

Flow Characterisation of Highly Integrated High-Aspect-Ratio Rectangular Nozzle

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ABSTRACT

The paper presents part of the experimental activities carried out within the framework of the NATO AVT-415 activities aimed at characterising the flow behaviour of a bidimensional bevel rectangular nozzle. The optimisation of Unmanned Air Vehicles (UAVs), for both military and civil applications, necessitates conducting advanced computational studies that rigorously analyse aerodynamic and aeroacoustic behaviours, particularly in proximity to the exhaust region of the propulsion system. This investigation focuses on a wing-blended vehicle with a fully integrated propulsion system. The primary objectives are to enhance aerodynamic performance while concurrently minimising radar cross-section, thermal detection and acoustic emissions. The activity foresees investigating the flow behaviour inside a bevel nozzle characterised by an internal S-shape, an internal section variation from elliptical at the nozzle entrance to rectangular at the exit, for three different mass flow rates. Pressure distribution along the nozzle symmetry plane was investigated by 44 pressure taps, inlet Mach distribution was investigated by two static and total pressure probe rakes and the flow evolution downstream the exit nozzle was depicted by multiplane PIV measurement up to 15 nozzle heights. Vertical and horizontal measurement planes were investigated to consider the three-dimensionality of the wing-bleed vehicle and the integrated nozzle. The paper deals with flow behaviour and pressure distribution inside and outside the nozzle. The velocity fields are discussed in terms of flow velocity and flow fluctuations, taking into consideration the highly three-dimensional nature of the flow velocity.

1 Introduction

The optimisation of Unmanned Air Vehicles (UAVs), for both military and civil applications, necessitates conducting advanced computational studies that rigorously analyse aerodynamic and aeroacoustic behaviours, particularly in proximity to the exhaust region of the propulsion system. This investigation focuses on a wing-blended vehicle with a fully integrated propulsion system, specifically the DLR-F24 MULDICON (MULTi-Disciplinary CONfiguration), which was developed within the framework of NATO AVT-251 and is elaborated by Nangia et al in 2019 and Liersch et al in 2020. The primary objectives were to enhance aerodynamic performance while concurrently

minimising radar cross-section and acoustic emissions. To achieve these goals, the propulsion system has been seamlessly integrated into the aerodynamic architecture of the wing body (Figure 1). Additionally, the design incorporates complexly curved intake and exhaust geometries aimed at attenuating the vehicle's infrared signature, thereby contributing to its stealth characteristics. The complete integration of the propulsion system into vehicle design led to the creation of a two-dimensional bevelled nozzle.

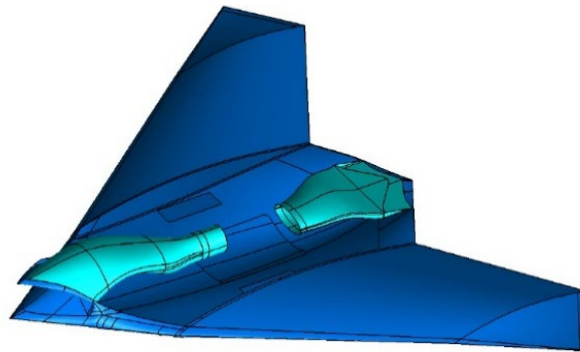


Figure 1 DLR-F24 Muldicon UCAV internal components geometry.

The impact of asymmetric nozzle geometries on jet development is gaining attention for their potential to control jet direction, mixing, and turbulence. Unlike symmetric nozzles, asymmetric designs create non-uniform boundary conditions at the exit, altering momentum distribution and downstream flow. This can result in jet deflection, uneven shear layer growth, and complex vortical structures. Early research on non-circular and asymmetric nozzles demonstrated changes in entrainment and mixing compared to traditional round jets. Studies by Gutmark and Grinstein (1999) showed that these geometries generate additional streamwise vortices, enhancing mixing and structuring breakdown in the shear layer. Mi et al. (2001) also found that exit geometry significantly affects jet spreading and turbulence evolution in the near field.

Bevel nozzles feature an inclined exit plane that creates asymmetric flow, resulting in a deflected jet with non-uniform velocity and pressure distributions. This inclination causes a directional bias in momentum flux, impacting jet trajectory and shear layer development, which leads to varying growth rates on the upper and lower flow sides and affects entrainment and mixing.

Experimental studies, such as those by Kumar et al. (2021), have shown that bevel geometries notably influence near-field jet behaviour. They found that the exit angle enhances mixing by increasing shear layer instabilities, resulting in higher turbulence intensity and quicker breakdown of coherent structures compared to straight-cut nozzles.

Asymmetric nozzle geometries have been studied for their effects on the aerodynamic and acoustic properties of jets. Research by Christophe et al. (2024) revealed that inclined nozzles can influence the turbulent structures that generate noise, suggesting potential noise reduction in propulsion systems. Despite the growing interest in asymmetric nozzle configurations, the specific case of bidimensional bevel nozzles remains relatively less explored. Most existing studies focus either on axisymmetric jets with modified exit geometries or on compressible flows associated with propulsion applications. Consequently, there is still limited experimental data available for planar jets issuing from bevelled exits, particularly for the purpose of validating numerical simulations.

In consideration of the aforementioned factors, the present study seeks to conduct a comprehensive experimental investigation of a bidimensional bevel nozzle at Mach number of 0.69 and mass flow of $Q=1.55\text{kg/s}$. The primary objective is to characterise the Mach number behaviour at the duct inlet, as well as to assess the internal pressure distribution and the flow field measurements in the region downstream of the nozzle exit. This analysis will specifically focus on the effects of bevel geometry on jet deflection, velocity distribution, and the development of the shear layer.

Experimental measurements are conducted to obtain detailed velocity profiles and flow field information in the near and intermediate regions of the jet to integrate the acoustic experimental campaign carried out at DLR and discussed by Rossignol and Delfs (2023). These results will be used to validate computational simulations performed using CFD methods.

2 Experimental setup

2.1 Nozzle Test Facility

The Nozzle Test Facility, for brevity NTF, is an experimental setup designed to test, analyse, and validate the performance of nozzles, devices that direct, shape and accelerate the flows. The NTF can feed the test article at a maximum flow rate of 2 kg/s over a pressure range of 1 to 10 barg. The system is fed by a centralised pressure station that provides a P_{line} of about 10 barg, monitored at the entrance of the pneumatic system by a dedicated pressure sensor (P_{line}). The pneumatic flow system includes a remotely controlled pressure valve regulator, an On/Off valve and sensors that measure the static temperature (T_{st}), static pressure (P_{in}), and mass flow (Q) downstream of the valve regulator and upstream of the On/Off valve. Downstream, the pipe forks to feed the nozzle from two opposite inlets. An active closed-loop control maintains the desired operative nozzle inlet pressure (P_{in}). Temperature, mass flow, and pressure are measured throughout the test.

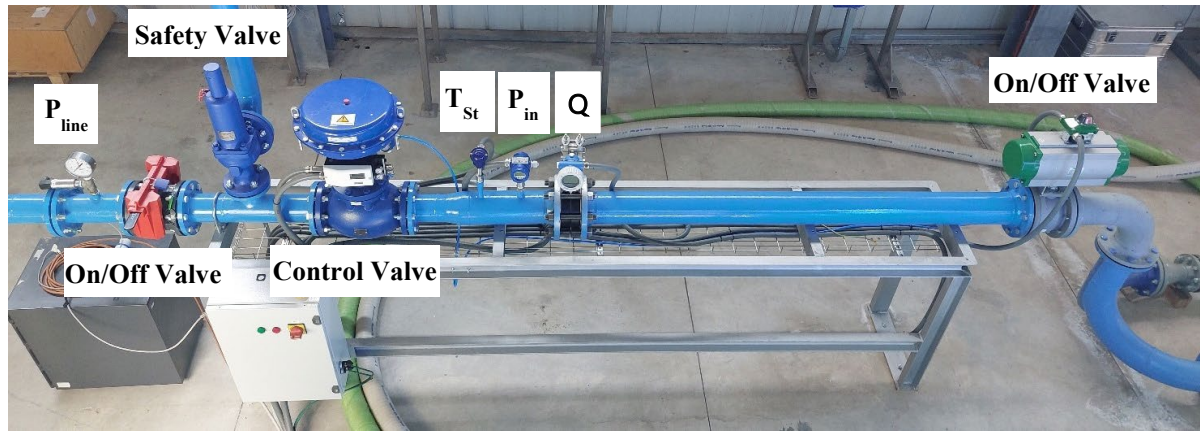


Figure 2 Nozzle Test Facility overview

2.2 Bi-dimensional bevel nozzle

The MULDICON foresees a propulsion system highly integrated in the swept flying wing for reducing the radar cross-section, comprising a bidimensional bevelled nozzle, characterised by a high-aspect ratio (AR) rectangular exit section, measuring 266 mm in width and 20 mm in height, resulting in an AR of 13.3. The vehicle presents a trailing edge sweep of $\Psi=30^\circ$ (Nanja et al 2019) and a triangular planform in correspondence with the jet exhaust as shown in Figure 3. Notably, the exit of the nozzle is bevelled, with the upper trailing edge surface positioned upstream of the lower surface by approximately $L = 79$ mm at the centreline, exhibiting an increment along the span of the nozzle. In the figure, the distances between the upper and lower trailing edges are shown at the locations where the PIV vertical measurement planes were located. The black dashed line indicates the location of the duct rectangular exit.

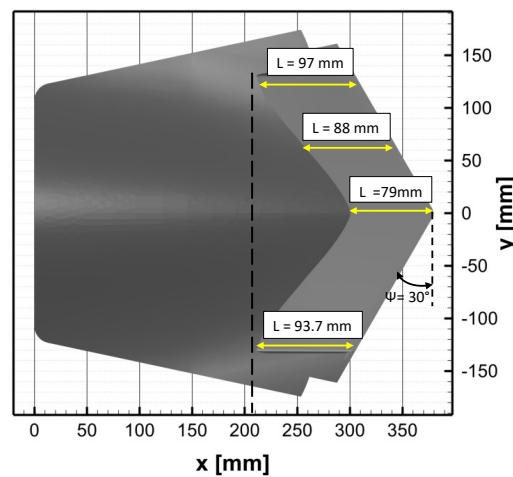


Figure 3 Bidirectional bevelled nozzle planform with main dimensions.

The internal centreline of the nozzle exhibits a double curvature, characterised by cross-sectional areas that increase to a maximum at 80 mm downstream from the stilling chamber. Beyond this point, the cross-sectional areas decrease at varying rates until they reach the exit of the nozzle (refer to Figure 4-a). At the entrance, the geometry of the nozzle is elliptical, transitioning to a rectangular shape with a high aspect ratio at the exit (refer to Figure 4-b).

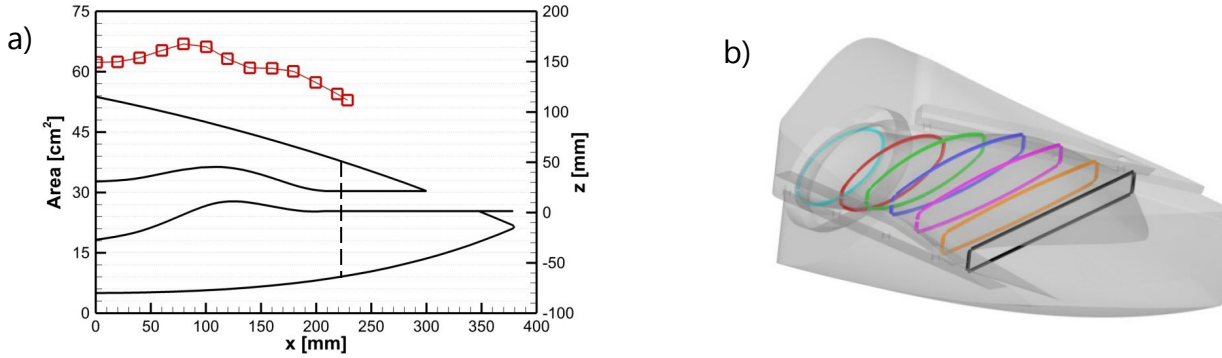


Figure 4 Bevelled Nozzle: Area distribution along x-direction (a), distributed internal nozzle cross-sections (b).

The nozzle model was equipped with 36 static pressure taps distributed on streamwise-aligned lines on the upper and lower walls of its duct, at the nozzle symmetry plane. Seven pressure taps were spread out streamwise, three taps on each side of the centre line. Two pressure taps and a single total pressure probe were in the stilling chamber. Pressure measurements were carried out with a PSI 8400 system using two differential ESP modules, each with 64 channels, accuracy of 0.05% FS, full scales of 5 and 15 psi, respectively. Details of the locations of the PTS are reported in the work of Camussi et al (2025).

2.3 Pressure rakes and nozzle pressure measurement system

To assess the uniformity of the inlet flow, the flow conditions at the entrance of the nozzle duct were systematically examined for a select number of cases using a series of pressure probe rakes. Each rake consisted of four static pressure probes and two total pressure probes. The probes were strategically positioned at a distance of 25 mm from the nozzle entrance, with one rake located at $y = -37$ mm and the other at $y = 37$ mm. The vertical distribution of the pressure probes was arranged in a manner that ensured equal spacing, approximately 6 mm apart. This configuration facilitated a comprehensive evaluation of the flow characteristics at the nozzle entrance. The Mach number is obtained through the knowledge of the total and static pressures using the isentropic law of a perfect gas.

$$M = \sqrt{\frac{2}{\gamma - 1} \left[\left(\frac{p_t}{p_s} \right)^{\frac{\gamma - 1}{\gamma}} - 1 \right]}$$

where, for air $\gamma = 1.4$.

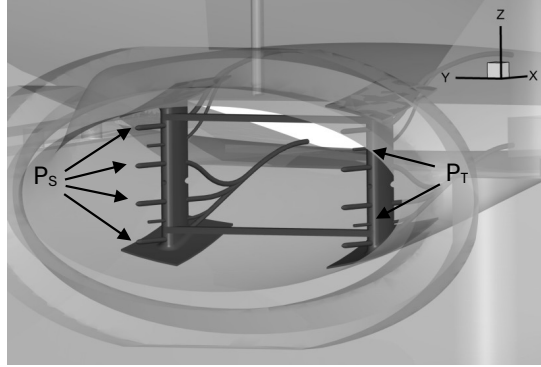


Figure 5: Pressure probe rakes. Long probes are the static pressure probes, and short ones are the total pressure probes.

2.4 PIV measurement system

The nozzle jet characteristics were measured by a two-component Particle Image Velocimetry (2C-PIV) measurement system. The setup was composed of a CFR 400 dual-head Nd-Yag laser with a pulse energy of $E=150$ mJ at a wavelength of $\lambda=532$ nm and a repetition rate of 10Hz. A system of two sCMOS cameras was installed, consisting of two ILA.PIV.sCMOS CLHS (25 frame rate, 2560×2160 pixels, 16-bit, pixel dimension $6.3 \mu\text{m}$). The two sCMOS cameras were equipped with a Canon ES lens featuring a fixed focal length of $f = 50$ mm, and the f-number was set to $f\# = 8$. The lens focus distance and aperture were remotely controlled by the operators. The cameras were installed on a two-axis linear traversing system to facilitate the camera positioning (Figure 6). As tracer particles, aerosolised diethylhexylsebacate (DEHS) oil was used. Special attention was paid to correctly seeding the inner and outer areas of the jet. The inner jet was seeded in the settling chamber by a dedicated seeding pipe rake upstream of the turbulent grid to remove any possible wake disturbance. The multi-Laskin nozzle generator was able to seed flows characterised by total pressure up to 6 barg. Full description is given in De Gregorio (2014).

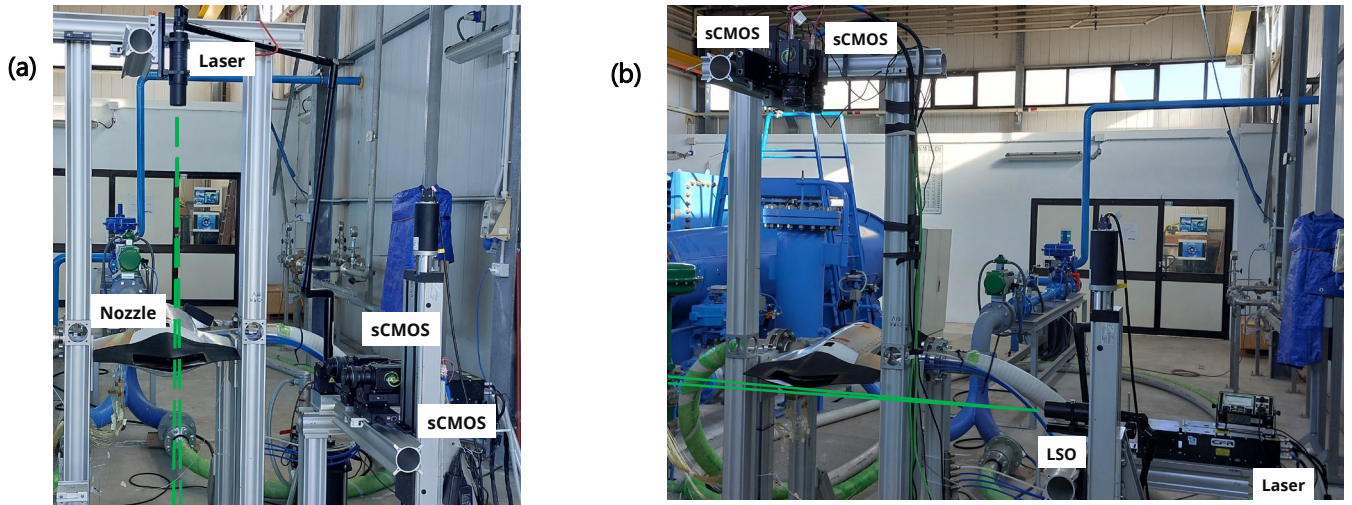


Figure 6 PIV experimental set-up: Vertical (a) and horizontal (b) measurement planes.

The rectangular nozzle jet was investigated on three vertical freestream parallel planes located at $y=0$ mm, 60 mm and 120 mm, respectively and on three horizontal freestream planes on $z = 0$ mm, $z = 10$ mm and $z = 20$ mm, respectively (Figure 7).

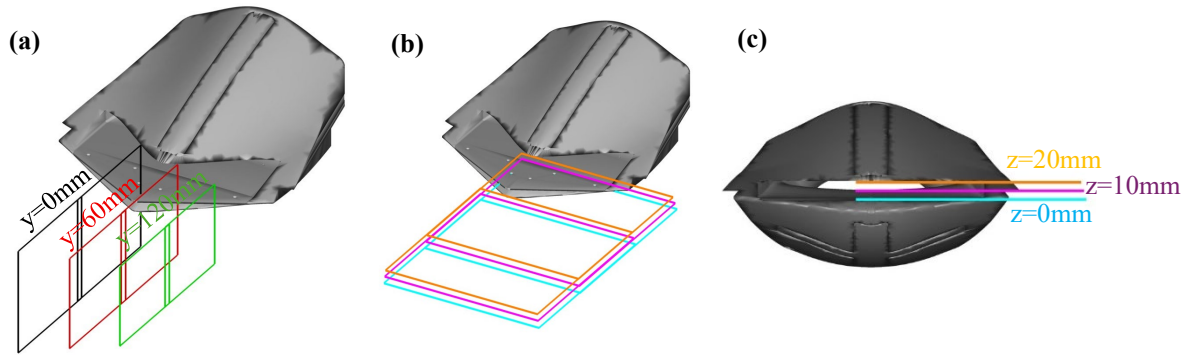


Figure 7 PIV measurement regions: Vertical longitudinal planes (a), Horizontal longitudinal planes (b and c)

The measurement region was located in proximity to the lower edge of the nozzle on a vertical plane ranging between $x = -15$ mm and $x = 320$ mm and $z = -80$ mm to $z = 80$ mm, with a magnification factor variable between 14 px/mm and 17.9 px/mm, by stitching together the images of the two cameras and partially overlapping. A larger region was recorded on the horizontal planes, ranging along the x -axis between -80 mm and 360 mm and spanwise between $y=-15$ mm and $y = 250$ mm with a corresponding magnification factor between 7.9 px/mm and 8.1 px/mm. The separation time between the laser double-pulses was set between $3 \mu\text{s}$ and $5 \mu\text{s}$ according to the highest expected velocities in the flow.

The PIV (Particle Image Velocimetry) images underwent a pre-processing phase that involved the application of background grey-level subtraction to enhance the signal quality. The particle image analysis was conducted using PivView v3.6.5, developed by PivTech GmbH. This analysis employed an iterative multigrid cross-correlation algorithm, concluding with a resolution of 32×24 px² and

a 50% overlap between interrogation windows. The results yielded a spatial resolution for velocity measurement of approximately $\Delta x = 1.0$ mm and $\Delta z = 0.76$ mm in the vertical planes, while lower resolutions were observed in the horizontal planes with values of $\Delta x = 2.0$ mm and $\Delta z = 1.5$ mm.

3 Results

3.1 Inlet Mach distribution

The static and total pressure probes, located at 25 mm downstream of the nozzle duct inlet, provide the flow behaviour at the spanwise stations of $y = 37$ mm and $y = -37$ mm, respectively. The Mach behaviour indicates a small asymmetry between the left and right stations, with the latter showing a higher value. Furthermore, the results indicated a smaller Mach number in the lower part of the inlet duct, increasing toward the upper surface (Figure 8). The full test campaign was carried out without the probe rakes to avoid blockage and flow disturbance.

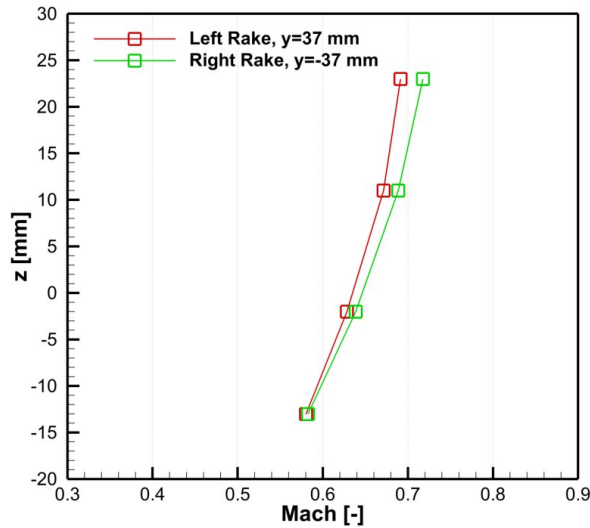


Figure 8: Inlet Mach distribution at $Q=1.55$ kg/s

3.2 Nozzle pressure distribution

The inlet nozzle duct was instrumented with 44 pressure taps to unveil the pressure distribution along the longitudinal centre line and spanwise direction at $x=200$ mm before the end of the internal duct. The pressure distribution was monitored on the upper and lower duct surfaces. Figure 9-a presents the nozzle geometry, with the PTS location and the pressure behaviours in psi magnitudes and referred to the external atmospheric pressure. The measured pressure standard deviation is presented in terms of vertical error bars. On the upper surface, the pressure indicates a pressure compression at the entrance up to $x = 100$ mm, then presents a pressure expansion up

to $x = 200$ mm. At this point, the duct is in proximity to the exit and the pressure re-compresses to reach the external atmospheric conditions.

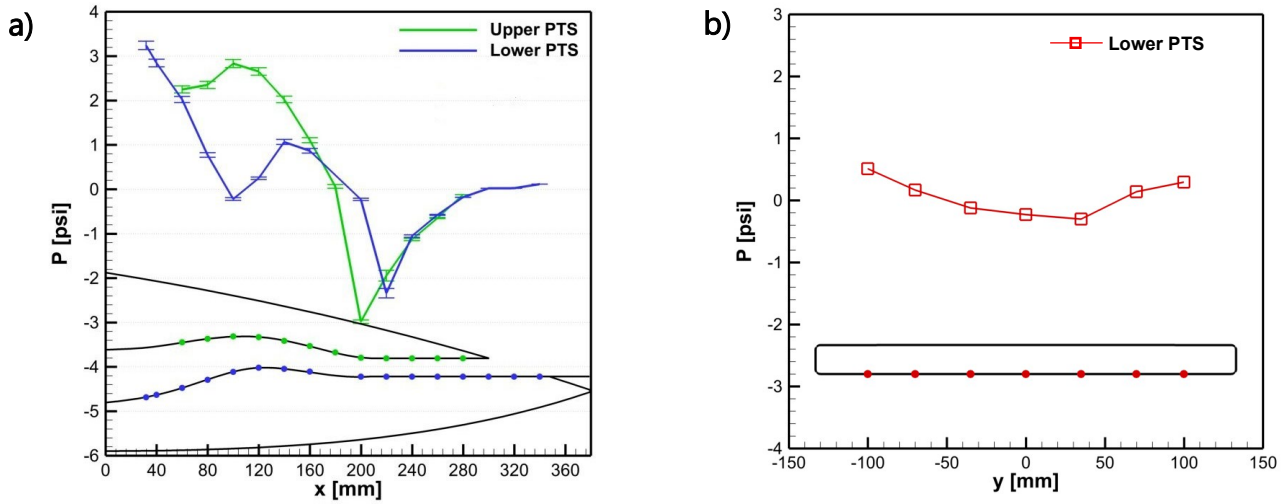


Figure 9: Nozzle duct pressure distribution: a) longitudinal centreline, b) spanwise at $y=200$ mm

The lower surface shows an expansion between the inlet to $x = 100$ mm, followed by a compression to $x = 140$ mm. Downstream, a large expansion to $x = 220$ mm, with consequent flow acceleration, then re-compressing to reach the external atmospheric pressure following the trend of the upper surface pressure. The pressure expansion on the lower surface agrees with the Mach behaviour at the duct lower inlet region, characterised by lower Mach with respect to the upper region, indicating an expansion on the lower side to uniform the vertical speed in the duct.

The spanwise pressure distribution shows a minimum pressure value on the symmetry plane and larger values moving toward the duct side boundaries, suggesting a gradient velocity, higher in the middle and lower on the sides.

3.3 Ensemble-averaged velocity Fields

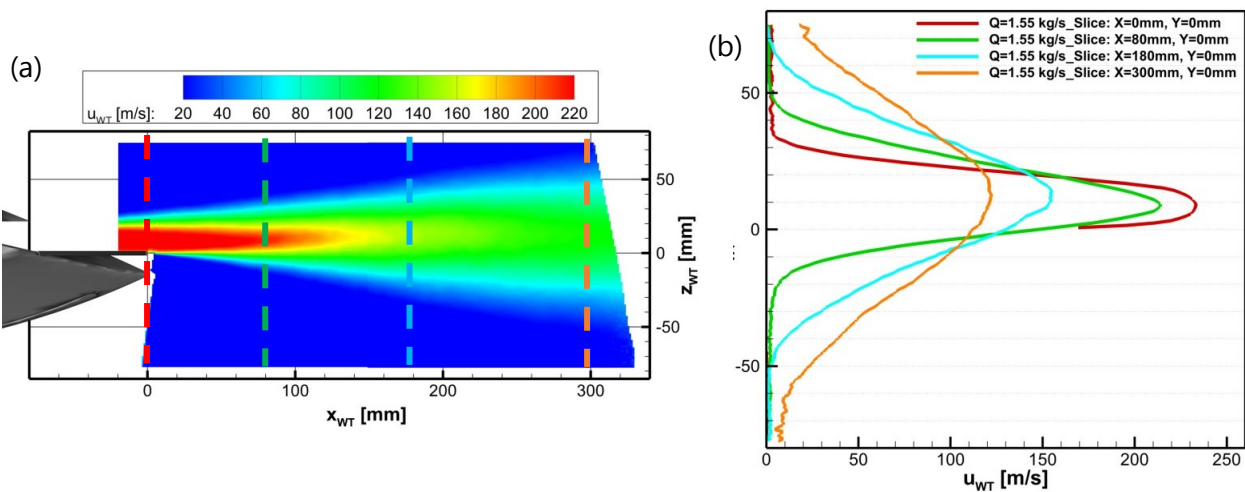
Particle Image Velocimetry (PIV) measurements were conducted to systematically examine the characteristics of the external jet across various longitudinal, vertical, and horizontal planes. Ensemble-averaged velocity fields were derived from five hundred instantaneous velocity datasets. The reference coordinate system was established with the origin defined at the nozzle's symmetry plane, specifically at the trailing edge of the nozzle's lower section. In this configuration, the x -axis aligns with the primary direction of the jet flow, the z -axis is oriented vertically upward, and the y -axis conforms to the right-hand rule.

The axial velocity colour map generated along the vertical symmetry plane illustrates jet behaviour extending approximately to $x = 300$ mm (refer to Figure 10-a). The core region of the jet is observed to span up to $x = 20$ mm. Notably, the colour map reveals an asymmetrical development between the upper and lower shear layers, with the upper shear layer exhibiting a more advanced state of development and a greater thickness compared to its lower counterpart.

Analysis of the axial velocity distribution along the vertical axis at various x -stations indicates a gradual reduction in maximum velocity, a smoothing of the shear layer slopes, and an expansion of the overall velocity profile. Furthermore, the profile peak velocity demonstrates an upward deviation of the jet stream as it moves away from the nozzle exit (see Figure 10-b).

The colour map illustrating the u -component of velocity at a position of $y = 60$ mm demonstrates an intensity reduction of the velocity; however, it exhibits behaviour consistent with that observed in the symmetry plane (refer to Figure 10-c). The core region of the velocity jet extends up to $x = 46$ mm, a characteristic derived from the horizontal plane measurements conducted at $z = 10$ mm, as depicted in Figure 12.

The u -component velocity profiles, analogous to those of the symmetry plane, reveal an upward displacement of the tip velocity, ultimately resulting in a deflected jet configuration (Figure 10-d). As one progresses spanwise to $y = 120$ mm, the mean velocity colour map is presented in Figure 10-e. At this location, the jet stream exhibits diminished intensity; however, it features an enlarged shear layer region, which is released further upstream in comparison to previous observations. Notably, the upper shear layer demonstrates greater development than the lower shear layer. Additionally, the axial velocity profiles analysed downstream from the nozzle exit indicate a continued upward jet deflection (illustrated in Figure 10-f).



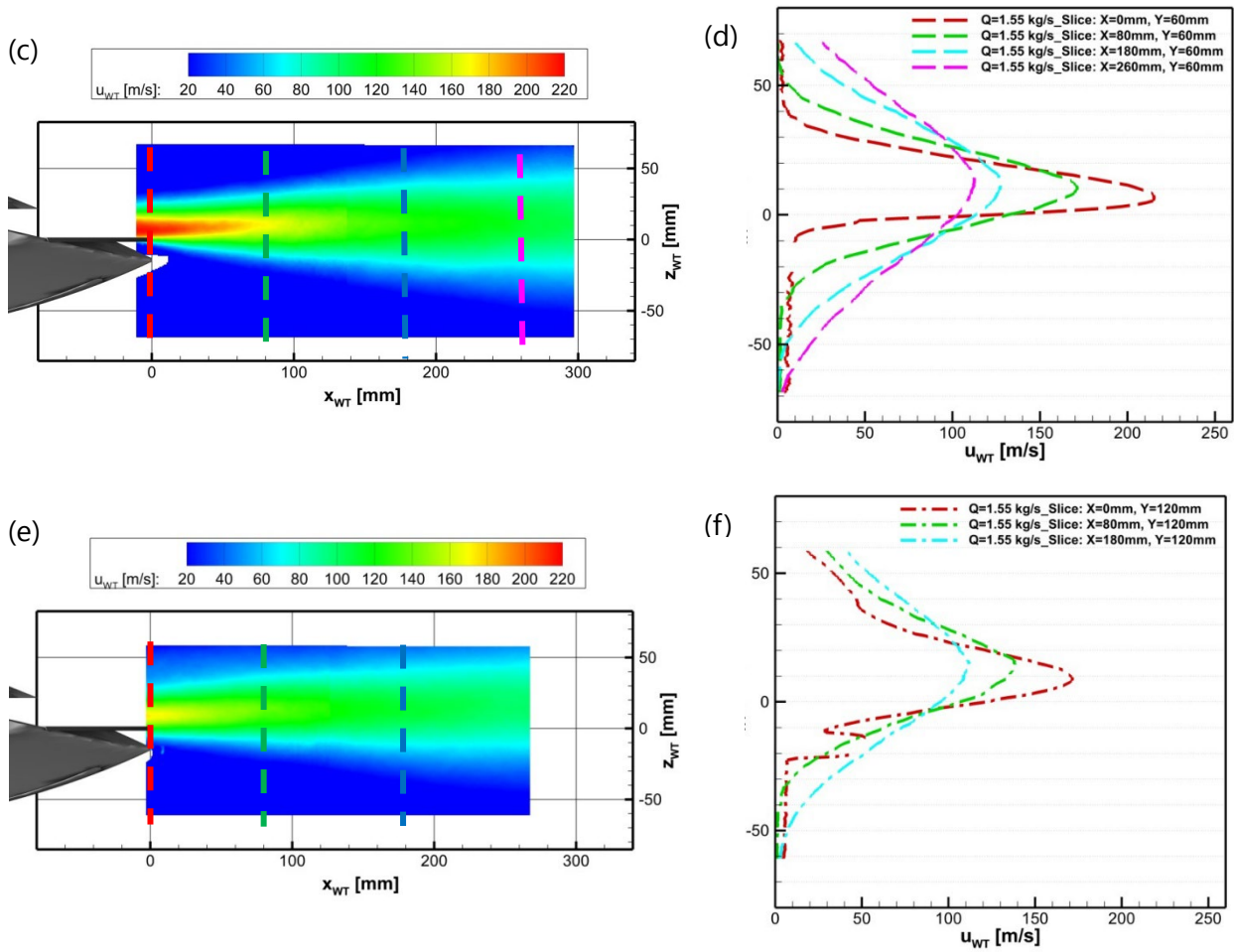


Figure 10 Axial velocity colour map at $y=0$ mm (a), $y=60$ mm (c) and $y=120$ mm (e) and Mach=0.69 (a) and related velocity profiles vs z -axis at $y=0$ mm (b), $y=60$ mm (d) and $y=120$ mm (f) at different x -stations.

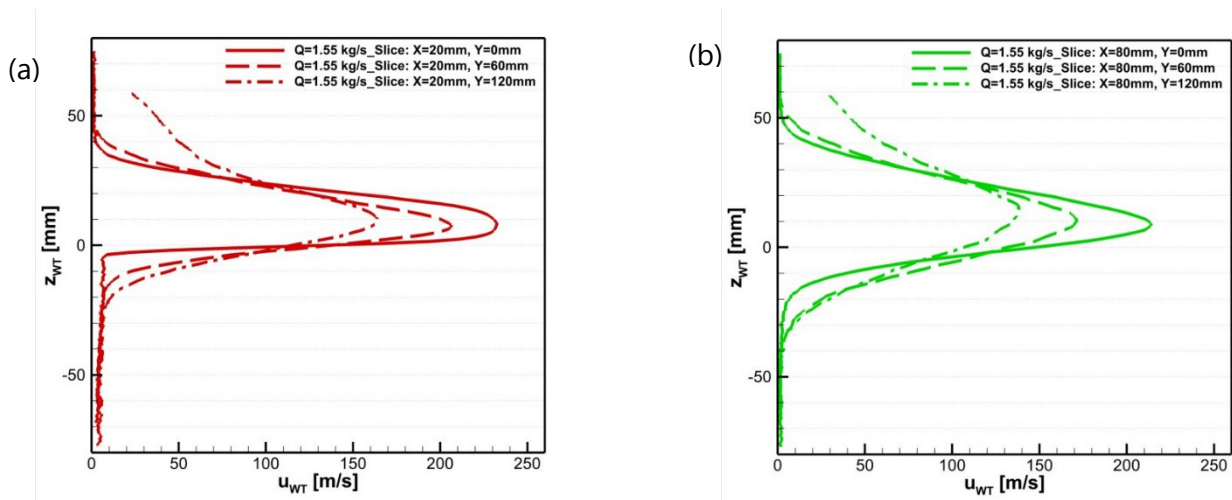


Figure 11: Axial velocity distribution along the z -direction, at different y -planes $Y=0$ mm (solid line), $Y=60$ mm (dashed line) and $Y=120$ mm (dot-dashed line). At $x=20$ mm (a) and $x=80$ mm (b).

The impact of the bevelled nozzle on jet deflection is also examined along the spanwise direction. The axial velocity distribution along the z -axis is compared at identical longitudinal distances, specifically at $x=20$ mm and $x=80$ mm, across different spanwise locations: $y=0$ mm, $y=60$ mm, and $y=120$ mm. The upward deflection of the jet is evident from both comparisons (Figure 11).

The experimental setup employed for the measurement of horizontal planes encompasses the jet region extending from immediately downstream of the upper trailing edge of the nozzle ($x = -79$ mm) to a distance of 440 mm ($x = 360$ mm). This setup also spans the cross-section from the centreline to the undisturbed flow zone at $y = 250$ mm.

The axial velocity contour map of the nozzle exit symmetry plane at $z=10$ mm is shown in Figure 12-a. The inner jet high-speed area presents a spanwise distribution characterised by an S-shape, with a maximum speed down to $x=150$ mm at the centreline and side-bounded at $y=130$ mm.

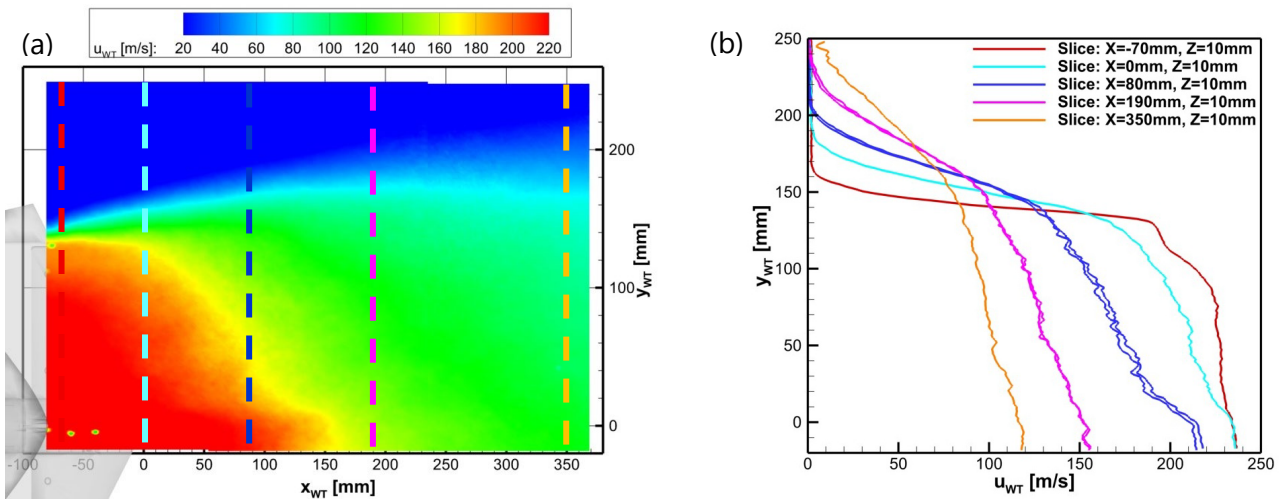


Figure 12 Mean jet velocity colour map at $Z=10$ mm and $Mach=0.69$ (a), velocity profiles vs y -axis at different x -stations (b)

The axial velocity profiles along the y -axis at various longitudinal positions provide a comprehensive understanding of the flow development characteristics. At $x=-70$ mm, the velocity presents a small velocity gradient between $y=0$ mm and 130 mm, followed by a steep slope in concomitance with the shear layer.

Moving downward along the x -axis, the velocity profiles depict tip speed reduction, an increment of the spanwise velocity gradient in the jet region and an increment of the shear layer size with a marked reduction of the velocity slopes.

The horizontal symmetry plane is illustrated through the spanwise velocity component (refer to Figure 13). The delineation of colour boundaries serves to enhance the visualisation of spanwise velocity behaviour. The colour map indicates that near the lateral edge of the nozzle exit, a

substantial region is characterised by positive values of the v -component, approximately 25 m/s. In contrast, a light blue region outside the jet shear layer denotes negative velocity, suggesting an entrainment of the external flow within the shear layer region. The axial velocity profiles at different longitudinal positions further elucidate the magnitude and behaviour of the flow dynamics (Figure 13-b).

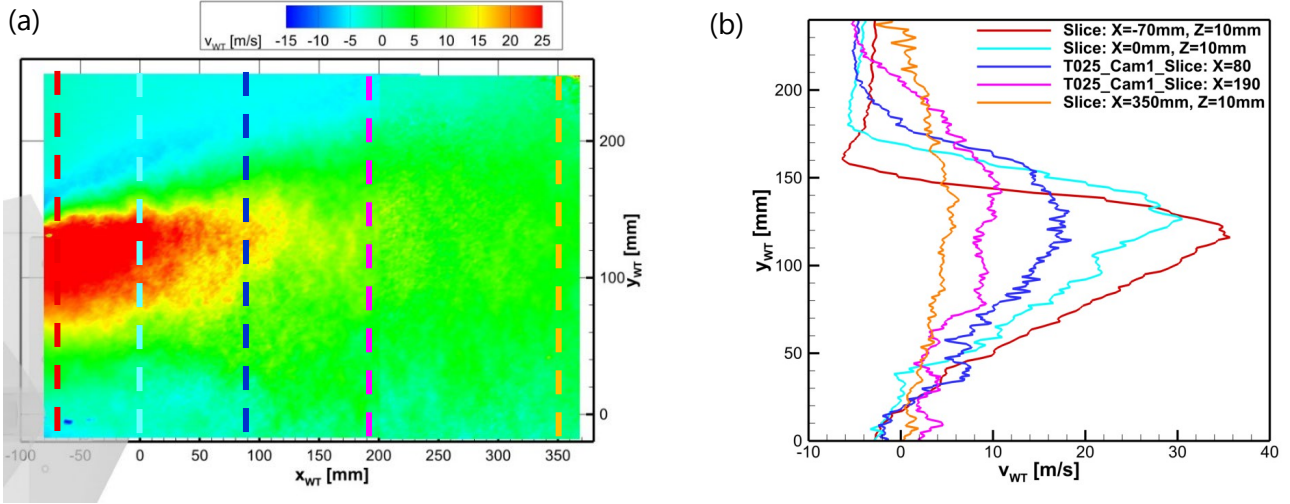


Figure 13: v -component colour map at $Z=10\text{mm}$ and $\text{Mach}=0.69$ (a), velocity profiles vs y -axis at different x -stations (b)

3.4 Standard deviation velocity fields

A preliminary analysis has been conducted focusing on velocity fluctuations, quantified as the standard deviation (STD) across 500 instantaneous velocity maps. The vertical longitudinal symmetry plane, represented as a colour map of the STD of the axial velocity component, highlights regions of high intensity associated with the shear layers (Figure 14-a). The upper shear layer is characterised by a greater thickness, while the lower layer, although thinner, exhibits higher intensity. Figure 14-b compares the vertical profiles of velocity fluctuations extracted from different locations along the x -direction. Up to $x = 40\text{ mm}$, the upper shear layer displays higher fluctuation intensity and greater thickness compared to the lower shear layer. At larger distances, the STD still demonstrates a bimodal behaviour, but the lower peak exhibits the highest value. Beyond $x = 220\text{ mm}$, the shear layers merge, resulting in a single modal distribution that reflects the flow fluctuations. Notably, the peak values in the shear layers are similar in magnitude to those measured with a single-component hot wire probe by Camussi et al. (2025) for the same test case. The standard deviation of the u -component on the horizontal plane at $z=10\text{ mm}$ presents a concentration of fluctuations shedding by the lateral edge of the high AR rectangular exit aligned with the axial velocity for then turns and moves parallel to the nozzle trailing edge (Figure 15-a).

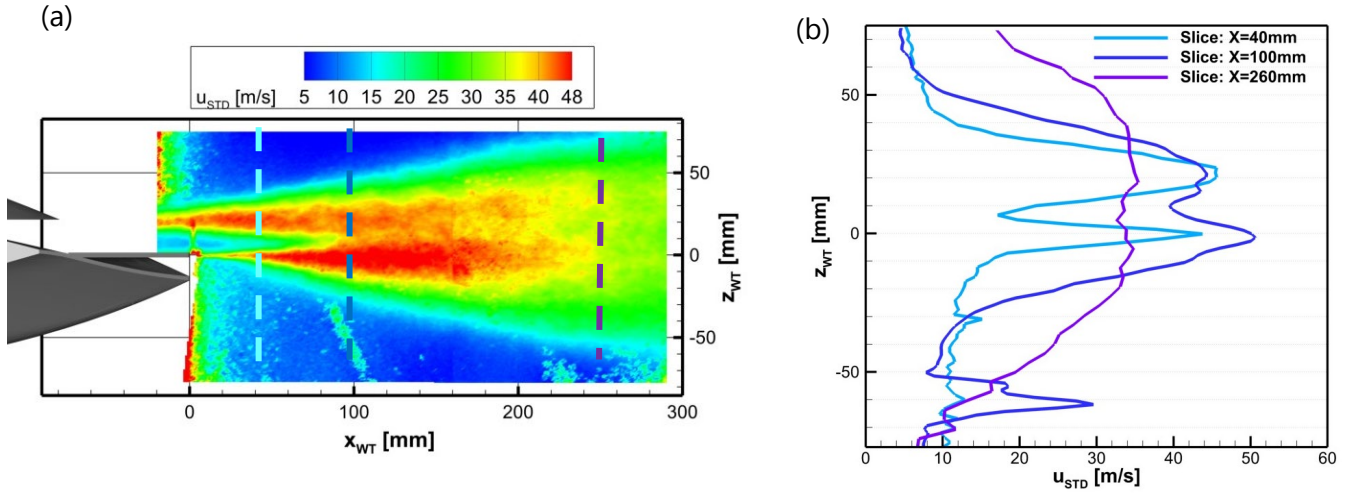


Figure 14 STD u-component velocity field colour-map on vertical symmetry plane $z=0$ mm (a) and STD vertical profiles at different x positions (b)

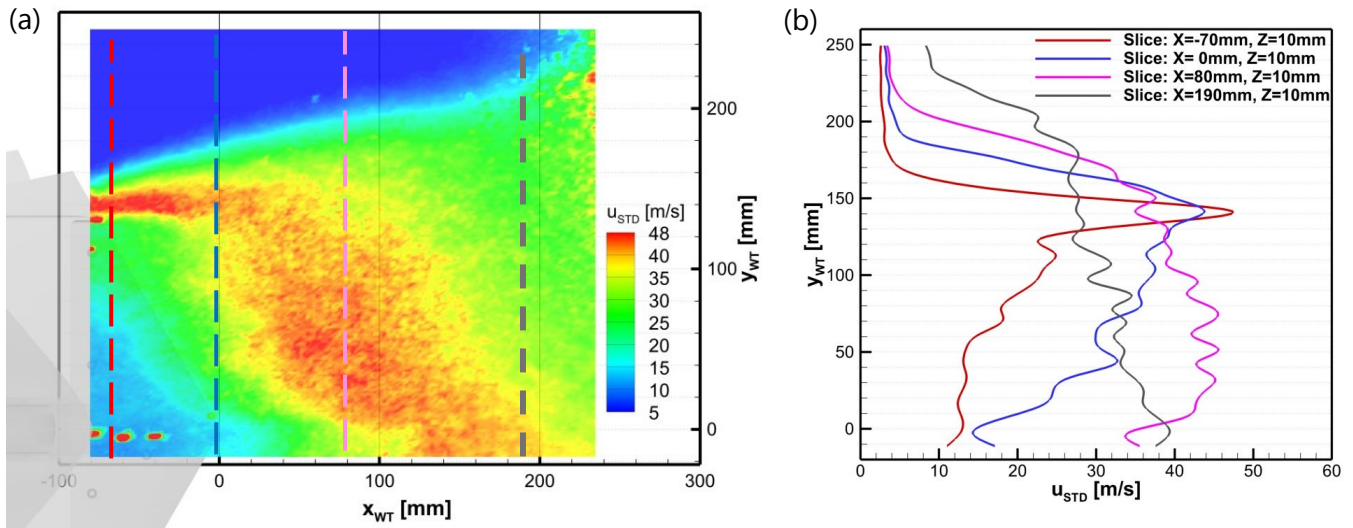


Figure 15: STD colour map of the u-component velocity field on horizontal plane $Z=10$ mm (a) and STD spanwise profiles at different x positions (b).

A transparency colour map is shown to visualise the nozzle trailing edge. The concentrated longitudinal stripe represents the nozzle side-edge shear layer, while the high-fluctuating inclined region is due to the upper and lower shear layers' coalescence, suggesting that the location is related to the distance from the lower nozzle trailing edge. The flow fluctuation horizontal distribution, at different x positions, shows in the interval between $x=-80$ mm to $x=0$ mm a clear peak at about $y=140$ mm. Moving far away from the nozzle exit down to $x=140$ mm, the STD reach a plateau of about 45 m/s along the spanwise direction between $y=0$ to $y=140$ mm.

Figure 16-a shows the standard deviation of the w -component in terms of a colour map. The upper shear layer presents smaller values with respect to the lower one and with respect to the STD of

the u velocity component (Figure 16-b). At $x=40\text{mm}$, the vertical fluctuation presents a bimodal behaviour with a maximum peak of the upper shear layer of about 32 m/s . At $x=100\text{ mm}$, the upper shear layer peak is of the order of 33 m/s while the lower peak is of about 51 m/s . At $x=260\text{ mm}$ the peaks coalesce in a single modal behaviour with a maximum of 32 m/s .

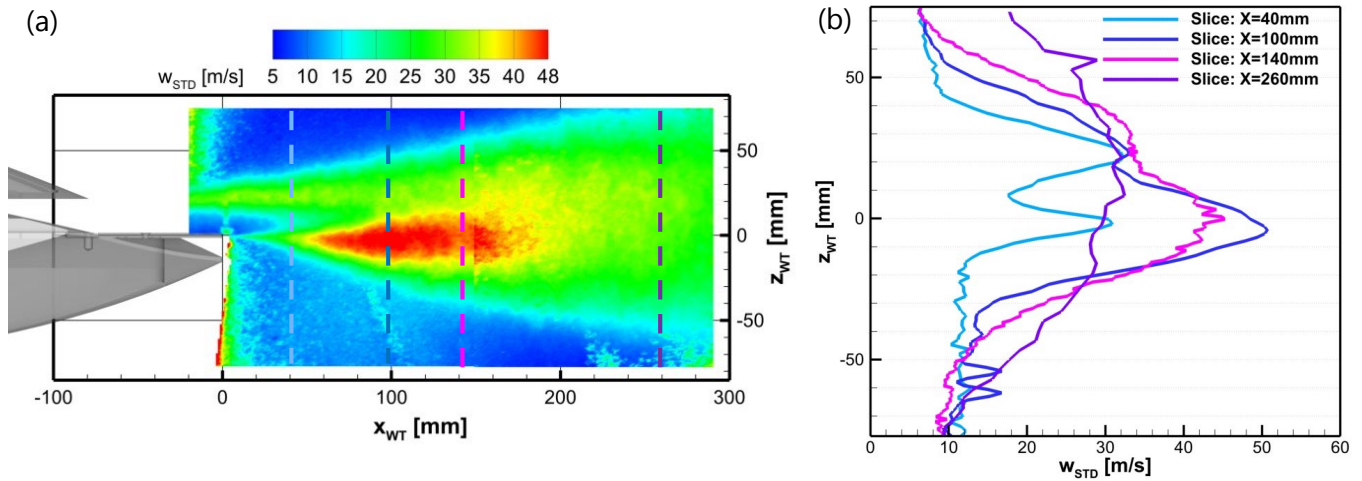


Figure 16: STD colour-map of the velocity w -component on vertical symmetry plane $z=0\text{ mm}$ (a) and STD vertical profiles at different x positions (b)

The standard deviation (STD) of the velocity v -component is illustrated as a colour map in Figure 17-a. A similar pattern is observed in the axial velocity fluctuations; however, these exhibit relatively lower magnitudes.

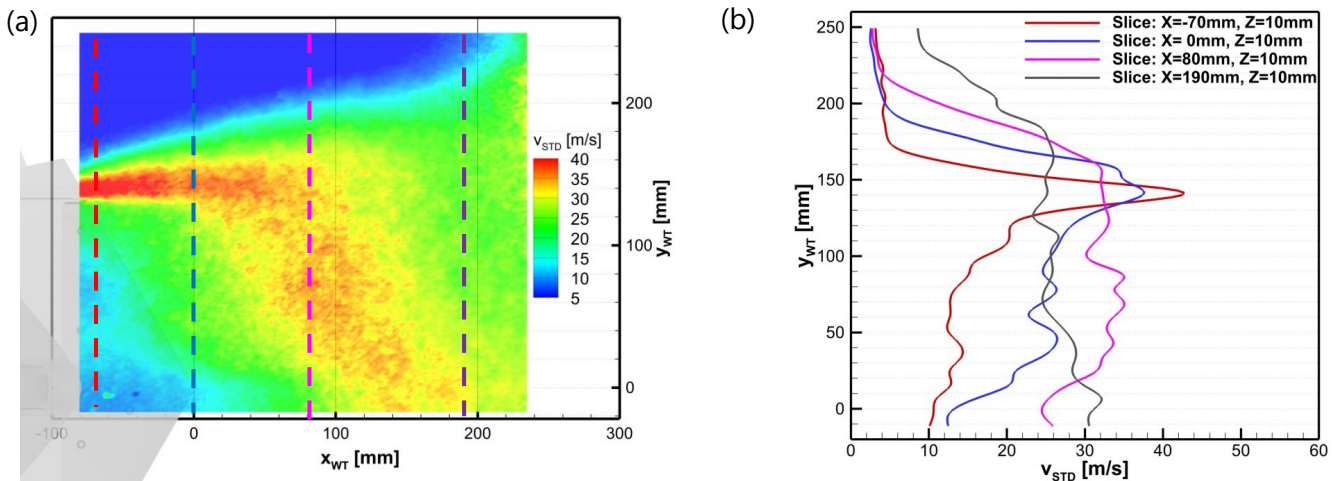


Figure 17: STD colour map of the velocity v -component on horizontal plane $Z=10\text{mm}$ (a) and STD spanwise profiles at different x positions (b).

At a position of $x = -70$ mm, the peak STD of the spanwise velocity reaches approximately 43 m/s, compared to 47.5 m/s for the axial velocity. At $x = 0$ mm, the peak STD of the spanwise velocity is recorded at 37.5 m/s, against an axial velocity of 44 m/s. In the interval between $x = 50$ mm and $x = 140$ mm, the velocity fluctuations transitioning from the undisturbed flow region to the jet stream demonstrate a pronounced slope before stabilising at a constant value of around 32 m/s. Further downstream, at $x = 190$ mm, a similar trend is observed, albeit with a smaller constant value.

4 Conclusions

A comprehensive experimental investigation was conducted on a highly integrated, high-aspect ratio rectangular nozzle embedded in a wing-blended body configuration, featuring a two-dimensional blended nozzle as part of the propulsion system. Tests were performed at a Mach number of 0.69, with the jet exhausting into undisturbed ambient air.

The inlet duct conditions were characterised by two pressure probe rakes, providing a small asymmetry from the upper and lower duct sides and from the left and right region. A non-uniform pressure distribution was measured due to the S-shape nozzle geometry and the variation from elliptical to rectangular shape. Different pressure distribution from upper and lower surfaces were measured due to the marked geometry differences.

The flow field velocity measurements depicted the expected asymmetry from the upper and lower jet shear layers. The upper one was thicker and more developed with respect to the lower one. The velocity behaviour showed an upward deflection of the jet flow in both the longitudinal and the spanwise directions.

A preliminary investigation on the velocity fluctuations indicates that in both velocity components, the lower shear layer presents higher intensity and merges with the upper shear layer at about four nozzle heights from the nozzle trailing edge, resulting in a highly fluctuating region parallel to the trailing edge on the horizontal symmetry plane.

The inlet duct flow characterisation with the pressure distribution, the previous acoustic and flow turbulence measurements together with the current PIV measurements, will provide a reliable experimental dataset for future comparisons with CFD and Large-Eddy Simulations (LES).

5 Acknowledgements

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