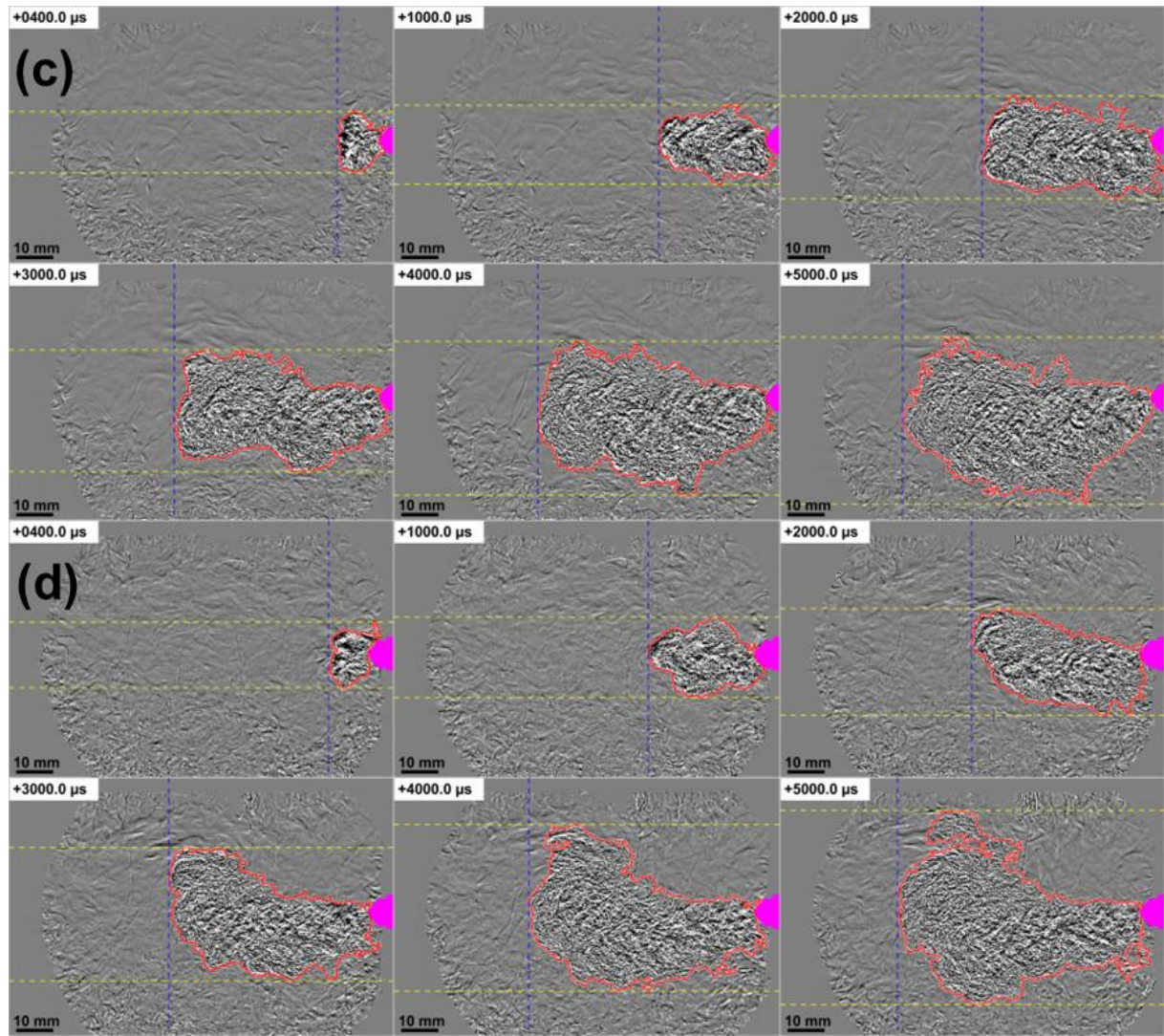


Fig. 9 (Continued) Temporal and spatial evolution of hydrogen injection in HPHT argon environment of (a) $P_{Ar,inj} = 23.7$ bar, $T_{inj} = 1111$ K, $X_{O_2,inj} = 0$; (b) $P_{Ar,inj} = 22.8$ bar, $T_{inj} = 1120$ K, $X_{O_2,inj} = 0.03$; (c) $P_{Ar,inj} = 53.5$ bar, $T_{inj} = 2509$ K, $X_{O_2,inj} = 0$; (d) $P_{Ar,inj} = 51.4$ bar, $T_{inj} = 2520$ K, $X_{O_2,inj} = 0.03$. For all conditions: $P_{fuel} = 150$ bar, injection duration 5 ms. The conditions are those of Cases 4 – 7 in Table 1.

Fig. 9 demonstrates, with representative instantaneous Schlieren images, the evolution of hydrogen injection in HPHT argon environment, which was created with the pre-burn method in the CVCC. These images are background corrected by subtracting the preceding image, as discussed in Fig. 3. The chamber had subcritical Ar for the conditions of Fig. 9a – b and supercritical Ar for the conditions of Fig. 9c – d (see Table 1). In addition, the test conditions of Fig. 9b and d allowed the injected hydrogen to combust, because the sufficient oxygen remained in the CVCC when injection occurred. The combustion was confirmed by monitoring the chamber pressure history in the CVCC with a fast response dynamic pressure transducer. It is worth

reiterating that the H_2 flow was expected to be choked at the injector nozzle for these injection conditions, implying the same mass flow rate and hydrogen flow velocity at the nozzle exit.

The instantaneous images of Fig. 9 show an absence of the distinct conical structure near the nozzle exit that was observed for LPLT injections (see Fig. 4) because of the nozzle geometry. This is consistent with the trend demonstrated in Fig. 4 that increasing ambient density reduces the spatial extent of this conical structure. In addition, the main body of the jet had a less cylindrical shape compared to the jet morphologies at LPLT conditions, especially when the jet had penetrated long into the ambient (e.g., $ASI = 4 - 5$ ms). Instead, the jet structure had a greater resemblance to that of a turbulent jet issuing from a round nozzle.

Although the ambient condition of the cases presented in Fig. 9 had the same density (see Table 1), the jet was found to have slower axial penetration in supercritical Ar than in the subcritical Ar, regardless of the presence of jet combustion. This is quantitatively demonstrated in Fig. 10a, which plots the temporal evolutions of jet axial penetration.

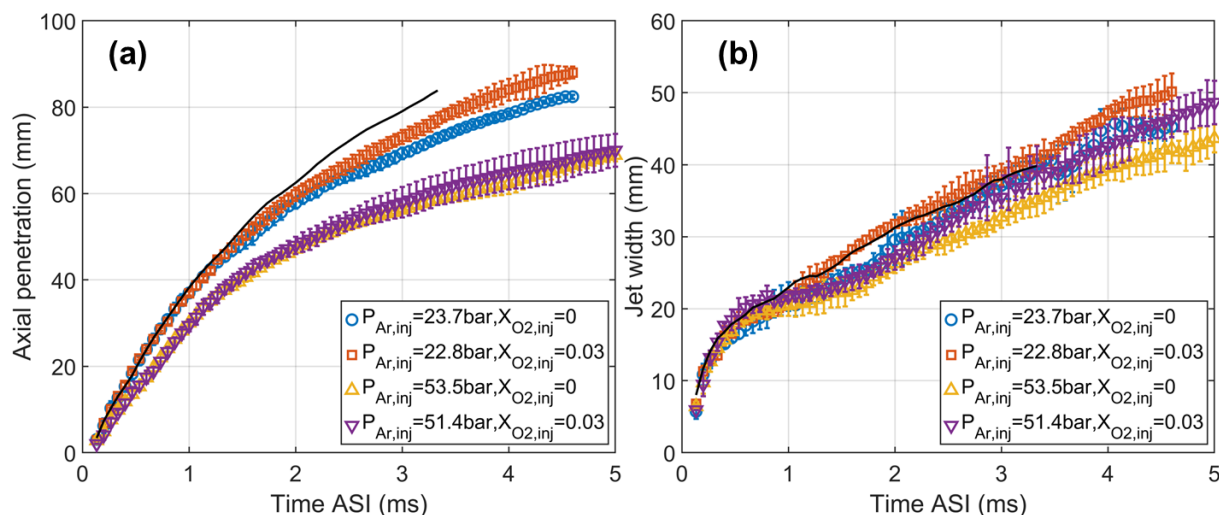


Fig. 10 Temporal variations of (a) axial penetration and (b) jet width for hydrogen injection in HPHT argon environment with different ambient pressures and oxygen concentrations. Symbols and error bars represent average and standard deviation of three repeated measurements. Black solid lines indicate the same results in Fig. 5 for helium injection into pure argon environment with $P_{Ar, inj} = 10$ bar. The conditions are those of Cases 4 – 7 in Table 1.

The evolution of the axial penetrations for the two supercritical Ar conditions was nearly identical throughout the injection period, suggesting that the axial penetration was independent of combustion. Similarly, identical axial penetration was observed for the two subcritical Ar conditions until approximately $ASI = 2$ ms, after which the reacting jet penetrated faster than its non-reacting counterpart, with the axial penetration being about 5% larger. Taking the evolution of the non-reacting jet in subcritical Ar as a base line, the axial penetration for jets in supercritical

Ar was about 20% lower throughout the injection duration. In addition, the LPLT injection results for $P_{inj} = 10$ bar from Fig. 5 are replotted as a black line in Fig. 10 for comparison, as its ambient density differed by no more than 5% from the HPHT injection conditions. Compared to the axial penetration of LPLT injection with $P_{inj} = 10$ bar, the penetration for injections in subcritical Ar was nearly identical until approximately $ASI = 1$ ms, after which it became progressively lower. These differences in axial penetration among different conditions in Fig. 10a cannot be explained by the dependence of the drag experienced by the jet on the ambient density, because the ambient density was nearly identical. These differences can possibly be attributed to the differences in the viscosity of the ambient gas due to the different ambient temperatures, which consequently affected the drag on the jet. The large differences in penetration between the subcritical and supercritical Ar conditions could also be caused by the presence of supercritical fluids.

Fig. 10b presents the temporal evolution of jet width for hydrogen injections in HPHT Ar environment, together with that for LPLT injection with $P_{inj} = 10$ bar. Prior to $ASI = 1$ ms, the jet width evolution for HPHT injections closely followed the LPLT injection evolution. Beyond this point, the jet width for the reacting jet in subcritical Ar environment maintained good agreement with the LPLT injection, whereas the widths for the other HPHT injection conditions were smaller than the LPLT injection. For injections in supercritical Ar, the combustion of the jet led to a more pronounced impact on jet width than on axial penetration, with the reacting jet width exceeding its non-reacting counterpart by approximately 10% after $ASI = 2.5$ ms. Conversely, the presence of supercritical fluids demonstrated a smaller impact on jet width than on axial penetration, with the non-reacting jet width in supercritical Ar being around 10% lower than that in subcritical Ar after $ASI = 1$ ms.

Given the power-law dependence of the jet penetration and width on ASI observed in the LPLT injection results (Fig. 6), the corresponding HPHT injection results are replotted on a logarithmic scale in Fig. 11. The power-law correlations derived from LPLT results are also included in Fig. 11 as black solid lines. The results indicate that both the penetration and width evolutions in HPHT environments deviate from the LPLT correlations, with the deviation being more pronounced for jet penetration. For $ASI > 2$ ms, the penetration and width evolutions in HPHT environments still exhibit a power-law dependence on ASI , though with different exponents than their counterparts in the LPLT correlations. Because the HPHT environments are more representative of the injection conditions in real combustors, the complexities of hydrogen injection in HPHT environments and the deviations from the LPLT injections, demonstrated here in Fig. 11, underscore the need for further research dedicated to hydrogen injection in HPHT environments.

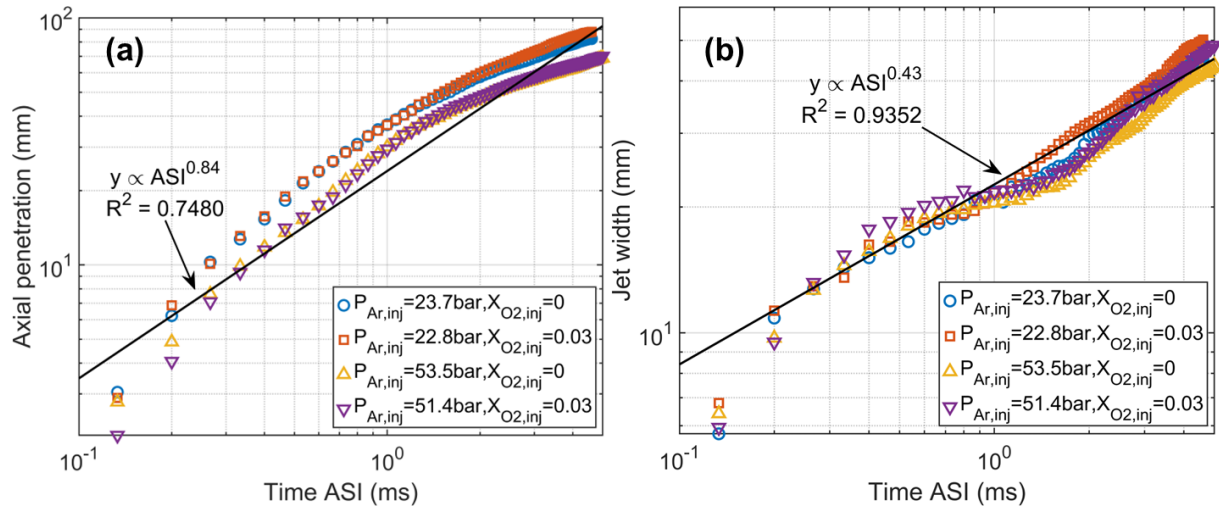


Fig. 11 Logarithm plots of (a) axial penetration and (b) jet width against ASI for hydrogen injection in HPHT argon environment with different ambient pressures and oxygen concentrations. The conditions are those of Cases 4 – 7 in Table 1. Black solid lines indicate power-law fits with exponent derived from the LPLT conditions.

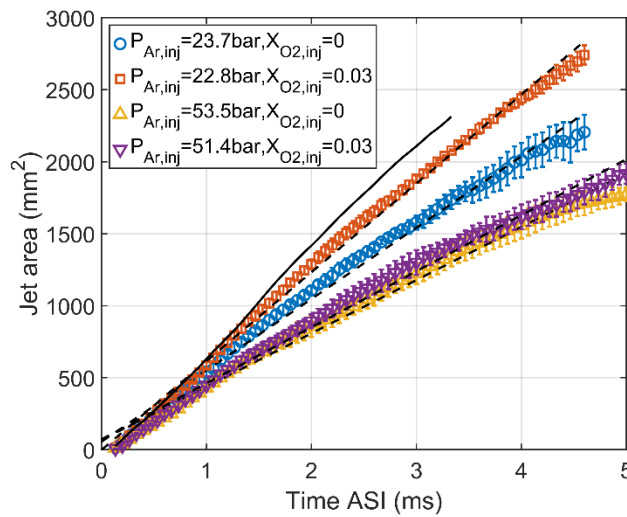


Fig. 12 Temporal variation of jet area for hydrogen injection in HPHT argon environment with different ambient pressures and oxygen concentrations. Symbols and error bars represent average and standard deviation of three repeated measurements. The conditions are those of Cases 4 – 7 in Table 1. The black solid line indicates the same results in Fig. 5 for helium injection into pure argon environment with $P_{Ar, inj} = 10$ bar, and black dashed lines represent linear fits with $R^2 > 0.989$.

Fig. 12 presents the temporal evolution of the jet area for injections in HPHT Ar environments. Despite the deviations from the evolution for LPLT injections presented in Fig. 11, the jet area evolution for HPHT injections still exhibited a linear correlation with the ASI, like the results for LPLT injections. The jet areas for the two supercritical Ar conditions, like the axial penetration, were nearly identical throughout the injection duration, which were also approximately 20% lower

than that for the non-reacting injection in subcritical Ar environment. The jet area for the reacting injection in subcritical Ar environment deviated from that for the non-reacting injection in subcritical Ar environment at approximately $ASI = 1$ ms, with the deviation becoming progressively larger and reaching about 25% at $ASI = 4.5$ ms. In addition, the jet areas for the injections in subcritical Ar environments were close to the results of LPLT injections with $P_{inj} = 10$ bar in the early stage but became progressively smaller than their LPLT counterparts after $ASI = 1$ ms.

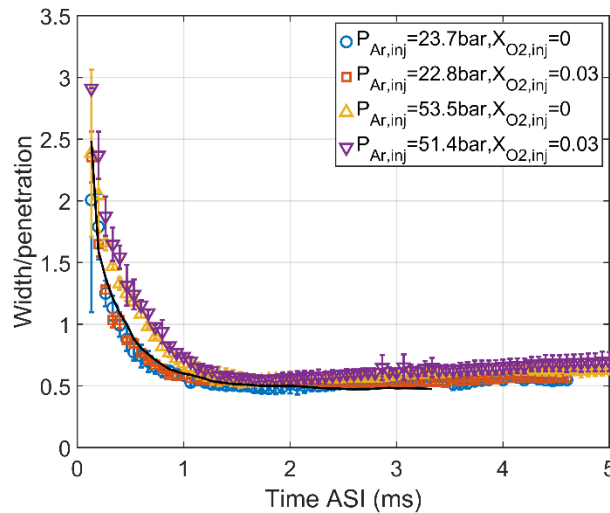


Fig. 13 Temporal variation of jet width-to-penetration ratio for hydrogen injection in HPHT argon environment with different ambient pressures and oxygen concentrations. The conditions are those of Cases 4 – 7 in Table 1. Symbols and error bars represent average and standard deviation of three repeated measurements. Black solid line indicates the same results in Fig. 5 for helium injection into pure argon environment with $P_{Ar, inj} = 10$ bar.

Fig. 13 presents the temporal variation of the width-to-penetration ratio – as an indicator of self-similarity – for hydrogen injection in HPHT Ar environments. The temporal evolution of the ratio for injections in subcritical Ar were nearly identical and closely followed that for LPLT injections (indicated as black solid line in Fig. 13), stabilizing at a value of about 0.5 after $ASI = 1.5$ ms. A similar trend of evolution was observed for injections in supercritical Ar, except that they exhibited a markedly higher width-to-penetration ratio during the early stages ($ASI < 1$ ms) and converged to a slightly higher value of around 0.6 for large $ASIs$; these differences indicate that the hydrogen jet underwent more prominent radial development in supercritical environments than under subcritical conditions, particularly during the early stages of injection.

4. Conclusions

Hydrogen injection in argon was experimentally investigated in a CVCC under a wide range of ambient conditions, spanning both subcritical and supercritical Ar environments. The ambient conditions examined here can be divided into two categories, namely LPLT and HPHT. LPLT conditions included different argon ambient pressures of 2 – 10 bar but the same temperature of 423 K, whereas HPHT conditions covered argon ambient pressures from 22.8 to 53.5 bar (with reduced pressure from 0.47 to 1.09) and temperatures from 1111 to 2520 K (with reduced temperature from 7.4 to 16.7). Hydrogen injection was performed with an outward-opening hollow cone injector, and the injection pressure, temperature and duration were fixed at 150 bar, 423 K and 5 ms, respectively. All injection conditions had choked flow at the nozzle exit. Injection evolution was visualized using highspeed Schlieren imaging and quantified with characteristics including axial penetration, jet width, jet area and width-to-penetration ratio. The main findings of this study are summarized as follows.

Under LPLT argon conditions, the jet morphology showed a conical structure near the nozzle and an approximately cylindrical main jet body. As the chamber pressure increased, the size of this conical structure, the axial penetration, the jet width and the jet area all decreased. When appropriately normalized using the ambient density, the evolutions of axial penetration and jet width under different chamber conditions followed a universal power-law correlation, with exponents of 0.84 and 0.43 respectively. Furthermore, the jet area linearly increased with ASI for all chamber conditions. The width-to-penetration ratio – utilized as an indicator of self-similarity – collapsed onto a single trend for different conditions, gradually decreasing with ASI before converging to a constant value of around 0.5 after $ASI = 1.5$ ms.

Under HPHT argon conditions, the jet morphology exhibited a less cylindrical shape, evolving into an overall more conical structure during late stages of injection that resembled a round-nozzle turbulent jet. Despite the same ambient density, the non-reacting HPHT injection with supercritical Ar ambient showed approximately 20% slower axial penetration, 10% smaller jet width and 20% reduced jet area compared to the subcritical Ar case. For injections in HPHT supercritical Ar environments, combustion had a negligible influence on axial penetration and jet area but enhanced the jet width by around 10% after $ASI = 2.5$ ms. Conversely, in HPHT subcritical Ar environments, combustion increased both jet width and area after $ASI = 1$ ms and accelerated axial penetration after $ASI = 2$ ms. Consequently, the temporal evolutions of axial penetration and jet width under HPHT conditions exhibited greater complexity than under LPLT conditions, making it impossible to identify a simple power-law correlation with ASI. The jet width-to-

penetration ratio showed no marked dependence on combustion under HPHT conditions, regardless of the presence of supercritical fluids. This ratio for HPHT subcritical Ar conditions closely followed the evolution under LPLT conditions; a similar general trend was observed under HPHT supercritical Ar conditions, but it exhibited a markedly higher value before $ASI = 1$ ms and converged to a slightly increased constant value of 0.6 thereafter.

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