

Total Pressure Distortion Reconstruction Methods from Velocimetry Data within an Aero-engine Intake at Crosswind

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Abstract

The integration of Very High Bypass Ratio (VHBR) turbofan engines with short intakes may present challenges due to increased total pressure distortion, particularly under crosswind conditions. Current industrial practices rely on a limited number of intrusive pressure sensors arranged on rakes at the Aerodynamic Interface Plane (AIP), to characterise this total pressure distortion. However, non-intrusive measurement techniques provide a more effective way to capture the complex, unsteady flow fields within the intake, offering higher spatial resolution compared to conventional methods. In this study, velocity data obtained from Stereoscopic Particle Image Velocimetry (S-PIV) during wind tunnel tests of a short intake configuration were employed to reconstruct the instantaneous total pressure fields at the AIP within the intake. Two reconstruction methods were used: Direct Spatial Integration (DSI) of the momentum equation and the Poisson Pressure Equation (PPE). These methods were first applied to numerical data from RANS simulations. The results of the reconstruction of the total pressure field based on the S-PIV data were compared against rake measurements. The methods enabled a more comprehensive assessment of total pressure distortion, offering improvements over conventional sensor-based approaches in identifying and characterising total pressure non-uniformities within an intake.

Keywords: Pressure-from-velocity reconstruction, short intake, crosswind, Stereoscopic Particle Image Velocimetry

1. Introduction

Total pressure distortion plays a key role in the integration of an aero-engine with its intake [1][2]. High levels of flow non-uniformity at the engine entry can significantly affect intake/engine aerodynamic and mechanical compatibility [3]. This issue is particularly exacerbated in short intake designs coupled with Very High Bypass Ratio (VHBR) turbofan engines. In efforts to reduce fuel burn penalties caused by the increased weight and drag of large fan diameter engines [4], intakes may need to be shortened [5]. However, short intake designs are more prone to flow separation and higher levels of flow non-uniformity compared to conventional, longer configurations [6][7]. Consequently, a detailed understanding of the unsteady flow field in a short intake is essential and particularly under off-design conditions, such as crosswind with a ground plane, where inlet flow distortions are inherently more complex [1].

Current industry standards rely on a limited number of intrusive pressure sensors which are typically arranged on rakes at the Aerodynamic Interface Plane (AIP) between the intake and the engine, to characterise intake flow fields [1]. However, due to the intrusive nature of total pressure measurements and the subsequent blockage effect prevent the use of a sufficient number of sensors to capture the full spatial complexity of the flow [8]. As a result, important flow details may be overlooked, thereby limiting the understanding of the unsteady distortion within the intake.

Recent research has successfully demonstrated the application of non-intrusive optical methods in wind tunnel environments [9] to measure unsteady velocity fields across a plane within an intake [10][11]. These measurements, conducted using Stereoscopic Particle Image Velocimetry (S-PIV), achieved spatial resolution approximately two orders of

magnitude greater than that provided by conventional methods [8].

Pressure reconstruction techniques, based on velocity measurements, have been developed in recent years to estimate total pressure from velocity data by reconstructing the AIP static and total pressure fields. These methods have proven reliable in various applications [12]-[18], particularly for determining aerodynamic forces on airfoils [19]-[25]. More recently, Frascella et al. [26] applied pressure reconstruction techniques to estimate the AIP total pressure field using numerical velocity data for an S-duct, enabling the assessment of total pressure distortion within the intake with high spatial and temporal resolution.

In this work, unsteady S-PIV velocity data obtained during an experimental study of an intake configuration in crosswind conditions in a wind tunnel [11], were used to reconstruct the instantaneous total pressure fields at the AIP. These instantaneous reconstructed total pressure data were then time-averaged to calculate the total pressure ratio distributions at the AIP within the intake and were used to estimate the time-averaged total pressure distortion characteristics. Two methods were employed for the reconstruction: the Direct Spatial Integration (DSI) of the momentum equation and the solution of the Poisson Pressure Equation (PPE). The results were compared with steady-state total pressure distortion measurements to assess the accuracy of the reconstruction techniques. To validate the methods, they were first applied to numerical data from steady-state (RANS) CFD simulations at similar intake operating conditions. This research represents a significant advancement in the measurement of synchronous, unsteady total pressure and swirl distortion using non-intrusive techniques, which has not been demonstrated before for a civil intake configuration.

2. Methodology

2.1. Experimental set-up

The experiments were carried out in the Low-Speed Tunnel at the German-Dutch Wind Tunnels (LST-DNW). This facility is a continuous, atmospheric wind tunnel designed for low-speed testing at a maximum achievable tunnel velocity of 80 m/s under empty conditions, featuring a test section of $3.022 \times 2.25 \text{ m}^2$. A schematic of the wind tunnel's test section is shown in Figure 1. A full account of the experimental set-up, instrumentation, and PIV arrangements is reported in [11].

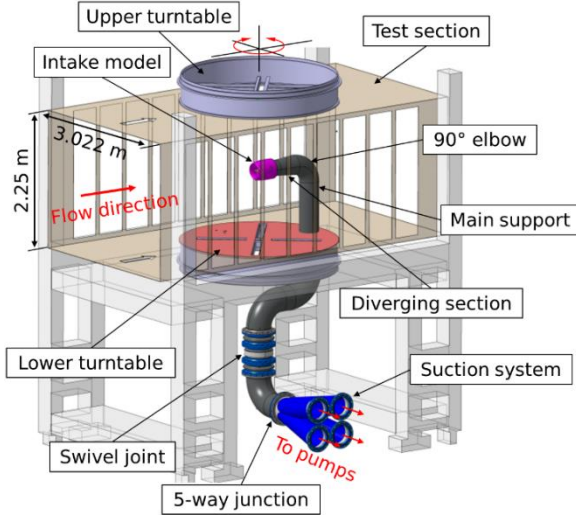


Figure 1 – Schematic of the LST-DNW wind tunnel test section.

The intake model was positioned at the centre of the test section and installed on a 90-degree bent duct that functioned as both suction system and model support. Four suction pumps were used to drive airflow through the model, which was placed on the wind tunnel turntable and oriented perpendicular to the flow to simulate crosswind conditions. A ground plane, which spanned the full width of the wind tunnel test section, was installed below the model at a fixed non-dimensional ground clearance of $h/D_{hi} = 0.3$, with h the distance between the ground base and the lowest point of the intake highlight plane, and D_{hi} the intake highlight diameter.

The test article was a scaled short intake with a conical centre-body, representative of a modern Very High Bypass Ratio (VHBR) turbofan engine intake configuration. The intake performance under crosswind conditions, with a ground plane at a fixed ground clearance, was investigated for different values of freestream velocity V_∞ (from 2.5 to 43 kts, or equivalently from 1.3 to 22.1 m/s, respectively) and intake mass flow rate $\dot{m}$. This resulted in different combinations of the intake Mass Flow Capture Ratio (*MFCR*) [27]:

$$MFCR = \frac{A_\infty}{A_{hi}} = \frac{\dot{m}}{\rho_\infty V_\infty A_{hi}} \quad (1)$$

with ρ_∞ the freestream air density and A_{hi} the intake highlight area. The Reynolds number Re was defined in terms of the intake inner diameter D_i and freestream velocity V_∞ :

$$Re = \frac{\rho_\infty V_\infty D_i}{\mu} \quad (2)$$

and ranged between 0.3×10^5 and 3.5×10^5 . To prevent early laminar separation boundary layer trips were used on the outer surface of the intake. Velocity measurements were performed using a multi-camera Stereoscopic Particle Image Velocimetry (S-PIV) set-up consisting of six LaVision Imager sCMOS cameras, as described in [11]. The flow was seeded with di-ethyl-hexyl sebacate (DEHS) particles of 1 micrometer median diameter. PIV measurements were acquired at a frequency of 15 Hz. Each PIV dataset consisted of 1,000 snapshots. The diameter of the measurement plane was 250 mm, and the spatial resolution was 1.5 mm in both directions, resulting in approximately 18,000 3D velocity vectors across the AIP. The post-processing of the PIV images was performed using LaVision's DaVis 11 software.

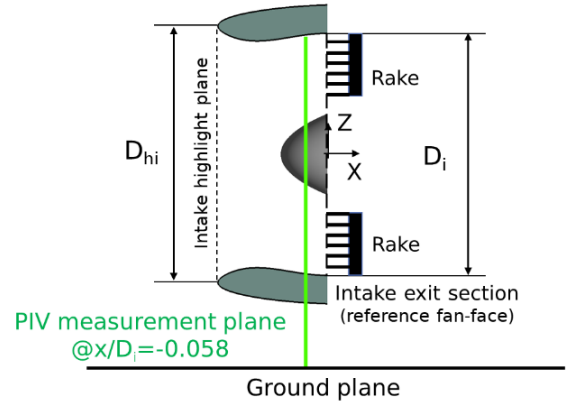


Figure 2 – Axial location of the S-PIV measurement plane within the intake.

A total of 80 pressure probes was installed at the intake exit section on 8 radial rakes, with each rake containing 10 probes (Figure 3). The intake model was also equipped with 194 lip pressure taps positioned at 10 azimuthal locations around the intake surface and 4 total temperature sensors.

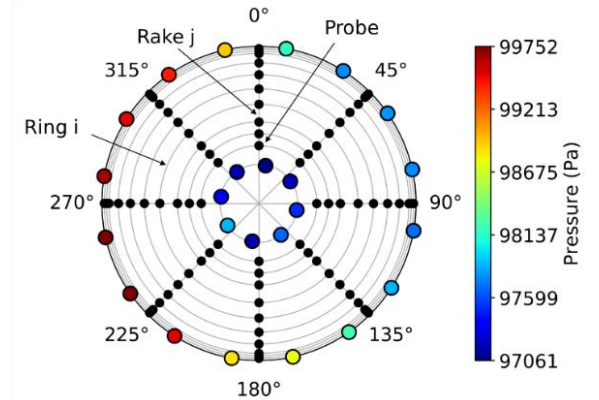


Figure 3 – Total pressure probes on the instrumented rake at the intake exit section (black markers) and circumferential static pressure taps used as boundary conditions for the pressure from velocity reconstruction.

A set of 24 static pressure taps was installed inside the intake to enable pressure reconstruction from velocity (Figure 3). Of these, 16 equally spaced pressure ports were located on the inner surface of the intake at intervals of 22.5° , starting from $\theta = 10^\circ$. These were located at an axial position in-line with the total pressure measurement plane. The remaining 8 static pressure taps were evenly distributed around the

surface of the centre-body at 10°, 55°, 100°, 145°, 190°, 235°, 280°, and 325°, at an axial location 2 mm upstream of the intake exit section. The static-pressure and total-pressure measurements were taken by means of a set of 6 Scanivalve ZOC (Zero Operate and Calibrate) modules. Each module had a range of ± 100 kPa with an uncertainty of 0.1%. The acquisition of the steady-state pressure data was conducted at a frequency of 10 Hz and averaging over a time of 20 s.

2.2. Computational model

Steady CFD simulations were conducted to generate numerical data for the verification of the pressure field reconstruction methods, which were later applied to the experimental velocity data. The computational domain (Figure 4) was a rectangular volume measuring $25D_{hi} \times 25D_{hi} \times 12.5D_{hi}$ in the x, y, and z directions, respectively, as that recommended by the 5th AIAA Propulsion Aerodynamic Workshop [28] and used in different computational studies on a similar configuration [29]–[32].

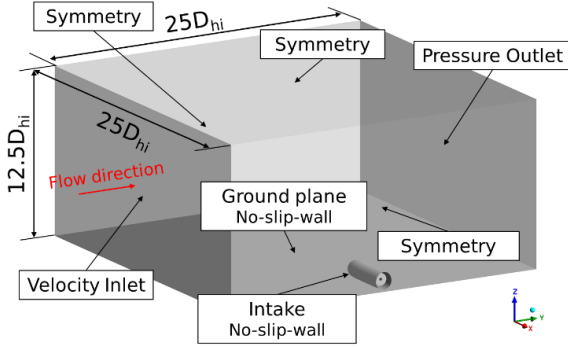


Figure 4 – Schematic of the computational domain used for the CFD simulations and boundary conditions.

A simplified geometry was used to reduce meshing complexity and computational time, excluding the support structure and suction system, the centre-body struts, and the instrumented rake inside the intake. To improve numerical convergence, the intake duct was extended by approximately $3.5D_{hi}$ downstream of the intake exit section. A fully structured, multi-block grid with about 19 million elements was generated using Cadence Fidelity Pointwise. Multiple inflation layers were included to ensure a non-dimensional wall distance of $y^+ < 1$ on the intake surfaces and on the ground plane, for proper resolution of the boundary layer. The boundary conditions shown in Figure 4 were applied to the various surfaces of the computational domain. A velocity-inlet boundary condition was applied at the domain inlet by specifying the corresponding experimental crosswind velocity for each case, while the domain outlet was set as a pressure-outlet, assuming ambient static pressure. A pressure-outlet condition with a target mass flow rate was applied at the intake exit. No-slip boundary conditions were imposed on both the ground plane and the intake surface, while the remaining surfaces were set as symmetry planes to prevent the domain from influencing the flow field around and within the intake. The freestream turbulence was specified in terms of turbulent intensity and hydraulic diameter of the wind tunnel $D_h = 4A/p$, with A cross-sectional area and p the wetted perimeter of the cross-section. A density-based implicit solver was used with second-order upwind spatial

discretization, Roe-FDS flux, and a Green-Gauss node-based gradient calculation [33][34]. The flow was modelled as compressible and fully turbulent, with viscosity modelled using the three-coefficient Sutherland's Law. The SST $k - \omega$ turbulence model [35] was chosen.

2.3. Pressure from velocity reconstruction methods

The reconstruction of the pressure field from the measured time-resolved velocity data was performed by considering the conservative form of the momentum equation:

$$\rho \left(\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \nabla \vec{u} \right) = -\nabla p + \mu \nabla^2 \vec{u} \quad (3)$$

with ρ and μ density and dynamic viscosity, respectively. Assuming a two-dimensional, incompressible, and inviscid flow, since the contribution of the viscous terms is negligible for sufficiently high Reynolds numbers ($Re > 10^3$, [36]), the pressure gradient ∇p in Equation (3) can be written as a function of the velocity field $\vec{u}$ as:

$$\nabla p = -\rho \left(\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \nabla \vec{u} \right) \quad (4)$$

Equation (4) was solved in cylindrical coordinates on the circular AIP:

$$\frac{\partial p}{\partial r} = -\rho \left(\frac{\partial v_r}{\partial t} + v_r \frac{\partial v_r}{\partial r} + \frac{v_\theta}{r} \frac{\partial v_r}{\partial \theta} - \frac{v_\theta^2}{r} + w \frac{\partial v_r}{\partial z} \right) \quad (5)$$

$$\frac{1}{r} \frac{\partial p}{\partial \theta} = -\rho \left(\frac{\partial v_\theta}{\partial t} + v_r \frac{\partial v_\theta}{\partial r} + \frac{v_\theta}{r} \frac{\partial v_\theta}{\partial \theta} - \frac{v_r v_\theta}{r} + w \frac{\partial v_\theta}{\partial z} \right) \quad (6)$$

by converting the S-PIV velocity field $\vec{u}(u, v, w)$ in Cartesian coordinates (x, y, z) into $\vec{u}(v_r, v_\theta, w)$ in the cylindrical frame of reference (r, θ, z) . A polar grid with 180 equispaced circumferential rings and 49 equally spaced rakes (Figure 5a) was used to discretise the reconstruction plane, with a spatial resolution similar to that of the S-PIV measurements. Equations (5) and (6) allow the calculation of the AIP pressure gradients using only spatial and temporal velocity derivatives and the pressure field can then be obtained by direct spatial integration (DSI), following the method outlined by Baur and Koenigter [37] and adapted to a polar grid by Frascella et al. [26].

The second approach used to reconstruct the pressure field involved solving the Poisson Pressure Equation (PPE):

$$\nabla^2 p = -\rho \nabla \cdot \left(\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \nabla \vec{u} \right) \quad (7)$$

Equation (7) is derived from Equation (4) by applying the divergence operator and considering that $\nabla \cdot \vec{u} = 0$ for an incompressible flow. Similar to Equation (4), Equation (7) can be expressed in cylindrical coordinates as:

$$\begin{aligned} \nabla^2 p = -\rho \nabla \cdot \left(\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \nabla \vec{u} \right) &= \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial p}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 p}{\partial \theta^2} + \frac{\partial^2 p}{\partial z^2} \\ &= -\rho \left(\frac{1}{r} \frac{\partial v_r}{\partial t} + \frac{\partial^2 v_r}{\partial r \partial t} + \frac{1}{r} \frac{\partial^2 v_\theta}{\partial \theta \partial t} + \frac{\partial^2 w}{\partial z \partial t} \right) \\ &\quad - \rho \left[\left(\frac{\partial v_r}{\partial r} \right)^2 + \frac{1}{r^2} \left(\frac{\partial v_\theta}{\partial \theta} \right)^2 + \left(\frac{\partial w}{\partial z} \right)^2 \right. \\ &\quad \left. + \frac{2}{r} \frac{\partial v_\theta}{\partial r} \frac{\partial v_r}{\partial \theta} + 2 \frac{\partial w}{\partial r} \frac{\partial v_r}{\partial z} + \frac{2}{r} \frac{\partial w}{\partial \theta} \frac{\partial v_\theta}{\partial z} + \left(\frac{v_r}{r} \right)^2 \right. \\ &\quad \left. - \frac{2v_\theta}{r} \frac{\partial v_\theta}{\partial r} + \frac{2v_r}{r^2} \frac{\partial v_\theta}{\partial \theta} \right] \end{aligned} \quad (8)$$

To calculate the pressure field across the plane, a circumferential static pressure distribution is required as a boundary condition. For the direct spatial integration of Equation (4), a circumferential pressure distribution along the grid's outer boundary was applied as boundary condition. This distribution was obtained through linear interpolation of the steady-state static pressure readings from the 16 static pressure taps positioned around the inner surface of the intake (Figure 3). To solve the Poisson Pressure Equation within the polar domain, an additional boundary condition was needed on the inner boundary, corresponding to the surface of the centre-body. This inner boundary was treated using either a Dirichlet boundary condition, by imposing the pressure distribution measured from the 8 taps located on the centre-body surface, or a Neumann boundary condition, by considering a virtual boundary within the domain, following the approach outlined by Frascella et al. [26].

The radial and circumferential velocity gradients in Equation (5) and Equation (6) were calculated using central finite difference approximations. Since data from only one PIV measurement plane was available, the out-of-plane partial derivatives ($\partial \vec{u}/\partial z$) were not evaluated. Similarly, time derivatives ($\partial \vec{u}/\partial t$) were omitted from the calculations, since including these terms when only temporally under-resolved velocity data is available, and without out-of-plane velocity gradients, was found to yield inaccurate estimations of static pressure gradients [26][38]. The influence of out-of-plane and temporal derivatives on the accuracy of the reconstructed pressure fields was previously investigated by Montenegro Pascual [38] using numerical data from an S-duct subsonic diffuser. The study concluded that omitting either the time derivatives or the out-of-plane gradients yield a significant increase in reconstruction error. When both derivatives were omitted, the error was lower than when only one derivative was excluded. Similar trends were observed for the distortion descriptors, where neglecting derivative increased error, particularly for DC60, while pressure recovery remained largely unaffected.

The integration of the pressure gradients across the discretised circular plane was performed by using the approach reported by Frascella et al. [26]. The static pressure at any point within the plane was determined using previously calculated pressure values from four adjacent points, with the calculation proceeding inward from the outer boundary where the static pressure is prescribed.

To account for compressibility effects, the ideal gas law $\rho = p/RT$ was used to derive the fluid density, while the static temperature was calculated by assuming constant total enthalpy as a function of the velocity magnitude:

$$T_0 = T + \frac{1}{2} \frac{V^2}{c_p} \quad (9)$$

where T_0 is the total temperature, V is the velocity magnitude, and c_p is the air specific heat at a constant pressure. Assuming adiabatic flow and introducing the above expressions into the momentum equation, the pressure gradient was calculated in terms of the velocity field, by specifying only the total temperature T_0 :

$$-\nabla p = -\rho \left(\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \nabla \vec{u} \right) = \frac{p}{RT} \left(\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \nabla \vec{u} \right) \quad (10)$$

$$-\frac{\nabla p}{p} = \frac{1}{R \left(T_0 - \frac{1}{2} \frac{V^2}{c_p} \right)} \left(\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \nabla \vec{u} \right) = -\nabla \ln p \quad (11)$$

The total temperature T_0 , used in the calculation, was the average total temperature measured within the intake, obtained from the readings of the four temperature sensors installed on the instrumented rake at the intake exit section.

To solve the Poisson Pressure Equation, the pressure terms on the left-hand side of Equation (8) were calculated using a second order central derivative scheme. The spatial velocity derivatives on the right-hand side were calculated using a central finite difference approximation, as done previously. The static pressure at each grid point across the discretised plane was then determined using an iterative Gauss-Seidel method with successive over-relaxation. The convergence criterion was defined such that the residuals, calculated as the absolute difference between the pressure values of successive iterations, fell below 10^{-6} . Additionally, a stopping criterion was imposed to end the iteration process if the number of iterations reached 10,000. The optimal successive over-relaxation (SOR) factor was determined as 0.98 based on past work [26]. The total time required to reconstruct an instantaneous flow field was approximately 2 seconds per iteration with the DSI method and 2 minutes per iteration with the PPE method. For a full dataset of 1000 iterations, this resulted in a total reconstruction time of 33 minutes for DSI and approximately 33 hours for PPE. The iterative calculation was initialised with a static pressure distribution derived from isentropic relations, assuming constant density, applied at each point of the grid across the AIP. No modification to the Poisson Pressure Equation was applied to account for compressibility.

2.4. Total pressure distortion assessment

To quantify the total pressure distortion at the AIP, the Intake Pressure Recovery IPR and the Distortion Coefficient $DC60$ were calculated:

$$IPR = \frac{\overline{p_{0AIP}}}{P_{0\infty}} \quad (12)$$

$$DC60 = \frac{\overline{p_{0AIP}} - \overline{p_{060^\circ}}}{\overline{q_{AIP}}} \quad (13)$$

where $\overline{p_{0AIP}}$ is the area-averaged total pressure at the AIP, $P_{0\infty}$ denotes the freestream total pressure, $\overline{p_{060^\circ}}$ is the area-averaged total pressure in the most distorted sector of 60° extent, and $\overline{q_{AIP}}$ is the area-averaged dynamic pressure at the AIP. Both metrics, IPR and $DC60$, were computed using an area-average method based on a ring-rake approach, following industrial [1].

The circumferential and radial variations in the total pressure field within the intake were also quantified by means of the conventional Circumferential Distortion Index (IDC) and Radial Distortion Index (IDR) [1], defined on a ring-by-ring basis. The circumferential distortion descriptor IDC (14) is defined as follows:

$$IDC = \max \left[\frac{1}{2} (IDC_i + IDC_{i+1}) \right] \quad (14)$$

where:

$$IDC_i = \frac{\overline{p_{0i}} - p_{0min,i}}{\overline{p_{0AIP}}} \quad (15)$$

and $\overline{p_{0i}}$ and $p_{0min,i}$ are the average and minimum total pressure values in the i -th ring, respectively. The radial distortion descriptor IDR is defined as the maximum between the IDR_i evaluated at the inner and outer ring:

$$IDR = \max(IDR_{in}, IDR_{out}) \quad (16)$$

$$IDR_i = \frac{\overline{p_{0AIP}} - \overline{p_{0i}}}{\overline{p_{0AIP}}} \quad (17)$$

where i is in or out.

To calculate the total pressure distortion descriptors, the pressure fields reconstructed from the CFD and PIV data

were first down sampled to 80 points, distributed across 8 rakes and 10 rings, to match the resolution of the total pressure rake measurements (Figure 5b). The total pressure fields were then interpolated onto a 24×10 grid, resulting in a circumferential resolution of 15° (Figure 5c). This is the minimum resolution required to calculate the distortion coefficient (DC) based on a spoiled sector of 60° , on which pressure distortion descriptors were calculated. Although rake measurements do not provide a definitive reference for assessing the accuracy of reconstruction method, due to their lower spatial resolution and inability to capture features like the ground vortex, the reconstructed distortion coefficients were compared to those from interpolated rake data to ensure consistency with the experimental setup and available measurements.

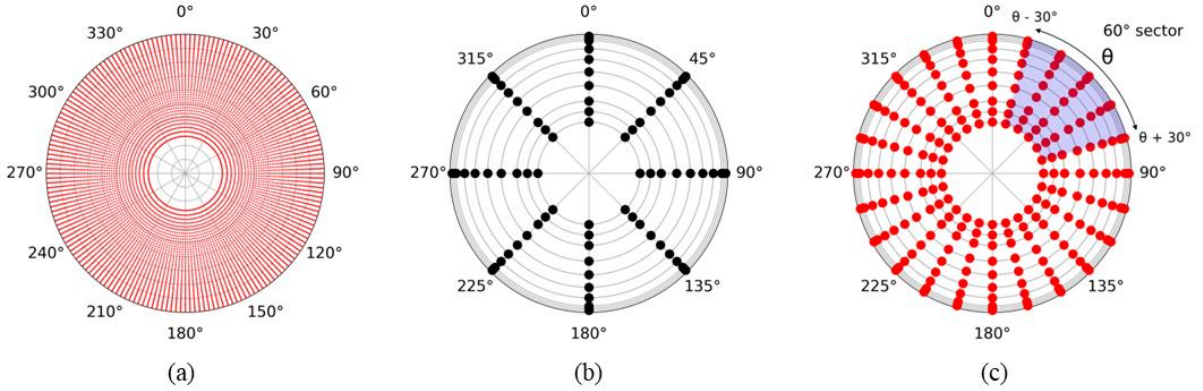


Figure 5 – Grid resolutions used for the pressure reconstruction workflow: (a) 180×49 grid used for pressure-from-velocity reconstruction; (b) 8×10 grid matching the measurement arrangement; (c) 24×10 grid used for calculating total pressure distortion descriptors.

3. Results and discussion

The reconstruction of the static pressure fields at the Aerodynamic Interface Plane (AIP) was performed using initially numerical data and subsequently PIV measurements. After computing the static pressure, the total pressure p_0 at each point across the AIP was determined by using the equation:

$$p_0 = p + q \quad (18)$$

for incompressible reconstruction where p represents the reconstructed static pressure values and $q = 1/2\rho V^2$ the dynamic pressure, or, for compressible reconstruction by using the isentropic relation:

$$p_0 = p \left(1 + \frac{\gamma - 1}{2} M^2 \right)^{\frac{\gamma}{\gamma - 1}} \quad (19)$$

To assess the accuracy of the pressure reconstruction based on numerical data from steady-state (RANS) simulations, the reconstructed total pressure ratio ($PR = p_0/P_{0\infty}$) distributions at the AIP were compared with those obtained from the CFD. The percentage discrepancy in total pressure relative to the CFD values was calculated as:

$$\Delta p_{0\%} = \left(\frac{p_{0rec} - p_{0CFD}}{p_{0CFD}} \right) \cdot 100\% \quad (20)$$

The discrepancy between the distortion metrics, calculated from the reconstructed total pressure fields and those obtained from CFD total pressure data, was quantified as:

$$\Delta X = X_{rec} - X_{CFD} \quad (21)$$

where X_{rec} is the distortion parameter calculated from the reconstructed total pressure, and X_{CFD} is the same descriptor calculated from the actual CFD total pressure data.

To evaluate the accuracy of the pressure reconstruction from PIV data, the time-averaged reconstructed total pressure ratio ($\langle PR \rangle = \langle p_0 \rangle / P_{0\infty}$) distributions at the AIP were compared with the experimental steady-state total pressure fields obtained under similar operating conditions, in terms of crosswind velocity and Mass Flow Capture Ratio ($MFCR$), as synchronous total pressure measurements were not taken during the PIV acquisition. The time-averaged reconstructed total pressure field was obtained by averaging the instantaneous reconstructed total pressure fields over time. In this case, the discrepancy between the time-averaged distortion metrics from the reconstructed total pressure fields and those calculated from the measured total pressure values was determined as:

$$\Delta X = X_{rec} - X_{exp} \quad (22)$$

where X_{rec} is the distortion parameter calculated from the reconstructed total pressure data from velocity data, and X_{exp} is the same descriptor calculated from the rake measured total pressure values.

3.1. Pressure field reconstruction from CFD data

CFD based total pressure reconstructions were performed by calculating the steady-state pressure fields at the AIP for three cases, all at constant crosswind velocity of 15 kts (7.7 m/s) and increasing *MFCR* of 5.9, 12.4, and 17.3, respectively. These cases were characterised by low-speed (diffusion-driven) separation, attached flow, and high-speed (shock-induced) separation, respectively [11]. The pressure reconstruction was performed using both the DSI method and the PPE methods. The CFD-based reconstructed steady-state total pressure ratio distributions at the AIP for the three cases considered, along with the contours of the relative percentage error ($\Delta p_{0\%}$), are presented in Figure 6, Figure 7, Figure 8, and are compared with the normalised total pressure fields obtained from the CFD simulations. The discrepancies between the distortion metrics calculated from the reconstructed total pressure fields and those obtained from the numerical total pressure values are summarised in Table 1, Table 2, and Table 3.

The case at *MFCR* = 5.9 (Figure 6a) is characterised by the presence of a ground vortex and a significant circumferential pressure variation across the AIP due to diffusion-driven separation. All methods used to reconstruct the steady-state total pressure field effectively capture the large separation region on the windward side of the intake, in both radial and circumferential extent. However, the DSI method, both with (Figure 6b) and without (Figure 6c) compressibility correction, tends to distort the ingested ground vortex compared to the PPE method (Figure 6d and Figure 6e). This is also reflected in the contours of $\Delta p_{0\%}$ (Figure 6b and Figure 6c, bottom row), which show slightly higher relative errors around the vortex region. This is primarily due to error propagation in the DSI scheme, where pressure calculations proceed from the outer boundary towards the centre, accumulating errors at each step of the algorithm and distorting the vortex core. Additionally, the total pressure deficit within the vortex core is overestimated by the DSI method compared to the CFD data. The pressure field reconstructed using the PPE method (Figure 6d and Figure 6e) shows the closest agreement to the CFD results (Figure 6a). Overall, the error in the calculation of the total pressure relative to CFD data is relatively low, indicating that at this low *MFCR*, the flow can still be treated as incompressible without compromising the accuracy of the reconstruction. The distortion descriptors calculated from the total pressure data for this case at low *MFCR* (Table 1) all show close agreement with the CFD-based descriptors. The overall accuracy is comparable across all methods, with the smallest discrepancies found in the calculation of intake pressure recovery. The largest discrepancies are seen in the calculation of the Distortion Coefficient (*DC60*) and the Radial Distortion Index (*IDR*).

At *MFCR* = 12.4 (Figure 7a), the flow within the intake is

attached, with total pressure variations at the AIP primarily caused by the ingested ground vortex. In this scenario, all reconstruction methods provide a pressure field that closely resembles the numerical one, with low numerical errors. Notably, the PPE method with mixed boundary conditions (Figure 7d) shows the closest agreement with the CFD data. In contrast, the PPE method with Dirichlet boundary conditions (Figure 7e) is influenced by the pressure distribution applied as a boundary condition on the centre-body surface, which affects the reconstruction in the inner part of the computational domain. At this intermediate *MFCR* value, compressibility effects are still not significant, so the incompressible assumption remains valid. The reconstructed distortion descriptors for *MFCR* = 12.4 (Table 2) shows a higher discrepancy from the directly calculated ones than the descriptors at *MFCR* = 5.9 (Table 1). The highest discrepancies are observed for the *DC60*, while the inlet pressure recovery is reasonably well predicted by both methods.

For the case at *MFCR* = 17.3 (Figure 8), where shock-induced separation occurs, the assumption of incompressibility is no longer valid. Although all methods effectively capture the circumferential and radial extent of the separated region on the windward side of the intake, the effect of compressibility becomes evident in the undisturbed flow region of the AIP for the methods without compressibility correction (Figure 8c, Figure 8d, and Figure 8e, top row). In these cases, the relative percentage errors are notably high (Figure 8c, Figure 8d, and Figure 8e, bottom row). The compressibility, along with the deformation of the ground vortex and the overestimation of total pressure deficits in the vortex core, affects the calculation of the descriptors from the reconstructed data (Table 3). Although the DSI method with compressibility correction exhibits the largest discrepancy in the calculation of the *DC60* (due to the vortex deformation and fictitious total pressure deficit in the central region of the AIP), its accuracy in calculating the other descriptors is relatively better compared to the other methods.

Overall, the DSI method with compressibility correction, despite slightly deforming the ground vortex core, provides reasonably accurate reconstructions in terms of total pressure distortion descriptors and $\Delta p_{0\%}$ across the entire range of *MFCR*, particularly at high *MFCR* and in presence of shock-induced separation, where compressibility effects cannot be ignored. The PPE method with mixed boundary conditions provides accurate flow field reconstructions at low and mid *MFCR*, when the flow is either attached, or when a diffusion-driven separation occurs and yields accurate descriptor estimates. At high *MFCR*, its accuracy is influenced by compressibility effects.

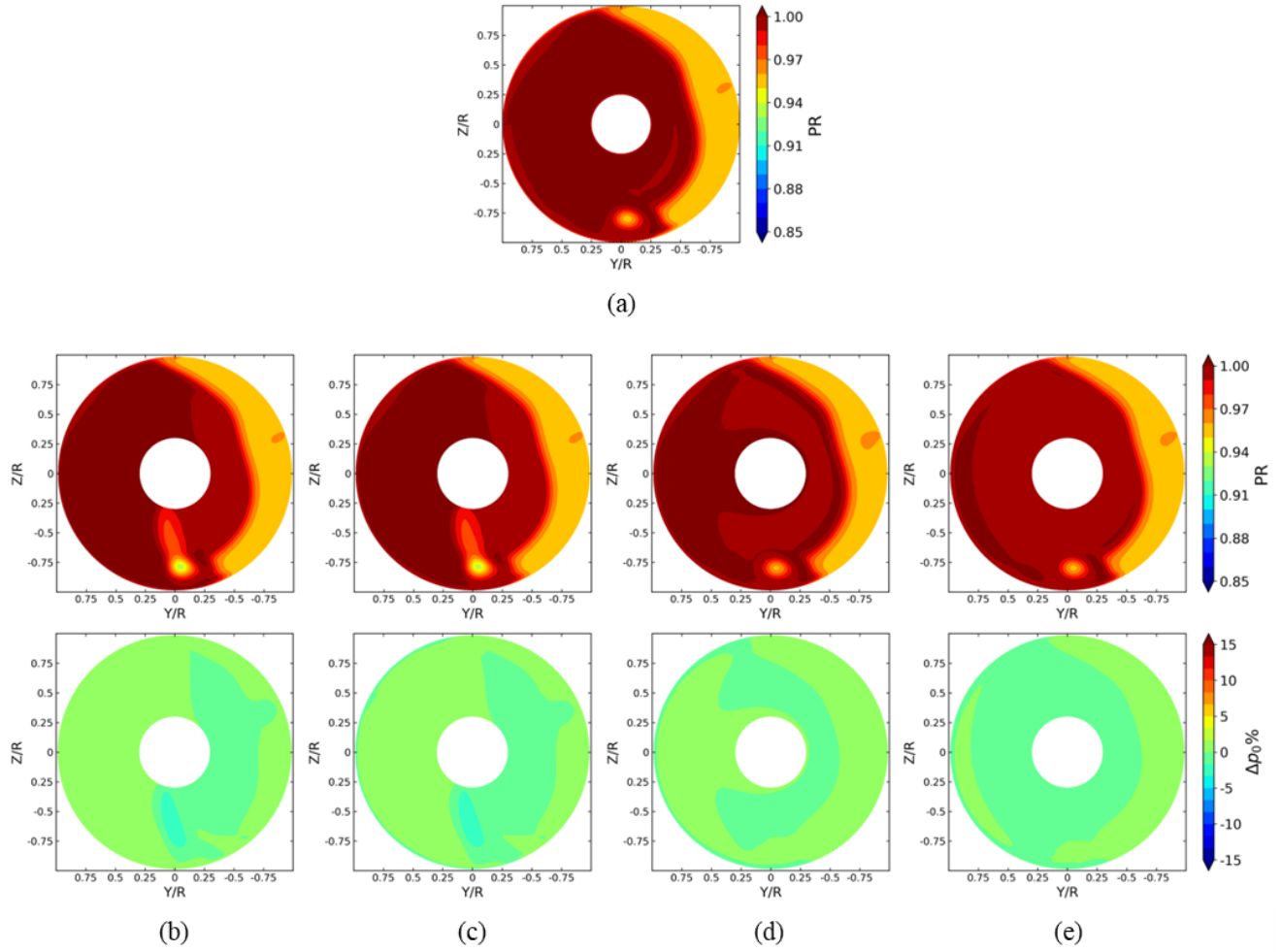


Figure 6 – Computed and reconstructed AIP total pressure ratio distributions for the case at 15 kts and $MFCR = 5.9$: (a) RANS computed steady total pressure ratio distribution; (b) DSI method, compressible; (c) DSI method, incompressible; (d) PPE method, incompressible with mixed boundary conditions; (e) PPE method, incompressible with Dirichlet type boundary conditions. (b)-(e) top row: reconstructed total pressure distributions. (b)-(e) bottom row: percentage discrepancy relative to the RANS predicted total pressure distribution. Crosswind direction from right to left (view looking downstream).

Table 1 – Distortion descriptor discrepancies for the different reconstruction methods at $MFCR = 5.9$.

Reconstruction method			ΔIPR	$\Delta DC60$	ΔIDC	ΔIDR
<i>Scheme</i>	<i>Compressibility</i>	<i>BCs</i>				
DSI	YES	mixed	0.000	+0.029	+0.001	-0.002
DSI	NO	mixed	-0.001	+0.023	0.000	-0.002
PPE	NO	mixed	+0.001	-0.011	-0.001	-0.001
PPE	NO	Dirichlet	-0.001	-0.038	-0.001	-0.002

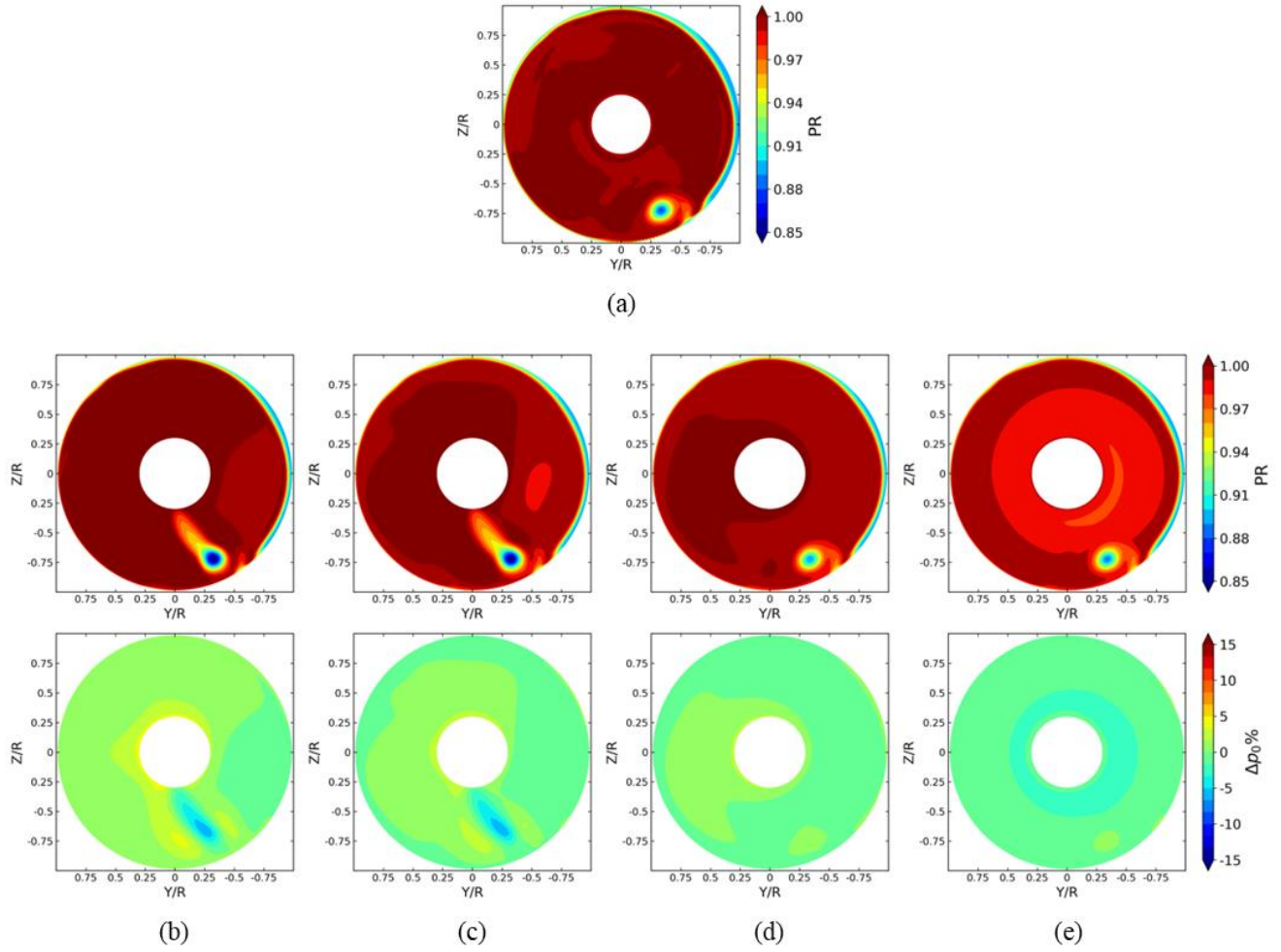


Figure 7 – Computed and reconstructed AIP total pressure ratio distributions for the case at 15 kts and $MFCR = 12.4$: (a) RANS computed steady total pressure ratio distribution; (b) DSI method, compressible; (c) DSI method, incompressible; (d) PPE method, incompressible with mixed boundary conditions; (e) PPE method, incompressible with Dirichlet type boundary conditions. (b)-(e) top row: reconstructed total pressure distributions. (b)-(e) bottom row: percentage discrepancy relative to the RANS predicted total pressure distribution. Crosswind direction from right to left (view looking downstream).

Table 2 – Distortion descriptor discrepancies for the different reconstruction methods at $MFCR = 12.4$.

Reconstruction method			ΔIPR	$\Delta DC60$	ΔIDC	ΔIDR
<i>Scheme</i>	<i>Compressibility</i>	<i>BCs</i>				
DSI	YES	mixed	+0.010	+0.044	0.000	-0.010
DSI	NO	mixed	+0.002	+0.038	-0.003	-0.014
PPE	NO	mixed	0.000	+0.015	-0.003	-0.016
PPE	NO	Dirichlet	-0.009	-0.000	-0.003	-0.025

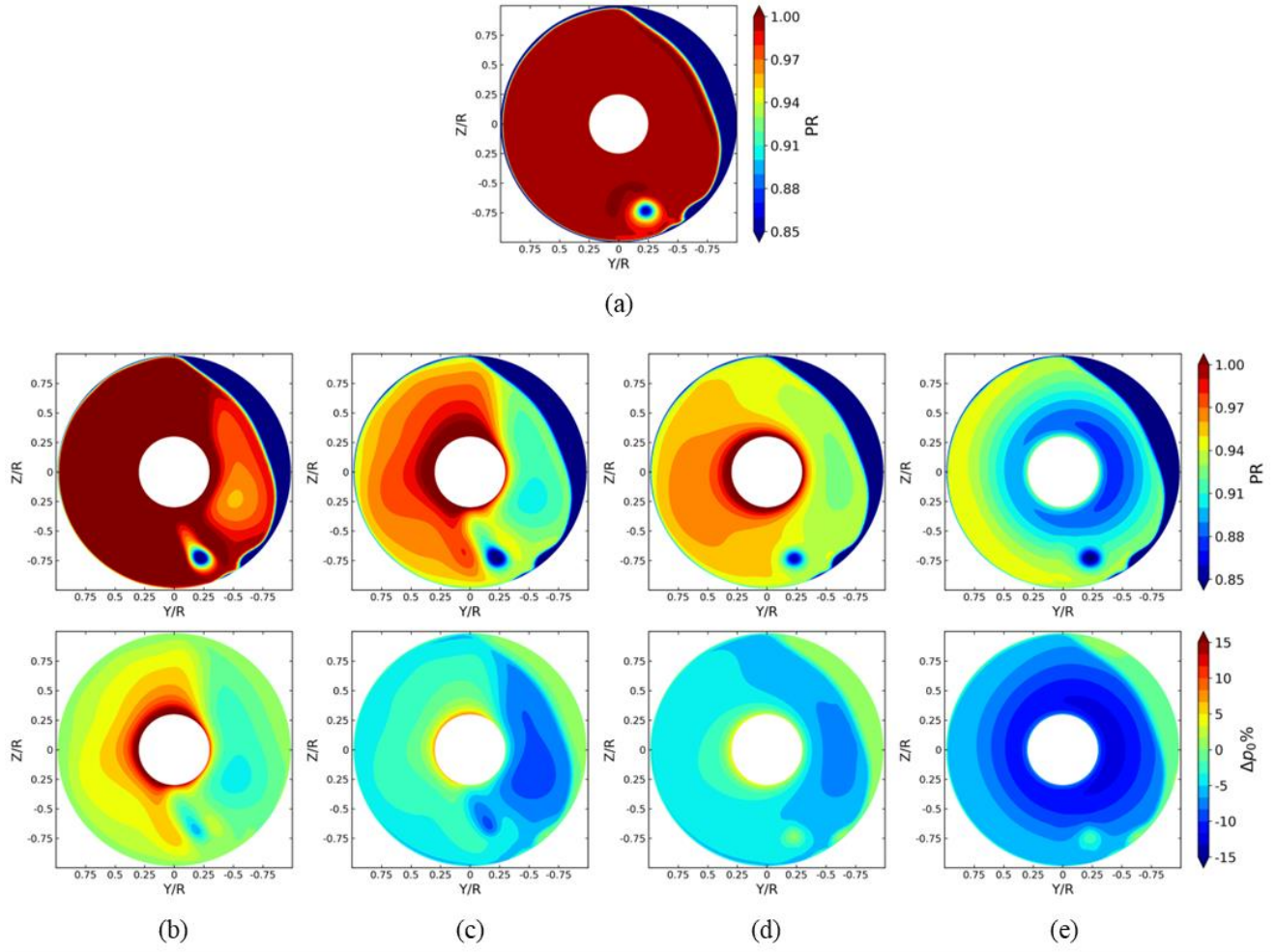


Figure 8 – Computed and reconstructed AIP total pressure ratio distributions for the case at 15 kts and $MFCR = 17.3$: (a) RANS computed steady total pressure ratio distribution; (b) DSI method, compressible; (c) DSI method, incompressible; (d) PPE method, incompressible with mixed boundary conditions; (e) PPE method, incompressible with Dirichlet type boundary conditions. (b)-(e) top row: reconstructed total pressure distributions. (b)-(e) bottom row: percentage discrepancy relative to the RANS predicted total pressure distribution. Crosswind direction from right to left (view looking downstream).

Table 3 – Distortion descriptor discrepancies for the different reconstruction methods at $MFCR = 17.3$.

Reconstruction method			ΔIPR	$\Delta DC60$	ΔIDC	ΔIDR
<i>Scheme</i>	<i>Compressibility</i>	<i>BCs</i>				
DSI	YES	mixed	+0.029	+0.115	+0.009	-0.023
DSI	NO	mixed	-0.032	+0.089	-0.021	-0.048
PPE	NO	mixed	-0.036	+0.022	-0.026	-0.052
PPE	NO	Dirichlet	-0.071	-0.001	-0.019	-0.086

3.2. Pressure field reconstruction from PIV data

The instantaneous pressure fields at the Aerodynamic Interface Plane (AIP) were reconstructed using the S-PIV data for three cases at a constant crosswind velocity of 15 kts (7.7 m/s), each with increasing *MFCR*. These cases correspond to low, intermediate, and high *MFCR*, characterised by low-speed (diffusion-driven) separation, attached flow condition, and high-speed (shock-induced) separation, respectively. Pressure reconstruction was carried out again by performing the direct spatial integration of the momentum equation and by solving the Poisson Pressure Equation. The reconstructed time-averaged total pressure ratio distributions at the AIP for cases with *MFCR* approximately equal to 8, 15, and 18 are shown in Figure 9, Figure 10, and Figure 11, respectively. The flow fields are shown at both the 180x49 point resolution used for the reconstruction and at the 8x10 resolution to match the pressure rake measurements. The discrepancy between the time-averaged distortion metrics calculated from the reconstructed total pressure fields and the descriptors calculated from the measured total pressure values, both calculated with the 24x10 point resolution (Figure 5), are summarised in Table 4, Table 5, and Table 6 for the three cases.

The significant advantage of reconstruction the total pressure field at the AIP using a resolution (180x49) close to that of the PIV data is that this offers the ability to capture the ground vortex. This was not possible when the measurement resolution was used, as the ground vortex trace was not captured by the pressure rakes. For *MFCR* $\approx$ 8 (Figure 9), the total pressure deficit caused by diffusion-driven separation on the windward side of the intake is under-predicted compared to experimental data, regardless of the reconstruction method used. This discrepancy is particularly evident in the PPE-based, time-averaged total pressure fields (Figure 9d and Figure 9e) and may be attributed to the different operating conditions under which the experimental total pressure data were acquired, as the magnitude of the total pressure deficit is strongly dependent on *MFCR*. The PPE method (Figure 9d and Figure 9e) underpredicts the radial extent of the total pressure deficit, while the DSI scheme (Figure 9b and Figure 9c) tends to distort the total pressure field around the region affected by the ingested ground vortex, as observed previously. This is due again to the error propagation inherent in the DSI scheme. Additionally, the DSI method predicts greater total pressure losses in the vortex core compared to the PPE scheme. The application of the compressibility correction to the DSI algorithm (Figure 9b) does not significantly improve accuracy. Similarly, imposing a second Dirichlet boundary condition on the inner boundary of the computational domain for the PPE method (Figure 9e), does not result in a more accurate pressure field reconstruction, as the static pressure values imposed heavily influence the reconstruction in the central region of the plane.

Both the DSI and PPE methods accurately predict the *IPR*, with a discrepancy of less than +0.01 from the experimental rake-based values. Although the reconstructed pressure fields show notable differences compared to the experimental distributions, particularly in the radial extent of the total pressure deficit for the PPE method (Figure 9d and Figure 9e) and the total pressure losses within and around the ground vortex core for the DSI scheme (Figure 9b and Figure 9c), these errors cancel out in the computation of the *IPR*,

since this descriptor is calculated on an area-averaged basis. The prediction of the other distortion descriptors is generally less accurate. The DSI method, with or without the compressibility correction, provides a similar level of accuracy in estimating the Distortion Coefficient (*DC60*), which is underestimated by about -0.09, although the discrepancy slightly decreases when the compressibility model is applied. The high inaccuracies observed in the DSI based *DC60* may be possibly attributed to the slight differences in *MFCR* of the operating conditions used for comparison, as well as the artificial deformation of the ground vortex core due to the inherent nature of the DSI reconstruction method. The PPE method consistently underpredicts *DC60*, regardless of the type of boundary conditions applied, with a discrepancy of -0.4. The *IDC* and *IDR* are predicted with varying accuracy depending on the reconstruction method used. For the DSI-based reconstructed total pressure values, *IDC* and *IDR* show a maximum deviation from the experimental rake-based values of approximately 0.0 and -0.007, respectively, regardless of whether the compressibility correction is applied. In contrast, the PPE-based *IDC* and *IDR* are both underpredicted with maximum discrepancy of around -0.008 and -0.001, respectively. These discrepancies are primarily attributed to the reconstruction method's ability to capture key flow features at the AIP, such as the shape and extent of the separated region, as well as the size of the ground vortex core and its associated total pressure deficit.

The overall flow topology of the time-averaged, reconstructed, normalised total pressure fields at fully attached conditions with *MFCR* $\approx$ 15 (Figure 10), indicates that the PPE based fields with mixed boundary conditions (Figure 10d) are slightly more accurate than those reconstructed using the DSI method, either with or without the compressibility correction (Figure 10b and Figure 10c). However, in this case the measured total pressure distribution (Figure 10a) indicates a low-pressure region which is not present in the reconstructed distributions, due to the slightly different *MFCR* at which the measurements were taken. The DSI based reconstruction (Figure 10b and Figure 10c) was found insensitive to the applied density correction, suggesting that the incompressible flow assumption remains valid also in this case. Applying a second static pressure distribution on the inner boundary when using the PPE method (Figure 10e) significantly influences the total pressure calculation in the central portion of the plane. This is due to significant flow acceleration around the centre-body, leading to non-isentropic effects. Additionally, the PIV acquisition plane does not extend to the centre-body surface, where the pressure taps are located, which can yield measurement offsets that can further contribute to the overall reconstruction uncertainty. Further uncertainty can be also possibly introduced by the discrepancy in the streamwise distance between the PIV plane and the circumferential static pressure measurements although it is believed that this would only have a second order impact (see [38]). In general, further work is needed to understand the overall uncertainty propagation of the various pressure reconstruction methods for inlet flow distortion cases. This should account for the uncertainties introduced by the measurement of the boundary conditions, the potential streamwise discrepancy between the PIV and the boundary condition measurement planes, the type and spatial resolution of the

applied boundary condition, data interpolation errors and the influence of the various derivatives involved in the pressure field calculations from velocimetry data. Noticeably, applying the compressibility correction to the DSI method (Figure 10b) only slightly improves reconstruction accuracy and the PPE method with constant density and mixed boundary conditions (Figure 10d) remains reasonably accurate.

Both the DSI-based and PPE-based time-averaged total pressure ratio distributions at the AIP for the case at $MFCR \approx 18$ (Figure 11), suggest similar conclusions about the accuracy of the reconstruction methods. These findings align with those observed in the lower $MFCR$ cases and the results previously outlined from the reconstruction using numerical data. Applying a second static pressure distribution on the inner boundary for the PPE method (Figure 11e) significantly affects the determination of total pressure in the central portion of the plane. This is attributed to the significant flow acceleration around the centre-body and related non-isentropic phenomena, resulting from the increased size of the separation region. This finding contradicts the outcomes from previous studies that examined the influence of the boundary condition type on pressure reconstruction accuracy (see Charonko et al. [39] as an example), however, the flow field studied herein presents significant differences from the simplified cases investigated previously. As such, a body of work to fully quantify the influence of the boundary condition setup is still needed. Finally, although applying the compressibility correction to the DSI method (Figure 11b) improves reconstruction accuracy, the PPE method with constant density and mixed boundary conditions (Figure 11d) still provides reasonably accurate results.

The analysis of the distortion descriptors calculated from the reconstructed total pressure data for the case at $MFCR \approx 15$ (Table 6) shows that the accuracy of the DSI method, both with and without compressibility correction, and the PPE

method with mixed boundary conditions is similar. For the $DC60$ coefficient, the discrepancy from the experimental rake-based values decreases when the compressibility effect is considered, compared to the method with constant density. Both the DSI-based IPR and PPE-based IPR are accurately predicted, with discrepancies from the experimental rake-based values of up to approximately 0.03. The higher discrepancies observed in estimating the IDC and IDR metrics, regardless of the reconstruction scheme, may be attributed to the slightly different operating conditions in terms of $MFCR$ at which the total pressure values were measured, as the difference between the calculated values from the reconstructed total pressure data is negligible. In contrast, the analysis for the case at $MFCR \approx 18$ (Table 6) shows that the discrepancy with respect to the experimental rake-based values is lowest when the compressibility model is used. The time-averaged descriptors calculated from the total pressure fields reconstructed with the PPE method exhibit the largest discrepancies with respect to the experimental values, due again to the constant density assumption. At high $MFCR$, applying the compressibility correction improves accuracy for some distortion metrics, as the estimation of both total pressure and dynamic pressure values becomes closer to the actual values when the density is correctly estimated. However, no clear conclusion regarding the influence of the compressibility correction can be drawn from the presented results, partially due to the time-average nature and coarse spatial resolution of the measured pressure distributions and partially because of the algebraic definitions of all distortion descriptors which are prone to non-linearities, especially when applied to spatially and temporally complex flows.

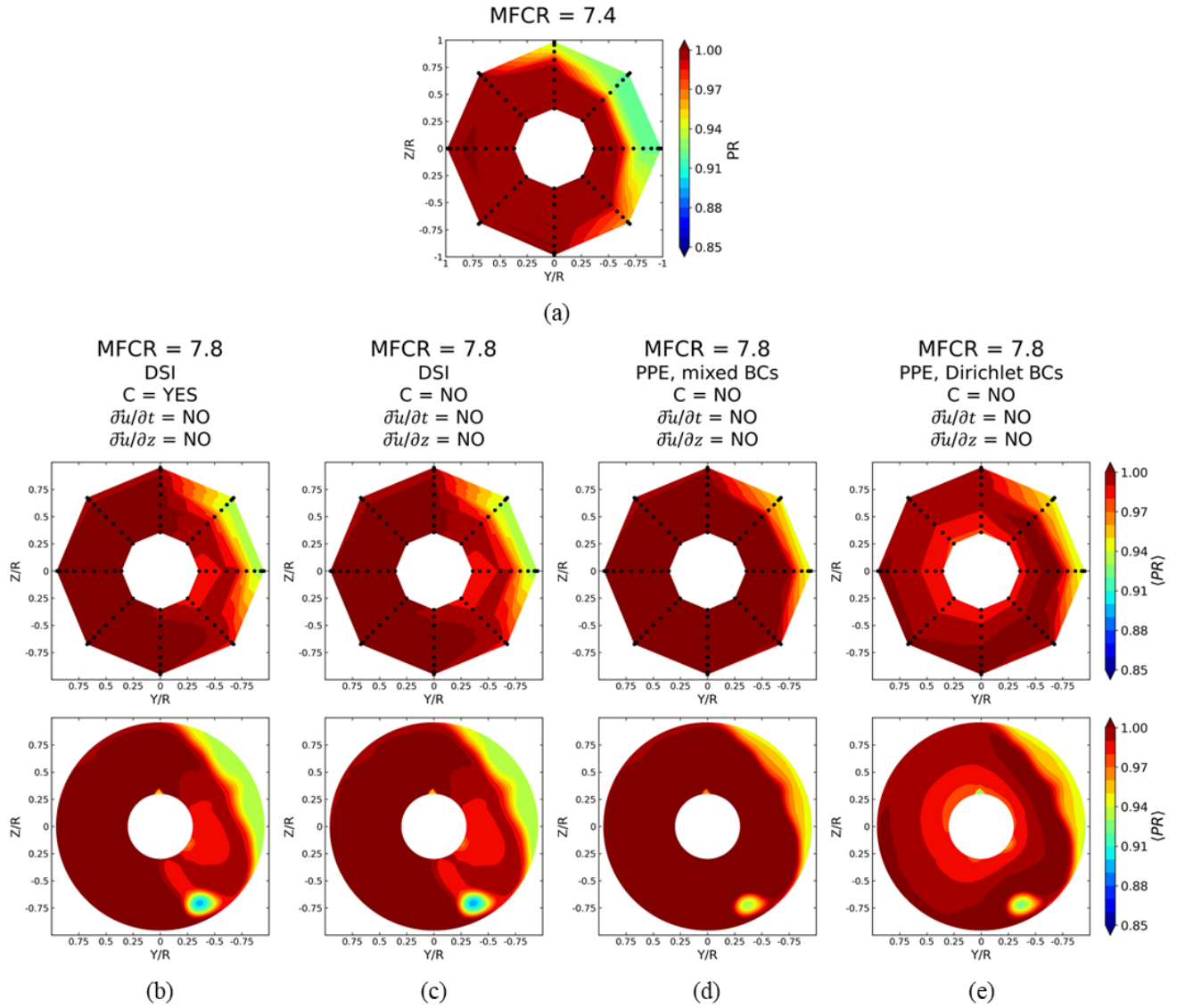


Figure 9 – Measured and reconstructed time-averaged total pressure ratio distributions for the case at 15 kts and $MFCR \approx 8$: (a) measured total pressure ratio distribution; (b) DSI method, compressible; (c) DSI method, incompressible; (d) PPE method, incompressible with mixed boundary conditions; (e) PPE method, incompressible with Dirichlet type boundary conditions. (b)-(e) top row: reconstructed total pressure distributions at the 8x10 rake resolution. (b)-(e) bottom row: reconstructed total pressure distributions at the full 180x49 resolution. Crosswind direction from right to left (view looking downstream).

Table 4 – Errors associated with the time-averaged distortion descriptors for the different reconstruction methods for the case at $MFCR \approx 8$.

Reconstruction method			ΔIPR	$\Delta DC60$	ΔIDC	ΔIDR
<i>Scheme</i>	<i>Compressibility</i>	<i>BCs</i>				
DSI	YES	mixed	+0.009	-0.081	0.000	-0.007
DSI	NO	mixed	+0.008	-0.094	0.000	-0.007
PPE	NO	mixed	+0.017	-0.413	-0.008	-0.001
PPE	NO	Dirichlet	+0.005	-0.385	-0.008	-0.001

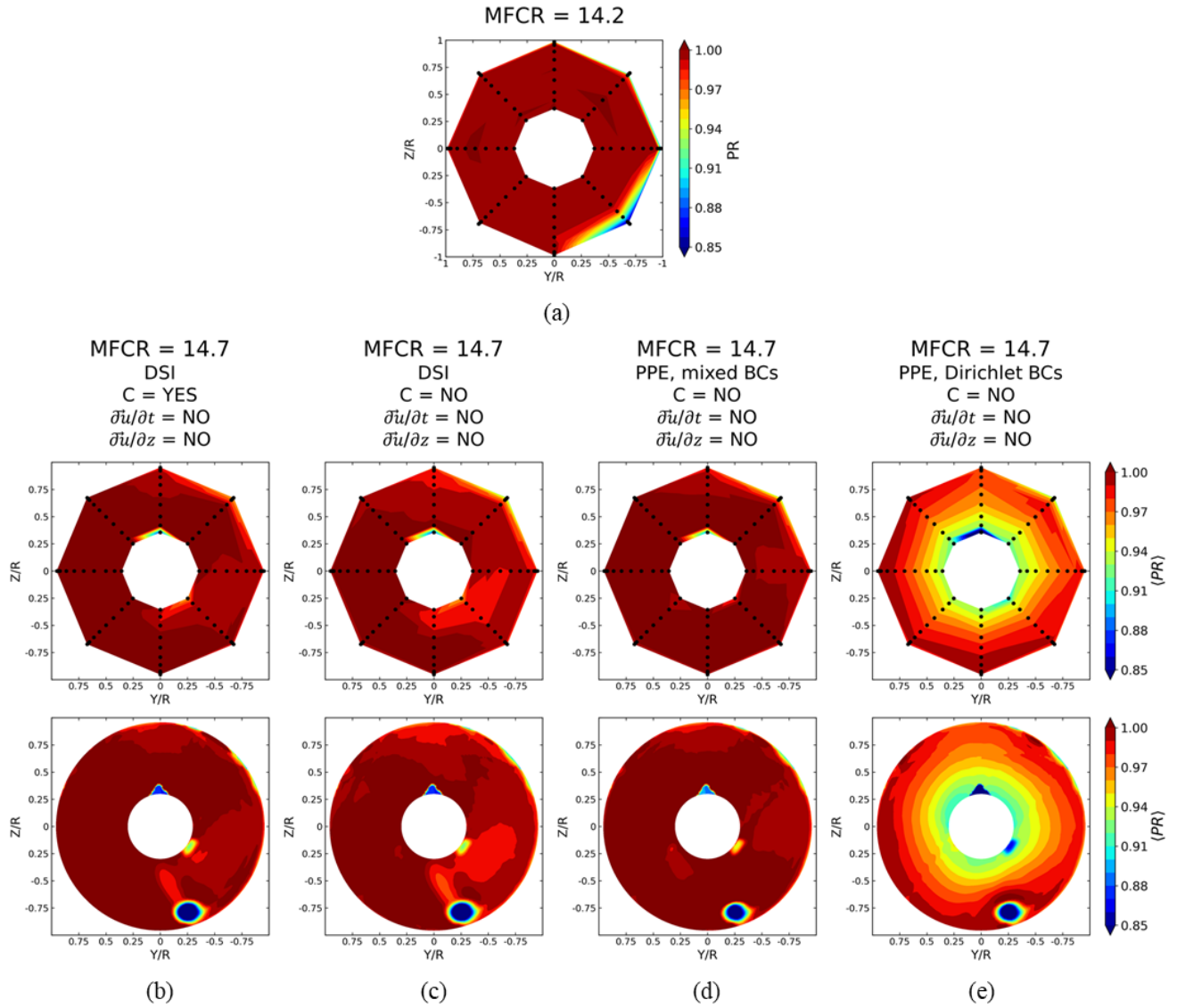


Figure 10 – Measured and reconstructed time-averaged total pressure ratio distributions for the case at 15 kts and $MFCR \approx 15$: (a) measured total pressure ratio distribution; (b) DSI method, compressible; (c) DSI method, incompressible; (d) PPE method, incompressible with mixed boundary conditions; (e) PPE method, incompressible with Dirichlet type boundary conditions. (b)-(e) top row: reconstructed total pressure distributions at the 8x10 rake resolution. (b)-(e) bottom row: reconstructed total pressure distributions at the full 180x49 resolution. Crosswind direction from right to left (view looking downstream).

Table 5 – Errors associated with the time-averaged distortion descriptors for the different reconstruction methods for the case at $MFCR \approx 15$.

Reconstruction method			ΔIPR	$\Delta DC60$	ΔIDC	ΔIDR
<i>Scheme</i>	<i>Compressibility</i>	<i>BCs</i>				
DSI	YES	mixed	+0.012	-0.037	-0.023	-0.033
DSI	NO	mixed	+0.003	-0.049	-0.032	-0.035
PPE	NO	mixed	+0.008	-0.047	-0.035	-0.033
PPE	NO	Dirichlet	-0.027	-0.020	-0.032	+0.005

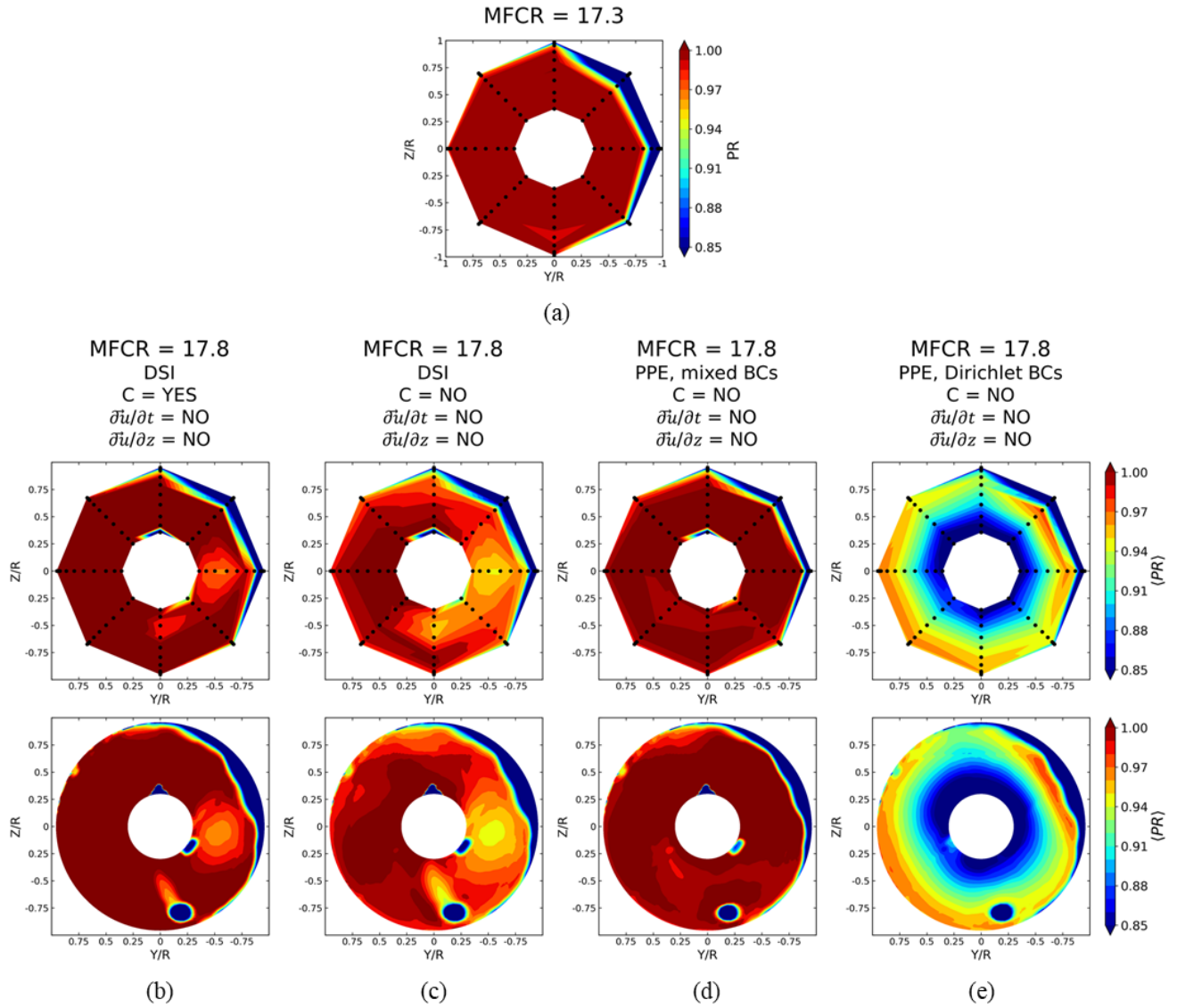


Figure 11 – Measured and reconstructed time-averaged total pressure ratio distributions for the case at 15 kts and $MFCR \approx 17$: (a) measured total pressure ratio distribution; (b) DSI method, compressible; (c) DSI method, incompressible; (d) PPE method, incompressible with mixed boundary conditions; (e) PPE method, incompressible with Dirichlet type boundary conditions. (b)-(e) top row: reconstructed total pressure distributions at the 8x10 rake resolution. (b)-(e) bottom row: reconstructed total pressure distributions at the full 180x49 resolution. Crosswind direction from right to left (view looking downstream).

Table 6 – Errors associated with the time-averaged distortion descriptors for the different reconstruction methods for the case at $MFCR \approx 18$.

Reconstruction method			ΔIPR	$\Delta DC60$	ΔIDC	ΔIDR
<i>Scheme</i>	<i>Compressibility</i>	<i>BCs</i>				
DSI	YES	mixed	+0.026	-0.009	-0.003	-0.028
DSI	NO	mixed	-0.006	-0.051	-0.020	-0.040
PPE	NO	mixed	+0.019	-0.161	-0.042	-0.030
PPE	NO	Dirichlet	-0.069	-0.107	-0.040	-0.006

4. Conclusions

In this study, pressure fields were reconstructed from velocity data obtained experimentally in a scaled short intake under crosswind conditions. Three cases were considered, all of them at a constant crosswind velocity of 15 kts with increasing Mass Flow Capture Ratio (*MFCR*), characterised by low-speed (diffusion-driven) separation, attached flow, and high-speed (shock-induced) separation. The pressure-from-velocity reconstruction was performed using two methods: Direct Spatial Integration (DSI) of the momentum equation and the Poisson Pressure Equation (PPE). These methods were initially validated using steady-state (RANS) simulations under similar intake conditions.

The CFD validation showed that the PPE method with mixed boundary conditions achieved the closest agreement with CFD data at low and intermediate *MFCR* values, while the DSI method with compressibility correction, although affected by higher errors around the vortex region due to inherent error propagation in the algorithm, performed better at higher *MFCR*.

The results of the pressure reconstruction from S-PIV data were subsequently compared with experimental steady-state rake measurements. The Direct Spatial Integration (DSI) method was found to distort the vortex core due to cumulative error propagation inherent to the algorithm. In contrast, the Pressure Poisson Equation (PPE) method, with mixed boundary conditions, provides more accurate pressure field reconstructions, particularly around the vortex core, at low and intermediate *MFCRs*, while at high *MFCRs* the accuracy of the reconstruction method is significantly affected by the compressibility. This method is preferable in scenarios at low *MFCR* values where compressibility effects are not significant. Both reconstruction methods were found to yield parts of the AIP where PR exceeded 1.0, which is unphysical. Further investigation showed that as far as the CFD reconstructions are concerned, this is related to the oscillations of the inlet stagnation pressure observed over the duration of the unsteady simulations. Regarding the experimental data, it was found that local $PR > 1.0$ was measured by the total pressure rakes during the test, due to oscillations of the tunnel's stagnation pressure. This was therefore propagated also to the reconstructed stagnation pressure distributions. In terms of distortion descriptors, both methods demonstrated good agreement in predicting Inlet Pressure Recovery (*IPR*) across all test conditions. The estimation of other descriptors, such as the Distortion Coefficient (*DC60*), Circumferential Distortion Index (*IDC*), and Radial Distortion Index (*IDR*), showed greater variation, dependent on the reconstruction method used and on the limited capability of the experimental 8x10 rakes to fully capture the flow feature at the AIP within the intake. The study confirms that both methods were able to reconstruct time-averaged total pressure fields from Particle Image Velocimetry (PIV) data, potentially reducing the need of intrusive measurements. PIV offers better spatial resolution than traditional rakes, revealing flow details in the total pressure fields, such as the ground vortex signature and a more clearly defined boundary of the separated region, that other conventional measurement techniques fail to capture. Despite their limitations, the pressure reconstruction methods show potential in enabling the simultaneous collection of pressure and swirl data during experiments.

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Nomenclature

V_∞	Crosswind velocity
u, v, w	Cartesian velocity components
<i>IDC</i>	Circumferential Distortion Index
v_r, v_θ, w	Cylindrical velocity components
<i>DC60</i>	Distortion Coefficient
q	Dynamic pressure
μ	Dynamic viscosity
ρ_∞	Freestream density
h	Ground clearance
A_{hi}	Highlight area
D_{hi}	Intake highlight diameter
D_h	Hydraulic diameter
<i>IPR</i>	Inlet Pressure Recovery
D_i	Intake inner diameter
M	Mach number
<i>MFCR</i>	Mass Flow Capture Ratio
$\dot{m}$	Mass flow rate
<i>IDR</i>	Radial Distortion Index
Re	Reynolds number
p	Static pressure
T	Static temperature
p_0	Total pressure
T_0	Total temperature
V	Velocity magnitude

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