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Experimental and numerical investigation of porous bleed control for supersonic/subsonic flows, and shock-wave/boundary-layer interactions

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ABSTRACT

This paper presents a comprehensive experimental and numerical investigation into the control of boundary layers using porous bleed systems. The study focuses on both supersonic and subsonic flow regimes, as well as on the control of shock-wave/boundary-layer interactions. By simplifying this complex problem into two separate scenarios, the research establishes the necessity of individually characterizing bleed systems for both supersonic and subsonic flow regimes due to variations in the flow topology within the bleed holes. In supersonic conditions, a strong agreement between experimental and numerical results validates the effectiveness of porous bleed in controlling boundary layers. Notably, three-dimensional effects are experimentally demonstrated, and variations of the boundary-layer profiles along the span are the first time experimentally proven. The study extends its scope to subsonic flows, revealing that while boundary-layer bleeding enhances flow momentum near the wall, mass removal induces a decrease in momentum in the outer boundary layer and external flow. The research also explores shock-wave/boundary-layer interaction control, achieving a remarkable alignment between simulations and experiments. The findings endorse the use of Reynolds-Averaged Navier-Stokes simulations for studying porous bleed systems in various flow conditions, providing valuable insights to enhance bleed models, especially in the context of shock-wave/boundary-layer interaction control.

1. Introduction

The presence of shock-wave/boundary-layer interactions may have detrimental effects on high-speed vehicles. These interactions can cause separation or distortion of the boundary layer, affecting the airflow for example inside air intakes, and disrupting the compression effects. Consequences are performance and efficiency losses or unsteady effects as shock oscillations (e.g., supersonic intake buzz), leading to the need for flow control techniques [1–3].

Various flow control techniques have been developed in recent years to mitigate the detrimental effects of shock waves. Passive methods such as shock control bumps [4,5] were demonstrated to reduce the wave drag and to delay the buffet onset if applied on transonic wings. However, their shape may result in the appearance of flow separation and the formation of streamwise vortices [6]. The combination of shock control bumps and active jets [7,8] resulted in a mitigation of the flow separation downstream of the bump crest.

Another passive control method is the application of vortex generators. These physical devices induce streamwise vortices, and hence,

a transfer of high-momentum fluid from the external flow to the wall while simultaneously removing low-momentum flow from the near-wall region [9]. From general interest is the application of so-called microvortex generators [9–11] with a size smaller than a boundary-layer thickness, resulting in a low drag penalty.

While physical vortex generators are designed for specific operation conditions, the application of fluidic or air-jet vortex generators [12–14] enables greater flexibility and reduces the drag penalty. Another highly flexible active flow control technique is the application of Joule heating methods [15] like plasma actuators [16].

A proven and widely used shock control technique within supersonic air intakes is the porous bleed [17,18]. The idea is to remove the low-momentum flow in the vicinity of the wall to make the boundary layer more resilient against adverse pressure gradients. Although the basic operation principle is simple, the flow physics inside the hole is difficult to understand and predict. The small size of the bleed holes, whose diameter is approximately the compressible boundary-layer displacement thickness [19,20], makes measurements inside the hole challenging if not impossible.

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Nomenclature

Latin symbols

A	Area
A_o	(Circular) extraction area
$A_{pl,ex}$	Plenum exit throat area
D	Hole diameter
H	Incompressible boundary-layer shape factor
L	Length
M	Mach number
\dot{m}	Mass flow rate
p	Static pressure
$Q_{sonic,w}$	Surface sonic flow coefficient
R	Specific gas constant (air)
Re	Reynolds number
T	Static temperature
T/D	Thickness-to-diameter ratio
TR	Throat ratio
v	Transpiration velocity
x, y, z	Cartesian coordinates in streamwise, wall-normal, and span wise direction
\hat{x}, \hat{x}	Streamwise position from start/end of bleed region

Greek symbols

α	Angle of attack
β	Stagger angle
δ	Boundary-layer thickness
δ_1	Boundary-layer displacement thickness
μ	Mach angle
ε_τ	Rise in wall shear stress
γ	Heat capacity ratio
ϕ	Porosity level
ρ	Density
τ	Shear stress

Subscripts

bl	Bleed
c	Compressible
h	Hole
pl	Plenum
$sonic$	Sonic
t	Total
w	External wall
∞	Free-stream
99	99% boundary-layer thickness

In contrast, numerical simulations enable the visualization of the flow physics inside the bleed holes including the so-called barrier shock [21]. Owing to the increase in computational power in previous years, numerical simulations investigating several bleed parameters became feasible [22]. Hamed et al. [23] proved a Reynolds number influence on the flow field downstream of the bleed region, while the sonic flow coefficient was not affected. Schwartz et al. [24] used Large Eddy simulations to investigate the influence of a porous bleed on the unsteadiness of an oblique shock-wave/boundary-layer interaction. In our previous study [25], an essential influence of the plate geometry on the bleed efficiency and effectiveness was revealed. However, numerical methods require validation, and therefore experiments.

Previous experimental studies were limited to a small range of geometrical parameters [26,27] or single-hole bleed systems [28]. Disregarding the interaction between the bleed holes by using a single-hole approach results in an overestimation of the bleed efficiency [25]. Moreover, these experiments were limited to supersonic flows. Experiments performed for subsonic conditions [20,29] showed significantly higher bleed rates, which is a result of a different flow topology inside the holes [30]. Other experiments on the complex flow case with a shock-wave/boundary-layer interaction [31] were performed without gaining detailed knowledge of the bleed behavior under subsonic conditions as found downstream of a normal shock.

Furthermore, numerical investigations neglect three-dimensional flow effects by limiting the domain using symmetry boundary conditions. In contrast, side wall effects and corner flow cannot be prevented and may influence the performance of the porous bleed. Moreover, the interaction of bleed systems with the corner flow is of high importance in supersonic air intakes, where shock waves interact with side walls. Previous studies have shown that the use of flow control in the center of the test section leads to an increase in the size of the corner flow [32,33].

Moreover, the bleed geometry induces three-dimensional effects on the flow field downstream of the bleed region [23,25,34]. Existing experiments focusing on the boundary-layer profiles were limited to the measurement at the wind tunnel center. Thus, important information about the flow field that may be used for the validation of numerical methods is missing.

In this study, we used a combination of experiments and three-dimensional steady-state Reynolds-averaged Navier-Stokes (RANS) simulations to address existing deficiencies. The experimental study of two perforated plates targeted the validation of our numerical setup, which was used to generate a comprehensive database showing the strong effects of different geometrical parameters [25]. Moreover, three-dimensional effects, such as the impact of the center bleed on the corner flow and the flow field variation along the span [23,25,34], are observed. Moreover, the complex flow case of controlling a shock-wave/boundary-layer interaction is simplified by first observing supersonic and subsonic flow control with porous bleeds separately. Thus, the numerical setup is validated for both conditions, before the shock control is numerically and experimentally examined.

The paper is organized as follows: In Sec. 2, we introduce the experimental and numerical setup. In the following section, the results are discussed. First, the supersonic turbulent boundary-layer bleeding is investigated. Both, the flow field at the wind tunnel center as well as the interaction of porous bleed with the corner flow are studied. In the second step, the subsonic turbulent boundary-layer bleeding is investigated before heading to the interaction of the bleed with the incident shock. Finally, our conclusions are presented in the final section.

2. Methodology

In this section, both the experimental and numerical techniques are presented. The first investigated problem was the boundary-layer bleeding on a flat plate for super- and subsonic turbulent flows to determine the working principles of a porous bleed in both flow regimes. In the second step, a shock generator was included in the setup to investigate the shock-wave/boundary-layer interaction control. The domains were identical in the experimental and numerical approaches.

2.1. Experimental setup

2.1.1. Wind tunnel

The experiments were performed in the continuous-running S8Ch supersonic wind tunnel of the ONERA in Meudon, supplied with dried atmospheric air. Fig. 1 shows a photograph of the test section. The convergent-divergent nozzle was designed to generate a Mach $M = 1.62$

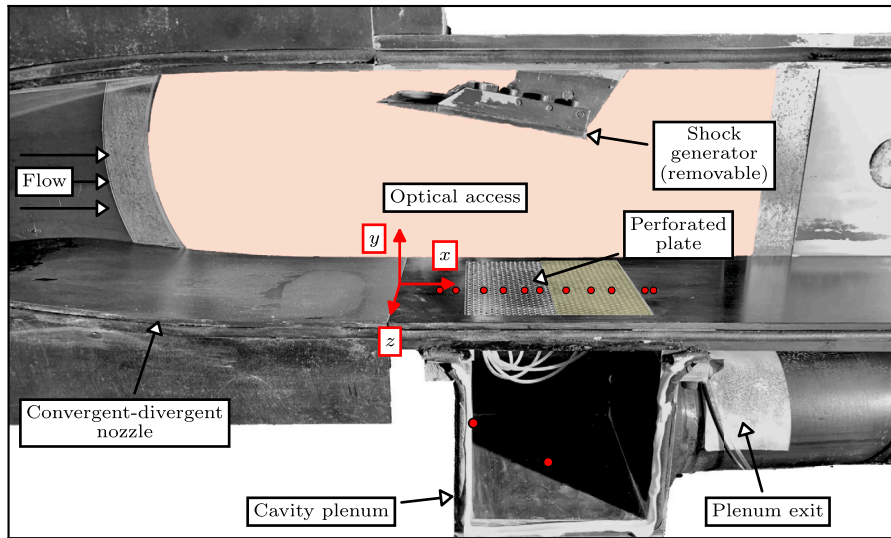


Fig. 1. Experimental setup.

flow. The size of the test section was 120 mm in width and 120 mm in height. The porous bleed system was installed 50 mm downstream from the nozzle end. Windows on the side walls allow optical access to the entire region of interest around the bleed region.

In addition, a shock generator can be mounted in the test section. Its position and angle of attack are adjustable so that the incident shock wave is located on the porous bleed system. A vent upstream of the compressor allowed the suction of air from a bypass channel. Thus, the mass flow rate passing the test section, and in turn, the Mach number can be varied for subsonic conditions, which was used in this study to also perform measurements for a fully subsonic flow inside the wind tunnel. A Mach number of $M = 0.5$ was selected to avoid the appearance of a normal shock inside the divergent part of the nozzle due to choking of the nozzle throat and an under-expanded working regime.

The experiments were performed over several months, resulting in variations in the atmospheric conditions, as presented in Table 1. Thus, the total conditions inside the test section could not be kept constant. Please note that the total conditions listed in Table 1 are independent of the Mach number.

2.1.2. Porous bleed system

The perforated plates had a length of 40 mm and a span of 80 mm, corresponding to 2/3 of the test section's span. The plate length can be increased to up to 80 mm, which is not used in this study to guarantee a choking of the holes for the highest bleed rate. As a consequence, the second half of the plate is filled with plaster, as highlighted by the grey-filled holes in Fig. 2. Preliminary numerical investigations have shown that wider plates do not affect the center flow but require higher bleed rates as the suction area is increased. Two perforated plates with 90-degree holes were utilized in this study with hole diameters equal to $D = 0.5$ mm and 2.0 mm. The plate with the smaller holes had a porosity of $\phi = 14.5\%$, whereas the second plate had a porosity of $\phi = 29.6\%$. Porosity levels and hole diameters were selected concerning the

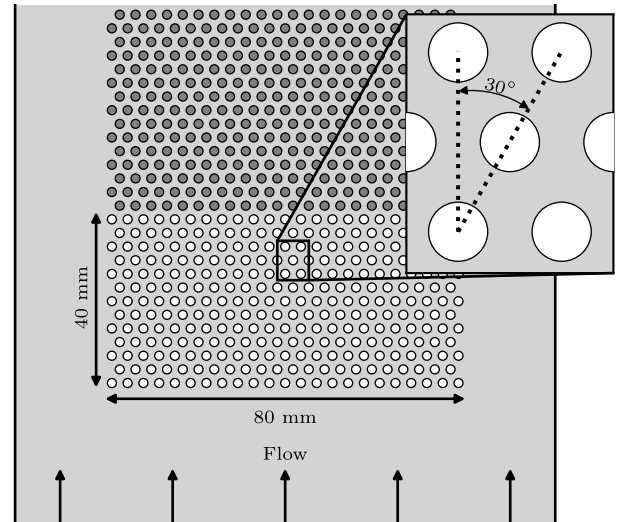


Fig. 2. Characteristics of perforated plates.

application in supersonic air intakes. The smaller holes were close to the typical ratio of $D/\delta_{1,c} = 1$ [20], while the second plate had significantly larger holes to observe negative effects induced by the bleed roughness [25]. Independent of the hole size, the thickness-to-diameter ratio was kept constant at $T/D = 1$. The holes are distributed in a triangular shape, resulting in different streamwise positions for every second column of the holes. The stagger angle between the columns was $\beta = 30^\circ$ for both the plates. Table 2 summarizes the geometric parameters of the perforated plates.

The bleed mass flow rate can be varied by using a choked throat at the plenum exit. The throat diameter varies from $D_{pl,ex} = 10$ mm to 50 mm, while the inner pipe diameter is 76.2 mm (3 inches). A stiffening system was installed inside the cavity plenum to avoid bending of the plate caused by high-pressure differences.

Table 1
Total conditions in experiments (range during all measurements) and simulations.

	P_t	T_t
Experiments	97370 Pa	290.6 K
	-	-
	101960 Pa	317.6 K
Simulations	93000 Pa	300 K

Table 2
Investigated perforated plates.

Plate	D [mm]	ϕ [%]	β [°]	T/D [-]
AR	0.5	14.5	30	1
HR	2.0	29.6	30	1

Table 3
Positions of wall pressure taps.

Plate	Position x [mm]											
AR	25	35	55	65	75	85	95	105	115	125	145	150
HR			50	62	76	86	98	110	122	-		

2.1.3. Laser-Doppler-velocimetry

A two-component Laser-Doppler-velocimetry system was used to describe the flow field around the bleed region. Two lasers from the *Coherent Genesis MX SLM-series* with wavelengths 514.5 nm and 488 nm were utilized to measure both streamwise and wall-normal velocity components of the flow. Both fringe patterns were tilted by 45° with respect to the flow to obtain the closest possible measurements to the wall. A 40 MHz frequency shift is added to one of the beams using the *FiberFlow* system from *Dantec* to resolve negative velocities.

Both the emitted beams had a waist diameter of 4.3 mm. The distance between the beams was set to 35 mm, a beam expander with a ratio of 1.95 and a converging lens with a focal length of 230 mm were used. The probe volume characteristics can be calculated using classical relations [35], resulting in probe diameters of 35.04 μm/33.23 μm, probe lengths of 0.46 mm/0.44 mm, and a fringe spacing of 3.39 μm/3.22 μm. With the given characteristics, sampling rates on the order of \mathcal{O} (1 kHz) were achieved.

2.1.4. Flow visualization

A Background Oriented Schlieren (BOS) system [36] was installed to monitor the flow in real time using a 2.3 MP camera. Using the BOS method, the deviation of the light rays induced by density gradients was measured by cross-correlating one image of a random pattern without flow and one with the flow. The deflections in the streamwise and wall-normal directions were estimated using the in-house *FOLKI* algorithm [37].

2.1.5. Pressure measurements

Static pressure measurements are performed to monitor the flow using *ESP-32HD* pressure scanners with a range of ± 15 PSI (103421 Pa) and a $\pm 0.03\%$ full-scale accuracy (31 Pa). Pressure taps on the top wall inside the convergent-divergent nozzle and test section were used to check the correct starting of the test section. Moreover, pressure taps on the bottom wall and perforated plate were installed with an offset of 10 mm from the center plane to acquire the wall pressure changes induced by boundary-layer bleeding. Inside the cavity plenum, pressure taps on the side and bottom walls were used to measure the plenum pressure, while pressure taps upstream and downstream of the sonic throat were used to prove choking conditions. With a hole diameter of $D = 0.4$ mm, the size of the pressure taps is in the same order of magnitude as the bleed holes for plate AR.

The streamwise positions of the pressure taps on the bottom wall are presented in Table 3 for both perforated plates. The positions are also highlighted by the red dots in Fig. 1 for plate HR. Moreover, the pressure tap locations inside the cavity plenum are illustrated.

2.2. Numerical setup

2.2.1. Geometry and mesh

The entire test section was meshed using the in-house pre-processing tool and mesh-generator *Cassiopee* [38]. For the supersonic cases with and without the shock generator, the convergent-divergent nozzle was added to the domain. The mesh around the holes was fully parameterized, allowing the variation of several bleed parameters, such as the plate length, hole diameter, or plate thickness. Each hole was modeled out of five blocks using a butterfly mesh, as shown in Fig. 3. A C-grid topology around the hole walls was used to accurately resolve the boundary layer by simultaneously reducing the number of cells. The minimum wall-normal cell size was set as 0.2 μm ($y^+ \approx 1$) inside

and outside the holes. A preliminary mesh sensitivity study was performed as part of our previous study [25] and showed that a cell-to-cell growth ratio of maximal 1.1 is required to accurately predict the local mass flow rate passing through the bleed holes.

The total number of cells was 6.2 million independent of the plenum pressure for the low-porosity plate AR and 1.9 million for the high-porosity plate HR in the quasi-two-dimensional (quasi-2D) setup, consisting of only two holes in the spanwise direction (see Fig. 3a). Moreover, simulations of the wind tunnel half-span were conducted for plate HR and a span of the perforated plate of 40 mm, resulting in 55.9 million cells. For the subsonic boundary-layer bleeding, the number of cells was reduced to 1.2 million and 3.7 million, respectively, because the convergent-divergent nozzle was not included in the mesh. To observe the effect of an incident shock, a shock generator was included in the wind tunnel mesh using a C-grid topology. Thus, the number of cells increased to 3.7 million and 10.7 million cells, respectively. Again, simulations of the half-span were performed with a mesh size of 106 million cells.

2.2.2. Flow solver

The compressible Navier-Stokes equations were solved numerically using the ONERA-Safran finite-volume solver *elsA* [39]. The Spalart-Allmaras turbulence model with the quadratic constitutive relation [40] was applied. The second-order-accurate Roe upwind scheme, combined with the min-mod limiter and the Harten entropic correction, was used as the spatial scheme, while a backward-Euler scheme was used for the time integration with local time-stepping.

A subsonic velocity inlet condition was set upstream of the convergent-divergent nozzle with the total conditions listed in Table 1. Variations in the atmospheric conditions in the experiments impeded the exact simulation of the experimental conditions. Thus, the total conditions were selected to roughly fit the Reynolds number. The cavity plenum exit was set as a supersonic outlet, along with the main outlet in the supersonic cases with and without shock-wave/boundary-layer interaction. For investigating the subsonic flow control, the main outlet was set as a pressure outlet, and the inlet was set to fit the experimentally acquired upstream boundary-layer profile. The top and bottom walls and walls around the holes were made no-slip walls, while a slip-wall was applied at the plenum side walls to reduce the mesh size inside the cavity plenum. The domain was limited using a symmetry boundary condition on the front and back for the quasi-2D simulations, and for the wind tunnel half-span simulations, the center plane was set as a symmetry boundary condition, while the back wall was treated as a no-slip wall.

Similarly to the experiments, the bleed mass flow rate was fixed by a choked nozzle. Therefore, the cavity plenum was prolonged, and its exit was shaped as a convergent-divergent nozzle (see Fig. 3b) to produce supersonic conditions at the outlet. The size of the choked plenum exit area $A_{pl,ex}$ was determined with respect to the bleed area A_{bl} , which was the sum of all bleed hole areas $A_{bl,i}$, by using the throat ratio

$$TR = \frac{A_{pl,ex}}{A_{bl}} = \frac{A_{pl,ex}}{\sum A_{bl,i}}. \quad (1)$$

For the comparison with the experiments, the static plenum pressure p_{pl} was extracted at a distance of three hole diameter to the exit of the holes inside the cavity plenum.

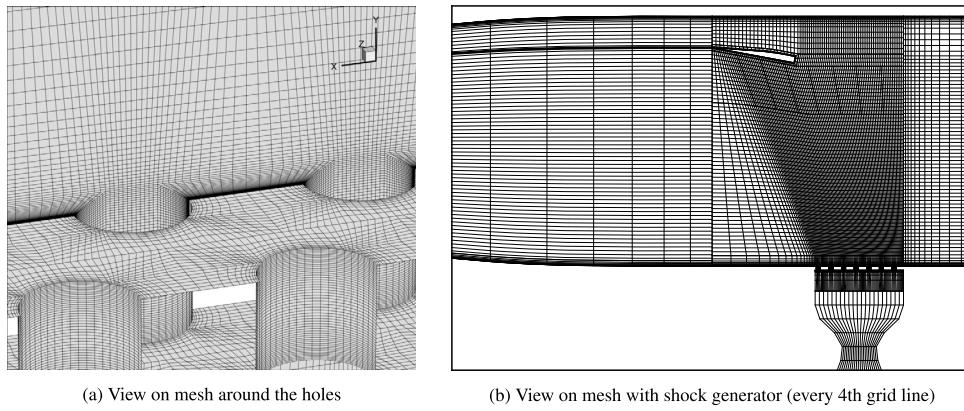


Fig. 3. Computational mesh.

3. Results

In the following, the experimental and numerical findings are compared. In the first step, the supersonic turbulent boundary-layer bleeding is investigated before heading to subsonic conditions, and in the final step to the control of the shock-wave/boundary-layer interaction.

3.1. Supersonic boundary-layer bleeding

3.1.1. Flow field analysis

The flow topology in the vicinity and inside the holes is shown for the quasi-2D simulations with both perforated plates in Fig. 4. The chosen working regime is characterized by choked holes, caused by a low-pressure ratio from external wall to cavity plenum. Thus, the bleed operates close to the limiting conditions, i.e., the maximum bleed rate. In Fig. 4a, the flow field for the plate with $D = 0.5$ mm is illustrated. Following the streamlines, a deflection of the flow towards the wall is noted at the beginning of the plate as part of the boundary layer is sucked. This leads to an increase in the Mach number as the flow is ac-

celerated. The so-called trailing shock is located at the end of the plate, where the perforated plate ends, redirecting the flow in the wall-parallel direction.

Close to the wall, further expansion and shock waves are generated by the flow streaming into the holes, as seen in the zoom view in Fig. 4. At each hole front, an expansion fan is located, bending the flow inside the hole. Further downstream, the barrier shock returns the flow parallel to the wall. Inside the hole, the flow is choked, leading to a supersonic under-expanded jet into the cavity plenum.

A similar flow field is apparent for plate HR, as shown in Fig. 4b. In comparison to the first plate, the thinning of the boundary layer is more prominent as highlighted by the stronger bending of the streamlines. This is a consequence of the higher porosity level, which is approximately twice the one for plate AR, and in turn, the higher bleed mass flow rate as the open area is increased. Moreover, the local flow phenomena induced by the bleed holes have a more significant effect on the flow field and penetrate deeper inside the boundary layer. The higher

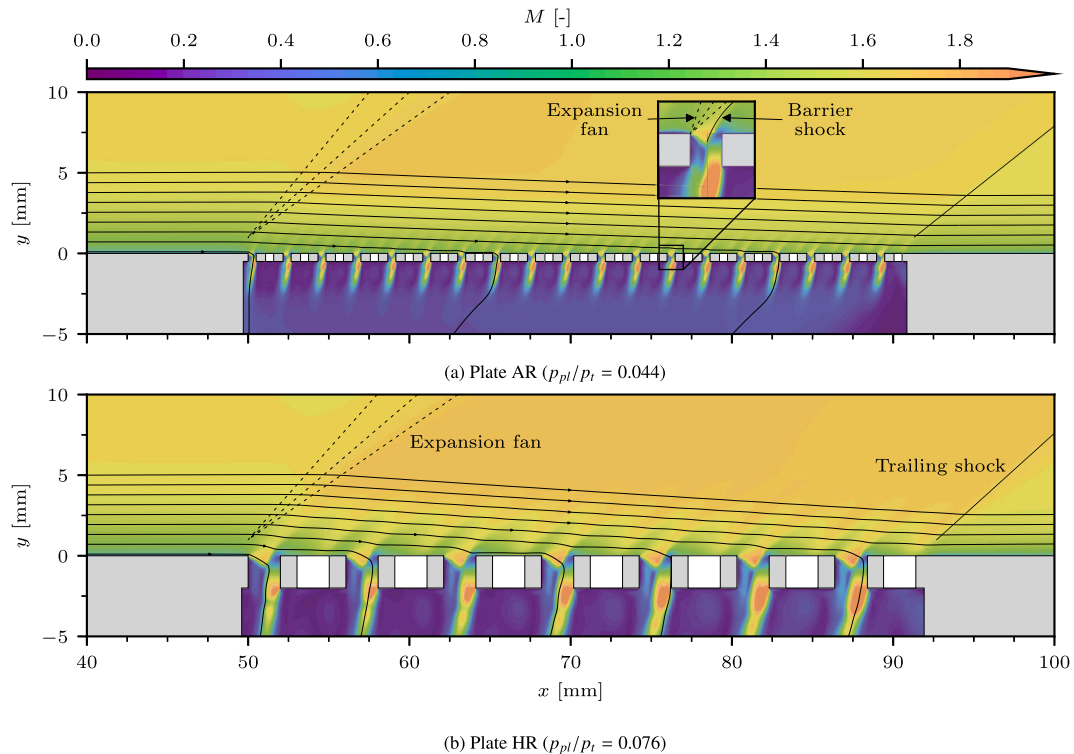


Fig. 4. Mach contour fields; white areas illustrate holes of the second column.

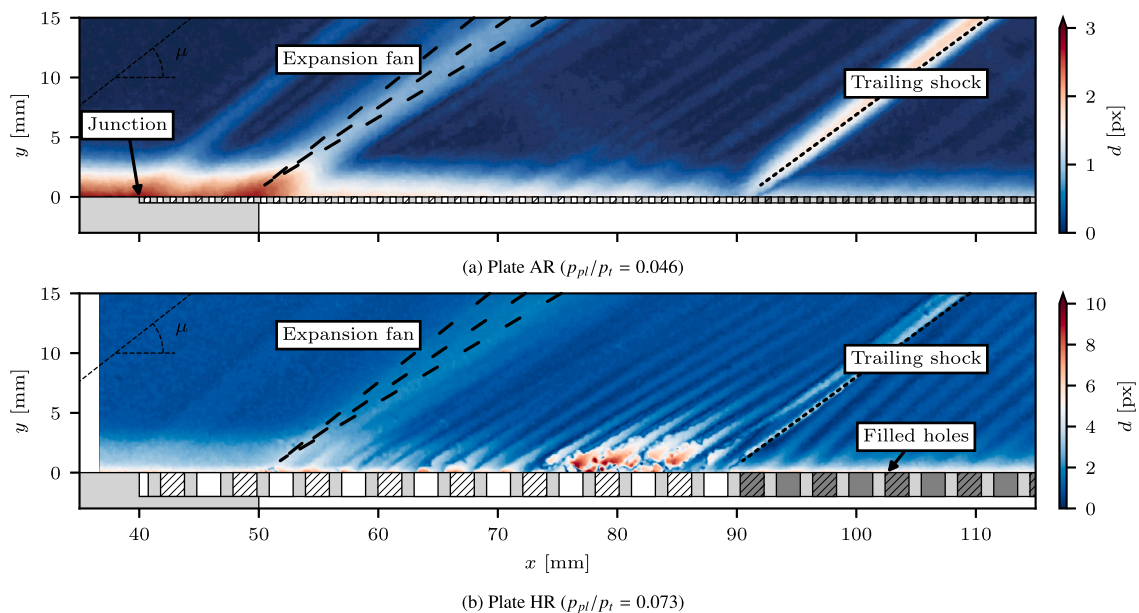


Fig. 5. BOS visualization of the flow around the perforated plate.

momentum of the captured flow is the reason since a higher flow momentum results in stronger barrier shocks [25].

The flow fields observed for both perforated plates using the BOS method are illustrated in Fig. 5. The pressure ratio from cavity plenum to total pressure p_{pl}/p_t is similar to those from the simulations shown in Fig. 4. Both the expansion fan at the beginning of the plate and the trailing shock at the end are visible. Moreover, as the displacement d is the highest close to the wall where the density gradient is the maximum, the thinning of the boundary layer is perceptible. Downstream of the bleed region, the boundary layer is significantly fuller and smaller in both cases.

On the perforated plate, the effect of the hole flow is apparent. Especially for plate HR with $D = 2.0$ mm holes, the effect on the flow inside the boundary layer is observed as expansion and compression waves are evident. Since the perforated plate is mounted on the floor, an overlapping of the pocket and the plate closes the holes located at the first 10 mm of the plate. Thus, no suction is present in this region, but the hole contour creates roughness. Also, a Mach wave caused by the junction from the floor to the perforated plate is present. The holes downstream of the bleed region are closed with plaster, which induces further Mach waves that do not affect the flow so that the measurement of the boundary-layer profiles in this region is feasible. The appearance of these Mach waves is more prominent for the larger holes as the filled area is increased.

Altogether, the same flow topology is found in both experiments (Fig. 5) and simulations (Fig. 4). However, expansion fans and shock waves are more smeared using the BOS visualization compared to the simulations. Contrary to a Schlieren visualization, no mirrors are used to obtain parallel light rays passing the wind tunnel. Thus, the view is only aligned with the span wise coordinate in the center of the image. Consequently, the deflection is higher in the center, resulting in occasional bad correlations, as visible in Fig. 5b.

For a more quantitative comparison, the whole flow field measured by means of LDV is shown against the numerical results in Fig. 6 in streamwise (Fig. 6a) and wall-normal direction (Fig. 6b). Both velocity components are normalized by the free-stream velocity to eliminate temperature variations that occurred between the different runs in the experiments.

A look at Fig. 6a illustrates a good fit of the streamwise component of the flow for both hole diameters. The effect of the bleed on the boundary layer is well modeled in the simulations for both plates. In

the case of the small holes, the LDV measurements are not able to fully resolve the local flow phenomena around the holes, which is caused by the size of the measurement volume in the span wise direction of approximately one hole diameter. On the contrary, the flow field is in the simulations directly extracted on the symmetry plane. Moreover, a Mach wave induced by the junction of the plates at $x = 40$ mm is apparent in the experimental data, leading to a slight thickening of the boundary layer. In contrast, no Mach wave is found in the LDV data for the larger holes, where the inflow is more homogeneous compared to the measurements for the $D = 0.5$ mm plate. Moreover, the expansion fans and barrier shocks induced by the bleed holes are resolved since the hole diameter is in this case significantly larger than the probe volume, and the phenomena are more pronounced.

Also, the wall-normal velocity component is well reproduced by the RANS simulations, as shown in Fig. 6b. A relatively low deflection of the flow towards the wall is found for the small holes compared to the large holes, caused by the lower porosity level. Moreover, the flow field is more homogeneous for the small hole diameters. In contrast, penetration of the expansion fans and barrier shocks even on the flow outside the boundary layer is notable. This effect is visible in the experimental data for the $D = 2.0$ mm holes. In comparison, the flow field acquired from the simulations looks more homogeneous.

The wall pressure along the bleed region is presented in Fig. 7. On the top, the numerically extracted pressure contour on the wall is illustrated for the first bleed holes with a diameter of $D = 0.5$ mm. The suction effect is evident: near the front of the holes, the pressure decreases because of the presence of an expansion fan. Further downstream, the so-called barrier shock inside the hole leads to an adverse pressure gradient resulting in a significantly higher wall pressure downstream of the hole. On the bottom, the high-porosity plate HR is shown, illustrating the same phenomena. However, the wall pressure below the holes is significantly lower, which is a result of the lower relative distance between the holes, and the consequently more effective flow control [25].

For a comparison with the experiment, the wall pressure is extracted on a line between two hole columns (dotted line), where the wall is fully solid for the plate with $D = 0.5$ mm holes, and largely fully for the second plate. The plot in the center details the trend of the wall pressure along these lines. At the beginning of the plate, where an expansion fan is located, the wall pressure drops. Along the perforated plate, the pressure fluctuates caused by the flow phenomena induced by the bleed

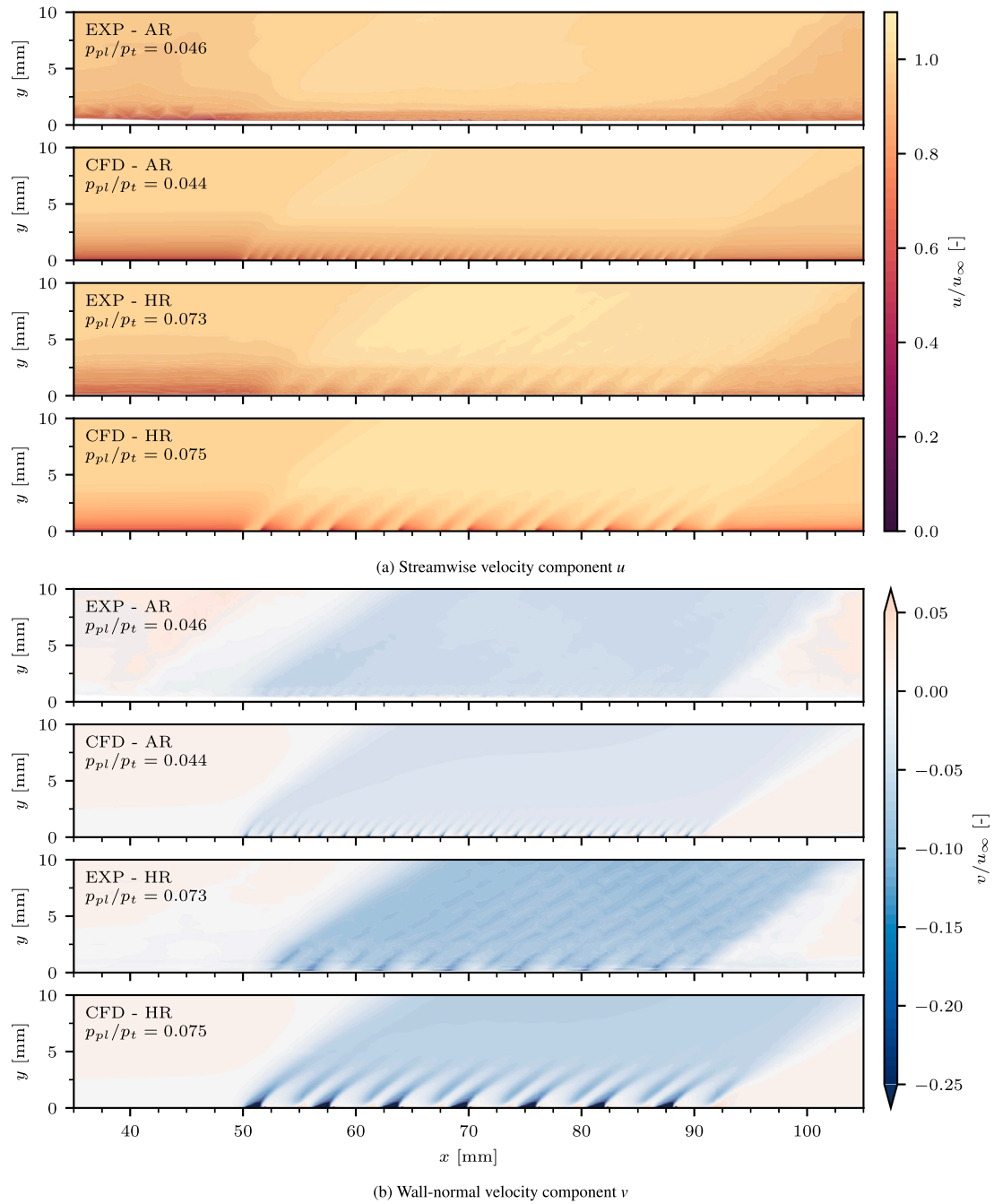


Fig. 6. Comparison of flow field from LDV measurements and simulations.

holes. These fluctuations are more prominent for the plate with the large holes. However, positive slopes along the plates are notable due to the compression along the perforated plates. Since the boundary-layer thinning is not linear but stronger at the beginning of the plate, the flow is continuously deflected towards the wall-normal direction [25]. At the end of the bleed region, the pressure increases because of the trailing shock, resulting in a slightly increased wall pressure downstream of the plate compared to the upstream pressure.

In the experiments, the wall pressure is measured at discrete locations around and in the bleed region, as illustrated by the points. Upstream and downstream of the bleed region, the measured wall pressure is slightly higher, which may be caused by the three-dimensionality of the flow inside the wind tunnel or Mach waves caused by the junction between the test section and the convergent-divergent nozzle. However, the deviation equals upstream and downstream, which proves the same

behavior of the bleed system. Along the plate, the measured pressure is within the range of the pressure fluctuations. The non-steady trend of the experiments results from the diameter of the pressure taps and their positions with respect to the bleed holes. As the diameter is of the same order of magnitude as the smaller bleed hole diameter, the pressure is averaged above a relatively large area. Depending on the position, the acquired pressure is mainly affected by the expansion fan or barrier shock and thus lower or higher.

Overall, the numerically and experimentally observed flow fields are similar. The same flow topology is apparent, and the flow is not strongly affected by any geometrical differences.

3.1.2. Boundary layer profiles at the center

In the following, the boundary-layer profiles are compared. Fig. 8 schematically visualizes the location of the observed profiles. The pro-

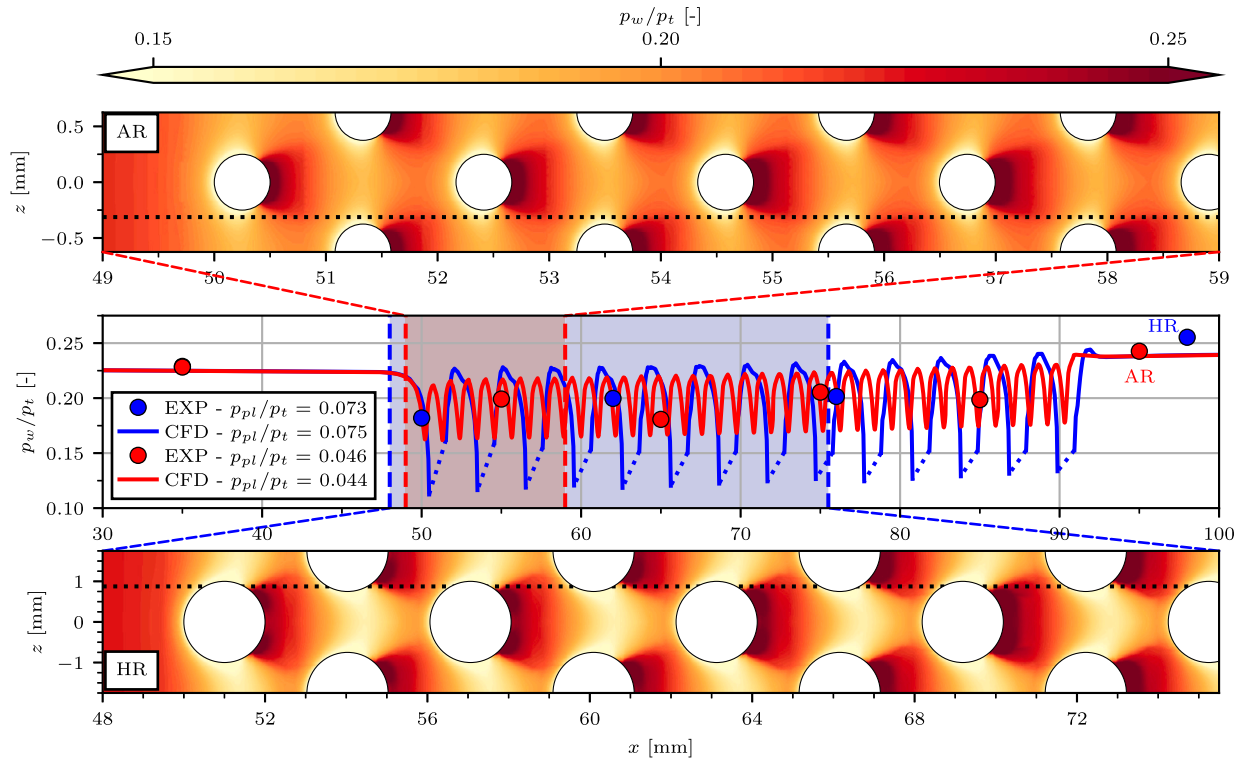


Fig. 7. Static wall pressure along the bleed region.

files are measured 15 mm upstream and downstream of the plate in both simulations and experiments. Upstream of the plate, this distance is chosen as the position is unaffected by the junction from the floor to the perforated plate and the non-suction holes. Moreover, the upstream influence of the porous bleed is numerically found to be below 5 mm, which results in similar boundary-layer profiles independent of the bleed rate.

As described in Sec. 3.1.1, a trailing shock is caused by a deflection of the flow at the end of the porous bleed. Consequently, the boundary layer downstream of the bleed region is disturbed by the shock and does not allow accurate measurements. Therefore, the same distance of 15 mm is selected here to assess the effect of bleeding on the boundary-layer profile. A view in Fig. 8 reveals that the boundary-layer thickness is slightly lower downstream of the trailing shock. However, the sonic height is significantly lower, resulting in a fuller boundary layer.

Fig. 9 compares the velocity profile extracted from the simulation and the measured profile using LDV. The closest point to the wall experimentally measured is located at a wall-normal distance $y = 0.2$ mm ($y^+ = \mathcal{O}(100)$). The simulation fits very well with the experimental measurements. The boundary-layer thickness $\delta_{99} = 4.3$ mm is equal in both experiments and simulations, even though the total conditions are slightly different (see Table 1).

The boundary-layer profile upstream of the bleed region (Fig. 9a) extracted from the simulations is slightly fuller than the extracted profile from the experiments. This is probably caused by the higher wall roughness in the experimental setup. However, the differences are negligibly minor.

With the aim of validating the simulations for different working conditions of the porous bleed, the boundary-layer profiles downstream of the bleed region are measured for several bleed rates. Comparison is made with the simulation for the same pressure in the cavity plenum. As the flow at the center plane is assumed to be two-dimensional, the ratio of plenum pressure to total pressure is more suitable than using the bleed mass flow rate, which may be affected by the three-dimensionality of the flow inside the wind tunnel close to the side walls. The pressure is expected to be more uniform than the bleed mass flux.

The comparison of the simulations and the experiments downstream of the bleed region is detailed in Fig. 9b for the lowest and the highest bleed rates. For the lowest bleed rate, the plenum pressure is slightly lower than the static wall pressure inside the test section ($p_w/p_t \approx 0.226$). Both experiments and simulations show the same trend again. However, the simulations predict a slightly fuller profile which is an artifact of the fuller inflow profile. Remarkably, the boundary-layer thickness $\delta_{99} = 4.8$ mm is thicker than upstream of the bleed region, which is caused by the trailing shock.

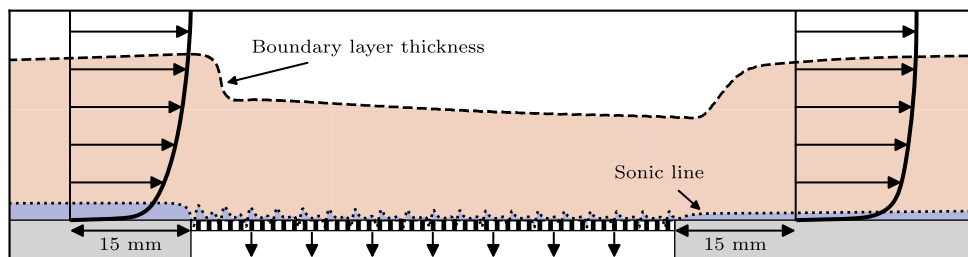


Fig. 8. Illustration on the effect of the porous bleed system on the boundary layer based on numerical results.

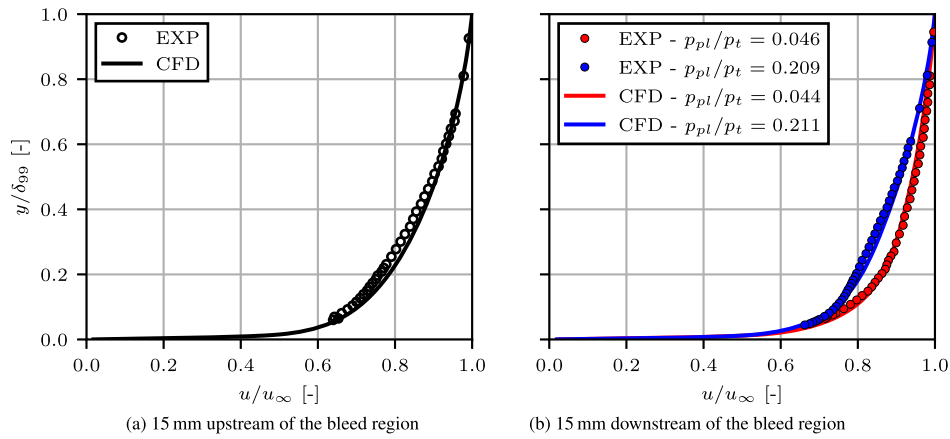


Fig. 9. Comparison of boundary-layer profiles for plate AR from experiments and simulations.

For the highest bleed rate, the holes are choked, as shown by the simulations in Fig. 4. The boundary-layer profiles obtained from simulations and experiments show an almost perfect fit in this case. The boundary layer is significantly fuller than in the case of a low bleed rate. Also, the boundary layer is thinner than the upstream profile with $\delta_{99} = 3.7$ mm.

All experimentally acquired boundary-layer profiles are compared in Fig. 10a for the $D = 0.5$ mm plate. Wall-normal coordinate and streamwise velocity are normalized with the inflow boundary-layer thickness and free-stream velocity. The significant influence of the cavity plenum pressure is apparent: The lower the plenum pressure, the higher the bleed rate and the fuller the boundary-layer profile. A significantly fuller boundary layer is already found for the lowest bleed rate. However, the suction mainly affects the lower part of the boundary layer, while the velocity is lower with further wall distance compared to the inflow.

A further increase in the bleed rate leads to an even fuller boundary-layer profile. Again, the major difference is found in the near-wall region, while the outer boundary layer is mainly unaffected. For more significant bleed rates, the whole boundary layer is fuller. From a pressure ratio $p_{pl}/p_t \approx 0.1$, the profiles converge, which means that the maximum effect is achieved, and a lower pressure inside the cavity plenum does not lead to fuller profiles. This results from choking the flow inside the holes, which limits the bleed mass flow rate.

The same trends are found in the numerical simulations, as shown in Fig. 10b. Low bleed rates mainly affect the near-wall region, while the outer boundary layer is unaffected, and natural boundary-layer growth is found. Lower pressure ratios increase the effectiveness of the porous

bleed system until choking is achieved, which limits the bleed effect. Moreover, a certain amount of bleed is required to sustain the inflow conditions and to prevent natural boundary-layer growth, which is additionally increased by the induced roughness due to the perforated plate geometry.

The same comparison is found for the plate with the $D = 2.0$ mm holes in Fig. 11. On the left side (Fig. 11a), the experimentally acquired profiles are shown for three different bleed rates. In the case of the lowest bleed rate, corresponding to the highest pressure ratio, a degradation of the boundary layer with respect to the inflow is found. Thus, the bleed mass flow rate is not enough to prevent boundary-layer growth. For higher mass removals, the boundary-layer profiles are significantly fuller. Again, the positive effect on the boundary layer first appears in the near-wall region and is found for higher mass flow rates also with further distance to the wall.

RANS simulations of the same plate validate the experimental findings, as shown in Fig. 11b. In comparison to the first plate, we see a more significant reduction in the boundary-layer thickness, which is a result of the higher effectiveness caused by the higher porosity level [25].

Moreover, the boundary-layer displacement thickness and shape factor are computed from the RANS simulations and presented in Fig. 12. For both plates, a reduction of the displacement thickness as a function of the plenum pressure ratio p_{pl}/p_t is observed. The lower the pressure in the cavity plenum, the higher the bleed rate, leading to a lower mass deficit in the boundary layer. However, a saturation is for low-pressure ratios. Moreover, a certain bleed rate is required to compensate the bleed roughness effect.

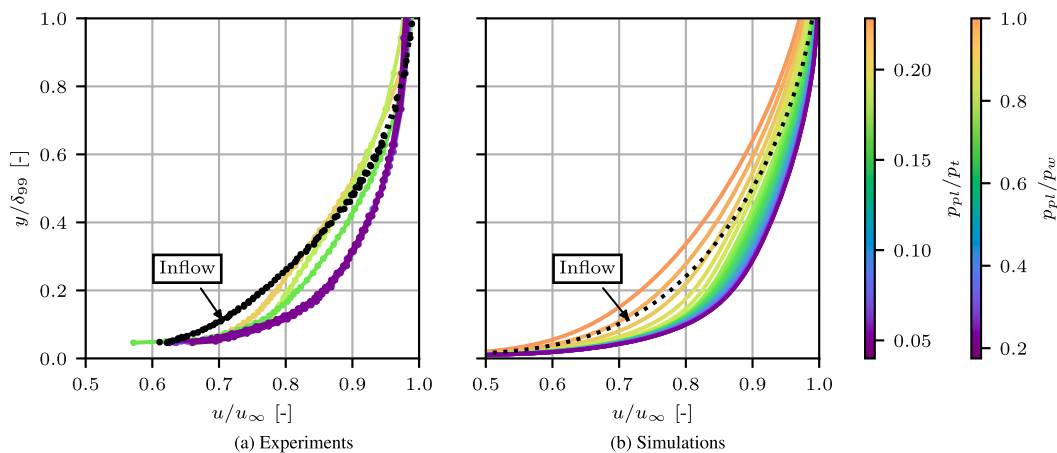


Fig. 10. Boundary layer profiles 15 mm downstream of the bleed region for plate AR.

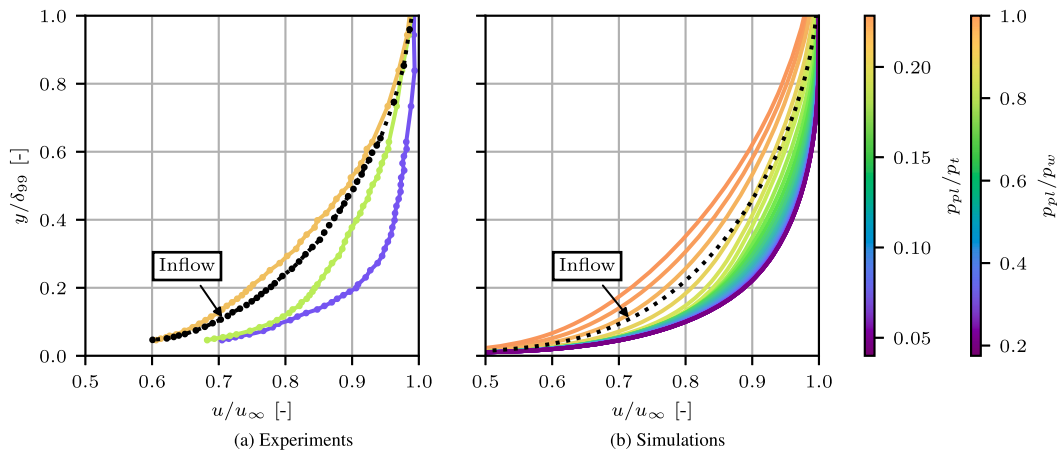


Fig. 11. Boundary layer profiles 15 mm downstream of the bleed region for plate HR.

The (incompressible) shape factor is a measure of the “fullness” of the boundary-layer profile. Earlier experiments [27] showed a quick saturation in the shape factor for small bleed rates. The same trend is observed in the current simulations independently of the plate characteristics. However, for the plate with the $D = 2.0$ mm holes, an increase in the shape factor is revealed for low cavity plenum pressures. This effect is assumed to be linked to the higher bleed roughness.

3.1.3. Three-dimensionality of the flow

The three-dimensionality of the flow field has been already proven in previous numerical [23,25,41,42] and experimental [34] studies. However, experiments showing the impact of the hole geometry on the boundary layer along the span are missing. In our previous numerical study [25], we could show a significant variation of the flow field along the span even in a quasi-2D flow field. Particularly large hole diameters lead to inhomogeneous flow fields since the inter-hole distance is large, and a high-momentum captured flow results in strong compressible effects. For the investigation of three-dimensional effects, we focus on plate HR with $D = 2.0$ mm holes as the flow field for small holes is too homogeneous and in the range of the experimental error. Moreover, the smaller amount of bleed holes in the case of large diameters makes simulations of the wind tunnel half-span feasible in terms of the required mesh size.

Fig. 13 illustrates the flow inside the wind tunnel off the center plane. Effects of the corner flow, but also variations of the flow field along the span downstream of the bleed region are significant. A gen-

eral overview of the flow field is given in Fig. 13a, visualizing the wall shear stress on the bottom and side wall of the wind tunnel, as well as a slice showing the flow field at a cross-section downstream of the bleed region, corresponding to the distance where the velocity profiles are extracted. Since the porous bleed covers only two-thirds of the span, the seemingly low impact on the corner flow is visible. Moreover, downstream of the bleed region, streaks of higher and lower wall shear stress are present.

A closer look at the last row of holes and the region downstream can be seen in Fig. 13b. Around the holes, the sonic height is extracted as a characteristic measure of the boundary-layer health. With regard to (strong) shock-wave/boundary-layer interactions, the sonic height can be directly linked to the interaction length and is therefore of major importance [2]. As seen in the figure, the sonic height varies significantly along the span. Downstream of the holes, a drastic increase is noted as the barrier shock induces a strong adverse pressure gradient. Also, a second streak of large sonic heights between the holes is found. Moreover, a low span wise influence of the porous bleed on the corner flow apparent. The flow close to the side walls seems to be unaffected as the sonic height is not reduced.

A better view at the effect on the corner flow is shown in Fig. 13c. As already stated before, the boundary-layer suction generates an expansion as the flow is redirected towards the wall. However, also flow from the side is captured, leading to the propagation of expansion waves in the span wise direction. As a consequence, the flow is redirected from the side walls to the bleed, as highlighted by the streamlines. The iso-

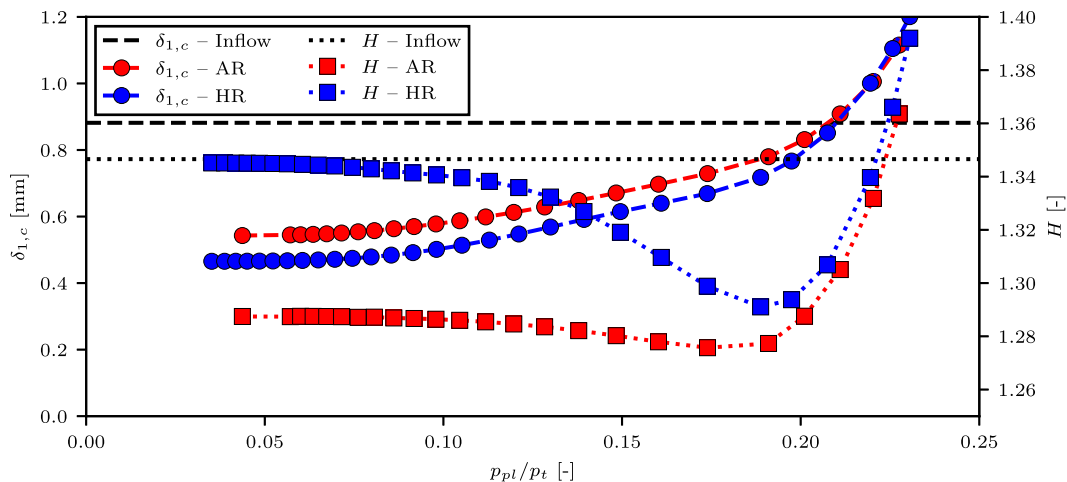


Fig. 12. Numerical acquired boundary-layer (incompressible) shape factor and displacement thickness as a function of the plenum pressure ratio for both perforated plates.

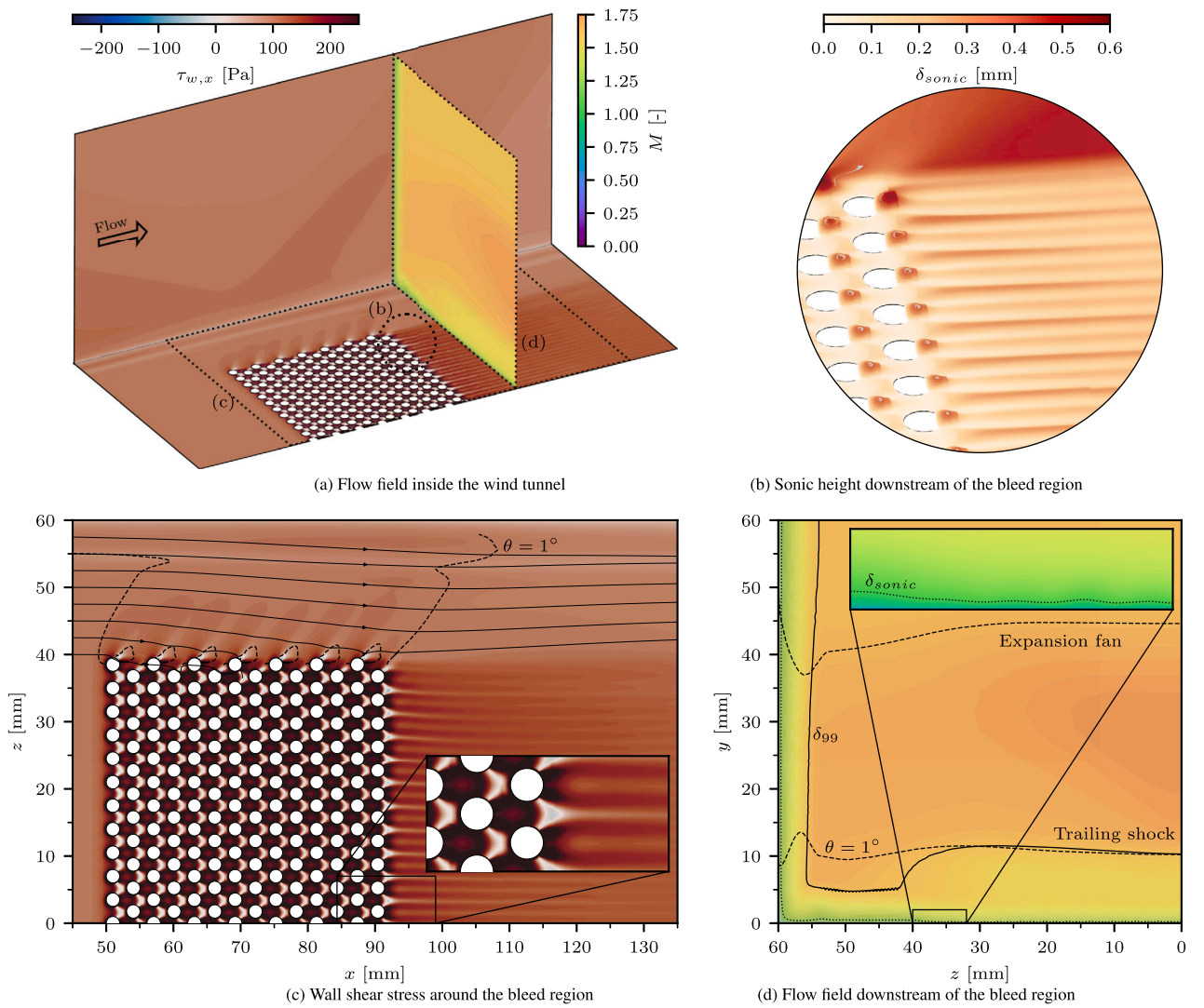


Fig. 13. Flow topology inside the wind tunnel for supersonic boundary-layer bleeding from simulation ($p_{pl}/p_t = 0.073$).

contours of a deflection angle of $\theta = 1^\circ$ illustrate the location of the first expansion waves, but also the propagation of the trailing shock further downstream at the plate end. Consequently, the application of the porous bleed on only two-thirds of the wind tunnel span leads to an increase in the size of the corner flow, which may result in a need for further flow control in these regions [33]. Since the flow-momentum decreases inside the corner, the flow is more vulnerable to separate if adverse pressure gradients are present.

Moreover, the footprints of the varying boundary-layer profiles along the span are found in the wall shear stress. The same streaks as for the sonic height are found. Directly downstream of the holes, as well as between the holes, the wall shear stress is significantly lower. The pattern of the footprint of the wall shear stress fits also very well the pattern found in the oil-flow visualization of Oorebeek and Babinsky [43] for a similar plate geometry, but a higher Mach number of $M = 2.5$.

The cross-section of the wind tunnel is shown in Fig. 13d. Here again, the propagation of the expansion fan in the span wise direction is notable, leading to an increase in the Mach number, as well as the propagation of the trailing shock. Moreover, the sonic line as well as the boundary-layer thickness, based on the 99% of the free-stream velocity at the inflow, are plotted as characteristic measures to evaluate the boundary-layer health. The trend of the boundary-layer thickness reveals apparently a thickening of the boundary layer. However, this

is caused by a decrease in the Mach number as a result of the losses due to several barrier shocks and the trailing shock. Consequently, the flow-momentum outside of the boundary layer is smaller. In contrast, the sonic height is reduced compared to the flow at the side walls, as visible in the zoom-view. As a result, the porous bleed achieved the aim of increasing the flow-momentum inside the boundary layer.

For the validation of the numerical findings, LDV measurements were performed at a horizontal plane with a distance of $y/D = 0.25$. At the same height, the velocity components in streamwise and wall-normal directions are extracted. Fig. 14 shows both the numerical and experimental results. Since the measurements were acquired aside of the center plane, the velocity components are compared to the full simulation including the side walls. Again, a bending of the streamlines towards the wind tunnel center is found in Fig. 14a and 14b, even downstream of the bleed region.

For the comparison with the experiments, we focus on the area between three columns of holes while the center column is staggered. The observed plane is acquired off the center plane. Fig. 14c shows the comparison of simulations and experiments for the streamwise component, which reveal the same flow characteristics. The holes induce expansion waves, leading to an increase in the flow velocity before passing the barrier shocks. Downstream of the last holes, the streaks are noted, as well as their bending towards the wind tunnel center. In contrast to the simulations, the measured velocity differences are smaller, which is a

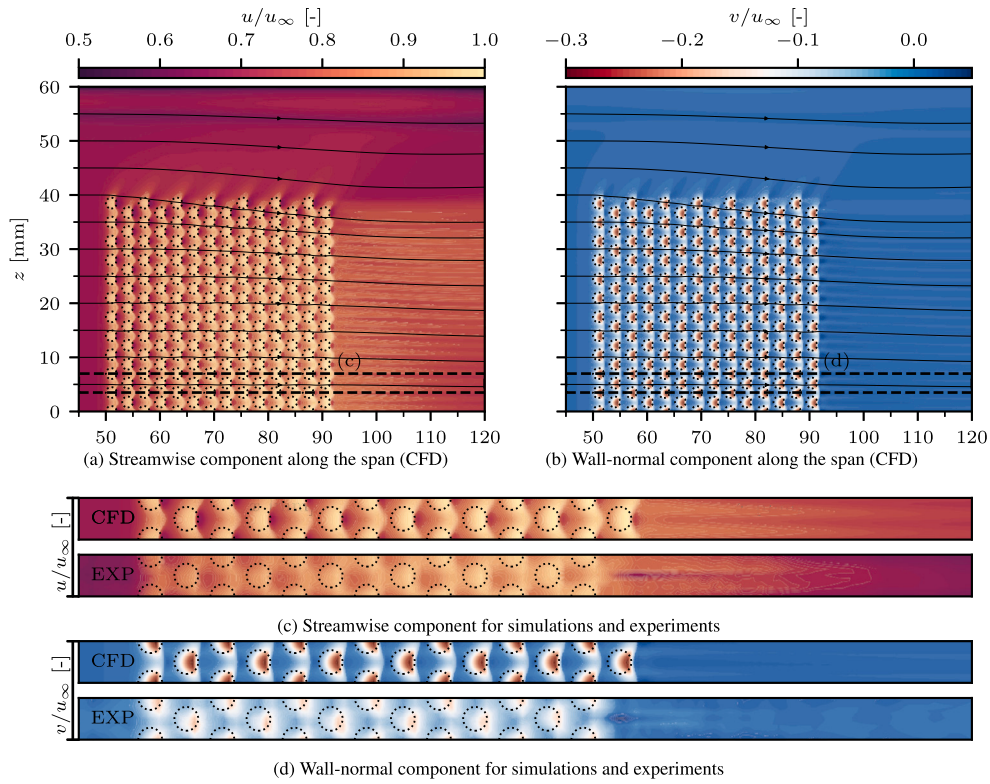


Fig. 14. Velocity contours at a wall-normal distance of $y/D = 0.25$ ($y/\delta_{99} \approx 0.12$) for experiments ($p_{pl}/p_t = 0.072$) and simulations ($p_{pl}/p_t = 0.073$); plots in (c) and (d) show zoom-view to area highlights by dashed lines.

result of the lower resolution of the measurements caused by the size of the measurement volume and the smaller amount of points. Consequently, the results are more smeared because of larger averaging areas. Please note, that the length of the perforated plate differs slightly between experiments and simulations as the staggered column has one hole less in the experiments. However, previous findings [25] showed only marginal differences at these plate lengths.

Also, the measurements in the wall-normal direction fit well with the simulations (see Fig. 14d). As stated before, the streaks are less characteristic than for the streamwise component. Again, the experimentally measured variations are smaller than in the simulations because of the lower resolution.

For a more detailed validation, multiple boundary-layer profiles at different span wise positions are acquired numerically and experimentally, and shown in Fig. 15. Fig. 15b visualizes the envelopes of

profiles dependent on the pressure ratio. A significant difference between high and low-pressure ratios is apparent. For high-pressure ratios, which correspond to low bleed rates, the profiles are found to be homogeneous in the simulations. The hole geometry does not cause any three-dimensional disturbances. With lower plenum pressures, the bleed rate increases, as well as the variability in the boundary-layer profiles along the span, which is mainly found in the lower 20% of the boundary layer. Further increase of the bleed rate by lowering the plenum pressure enhances the variability as the strength of the barrier shocks and expansion fans induced by the holes increase.

The experiments mirror the same trend, as visible in Fig. 15a. For the highest pressure ratio, the measurements at three different span wise positions vary only marginally. For a lower pressure ratio, the variation is found to be larger between the three positions. For the lowest pressure ratio, the measurements were conducted at eight different positions,

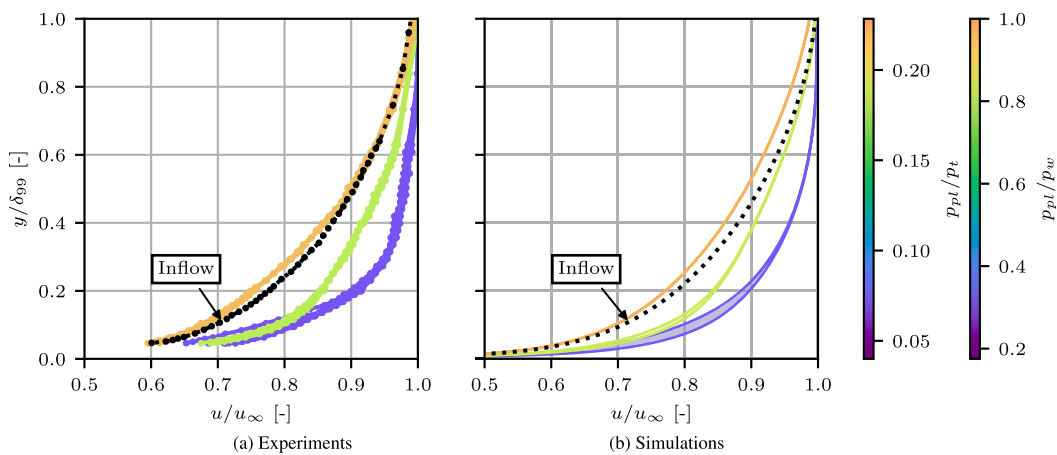


Fig. 15. Variations in the boundary-layer profiles 15 mm downstream of the bleed region along the span.

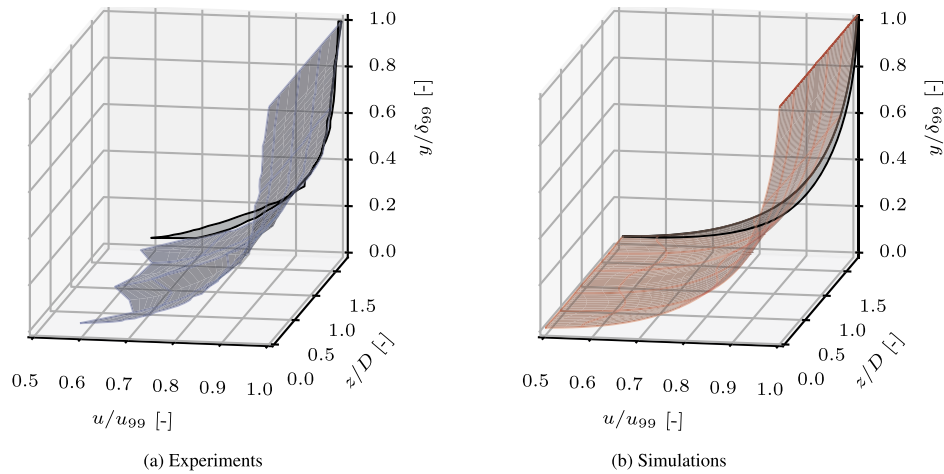


Fig. 16. Illustration of the velocity profiles along the span for experiments ($p_{pl}/p_t = 0.072$) and simulations ($p_{pl}/p_t = 0.073$).

showing the largest variability. All these measurements are shown in comparison to the simulations in Fig. 16, showing a periodic variation in the boundary-layer profiles caused by the periodic pattern of the holes.

3.2. Subsonic boundary-layer bleeding

After investigating supersonic boundary-layer bleeding, we focus on subsonic flows since we found them downstream of normal shock-wave/boundary-layer interactions. Therefore, experiments were conducted in the same test section using the convergent-divergent nozzle in an entirely subsonic regime, resulting in a free-stream Mach number of $M = 0.5$. The subsonic experiments were limited to the $D = 0.5$ mm as simulations have shown no significant variations of the boundary-layer profiles along the span. Moreover, the lower porosity level results in a lower bleed mass flow rate, which facilitates keeping the inflow conditions constant. Since the subsonic bleed influences the flow in the upstream direction, high bleed rates may result in fuller inflow profiles or an increase of the external Mach number.

The flow topology around a subsonic bleed is illustrated in Fig. 17. Like a supersonic bleed, the flow is redirected towards the wall, creating a diverging stream tube. Contrary to supersonic flows, the result is not an acceleration but a deceleration of the flow, as highlighted by the contour lines for the Mach number $M = 0.45$ and $M = 0.5$. Since the

observed case in an internal flow, the diffuser effect is even more pronounced as the stream tube is limited in size. However, simulations without a top wall limiting the domain have shown similar results. Also, a strong upstream influence is noted in contrary to the supersonic bleed, resulting in an acceleration of the flow upstream of the bleed. The zoomed view gives an impression of the flow topology inside the holes. In this case, the flow is fully subsonic. In comparison to Fig. 4a, the separated area in the front of the hole is smaller. Since no barrier shock exists, the losses are smaller compared to the supersonic case, and the effectiveness of the bleed in increasing the flow momentum in the wall vicinity is assumed to be higher.

In the next step, we focus on the effect of the porous bleed on the boundary-layer profiles. Fig. 18 shows the state of the boundary layer upstream and downstream of the porous bleed acquired from the experiments and the simulations. Again, the profiles are normalized by the inflow boundary-layer thickness and the free-stream velocity. The simulations (see Fig. 18b) demonstrate the effect of the bleed. Even low bleed rates lead to an increase in the momentum in the lower 20% of the boundary layer. Lowering the pressure ratio, and in turn, the bleed rate, results in a saturation of the effect. Below a pressure ratio of $p_{pl}/p_t \approx 0.7$, the maximum achievable improvement is achieved. On the contrary, there is still a change in the effect for the outer boundary layer notable. A further decrease in the pressure ratio increases the

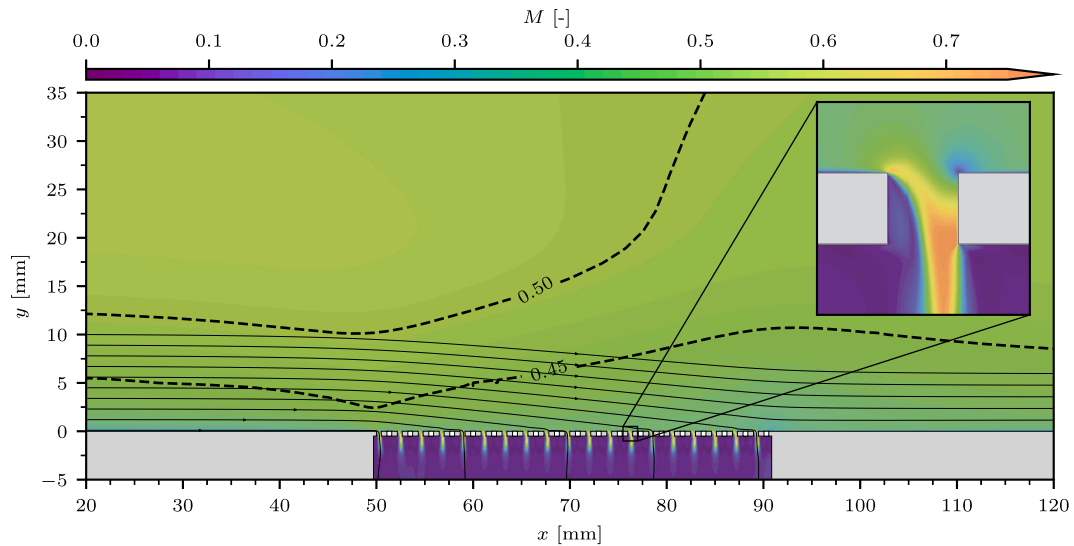


Fig. 17. Mach contour field for plate HR ($p_{pl}/p_t = 0.651$); white areas illustrate holes of the second column.

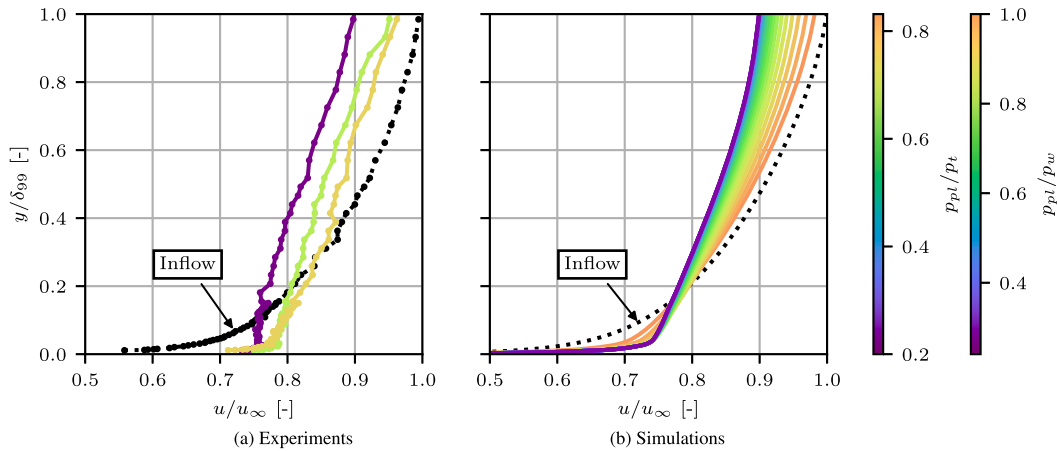


Fig. 18. Boundary layer profiles 15 mm downstream of the bleed region for subsonic conditions.

bleed rate and consequently reduces the external flow velocity as more mass is removed and the bleed generates a larger divergent stream tube.

The experimentally measured boundary-layer profiles are illustrated in Fig. 18a. The findings are similar to the simulations, even though the velocity in the vicinity of the wall is found to be smaller for low-pressure ratios. This deviation is assumed to be a consequence of the experimental methodology. As the bleed has an upstream influence, high bleed rates lead to higher inflow mass flow rates. Moreover, the inflow profile becomes asymmetric, meaning the free-stream velocity is higher in the lower part of the wind tunnel where the suction occurs compared to the upper, uncontrolled flow. The missing momentum in the upper part increases the diffuser effect, and thus, even the velocity in the boundary layer is found to be smaller. However, the inflow profiles measured upstream of the bleed region were equal independently of the bleed rate. In contrast, the numerical inlet was defined to be constant outside the boundary layer. Thus, the overall mass flowing through the test section might be higher as the momentum in the upper part is larger.

3.3. Shock/boundary-layer interaction control

In the last step, the control of a shock-wave/boundary-layer interaction is investigated. A shock generator is mounted with an angle-of-attack of $\alpha = 9.5^\circ$ in the test section, as visible in Fig. 1. Simulations were conducted in the quasi-2D setup with symmetry planes on the front and back of the domain, as well as three-dimensionally by simulating the wind tunnel half-span with the high-porosity plate HR. In the quasi-2D numerical domain, the angle-of-attack has to be increased by 1.0° to obtain the same location of the incident shock as the three-dimensionality of the flow induced by the corner flow leads to a more intense shock.

The flow field around the incident shock is illustrated in Fig. 19 for the quasi-2D simulations. In the top (Fig. 19a), the uncontrolled case is shown. The deflection angle of the incident shock is too high for a regular reflection of the shock, leading to a so-called Mach-reflection. Thus, a normal shock (Mach stem) is found in the vicinity of the wall. The adverse pressure gradient of the shock is sufficiently high to make the flow separate, resulting in a separation bubble with its length being approximately the size of the bleed region.

The successfully controlled interaction is shown in Fig. 19b, demonstrating the effect of the porous bleed. The flow separation is significantly mitigated, resulting in the elimination of the Lambda shock foot and a downstream movement of the shock foot. Since the porous bleed induces a bending of the flow towards the wall, the deflection angle along the shock, and hence the shock intensity decreases. Especially downstream of the incident shock, a strong aspiration flow is generated, resulting in a seemingly regular shock reflection. However, a small

Mach-stem is found and decelerates the flow to subsonic conditions in the wall vicinity.

The zoom-views visualize the flow topology inside the holes upstream and downstream of the shock. On the right side, the flow topology is identical to the bleed in the purely supersonic case. The expansion fan at the hole front and the barrier shock are notable. In this area, the momentum in boundary layer is increased to decrease the upstream influence of the adverse pressure gradient. In contrast, the flow inside the holes downstream of the shock is identical to a subsonic porous bleed. The flow around the hole is purely subsonic and accelerated to supersonic conditions at the hole inlet because of the low-pressure ratio. The separated region in the front of the hole is found to be significantly smaller than upstream of the shock, resulting in higher bleed rates. The presence of different flow topologies upstream and downstream of the incident shock is essential for the derivation of an adequate porous bleed model since both super- and subsonic regimes need to be considered to predict the effect of the porous bleed on the shock-wave/boundary-layer interaction.

The trend of the wall pressure is shown for both plates in Fig. 20. Again, the numerical pressure contour fields are visualized at the top and the bottom while the curves are compared to the acquired data from the pressure taps. For both plates, the pressure fields focus on the region around the shock foot to illustrate the pressure rise. A different location of the shock foot is apparent, which is caused by the different porosity levels, resulting in a higher bleed rate in the case of the high-porosity plate HR. At the center, the curves along the bleed region are shown. Here again, the shock foot is found to be located further upstream for the low-porosity plate AR (red), as seen by the pressure rise around $x = 82$ mm. Further downstream, the pressure continues to increase steadily until the end of the bleed region, terminated by the trailing shock. The same trend is apparent for plate HR, with the difference of a further downstream located pressure rise. Moreover, the experimentally acquired pressure values fit very well with the simulations.

For the comparison of experiments and simulations, velocity profiles were acquired along the bleed region. As described in Sec. 3.1.3, the large size of the holes of the high-porosity plate HR results in strong variations of the boundary-layer profiles along the span. For this reason, LDV measurements have been only performed on plate AR with $D = 0.5$ mm to keep the number of required measurements low. All the measurements, as well as the numerically extracted profiles, are shown in Fig. 21. At the top, the unscaled profiles are illustrated to evaluate the conformity of the overall flow field for the quasi-2D simulations and the experiments. In both cases, the incident shock has the same shock angle, as seen by the knee in the profiles in Fig. 21a independent of the bleed rate. In contrast, the shock reflection is found to be affected by the porous bleed. The lower the pressure ratio and the higher the bleed rate, the further the downstream movement of the shock. Hence,

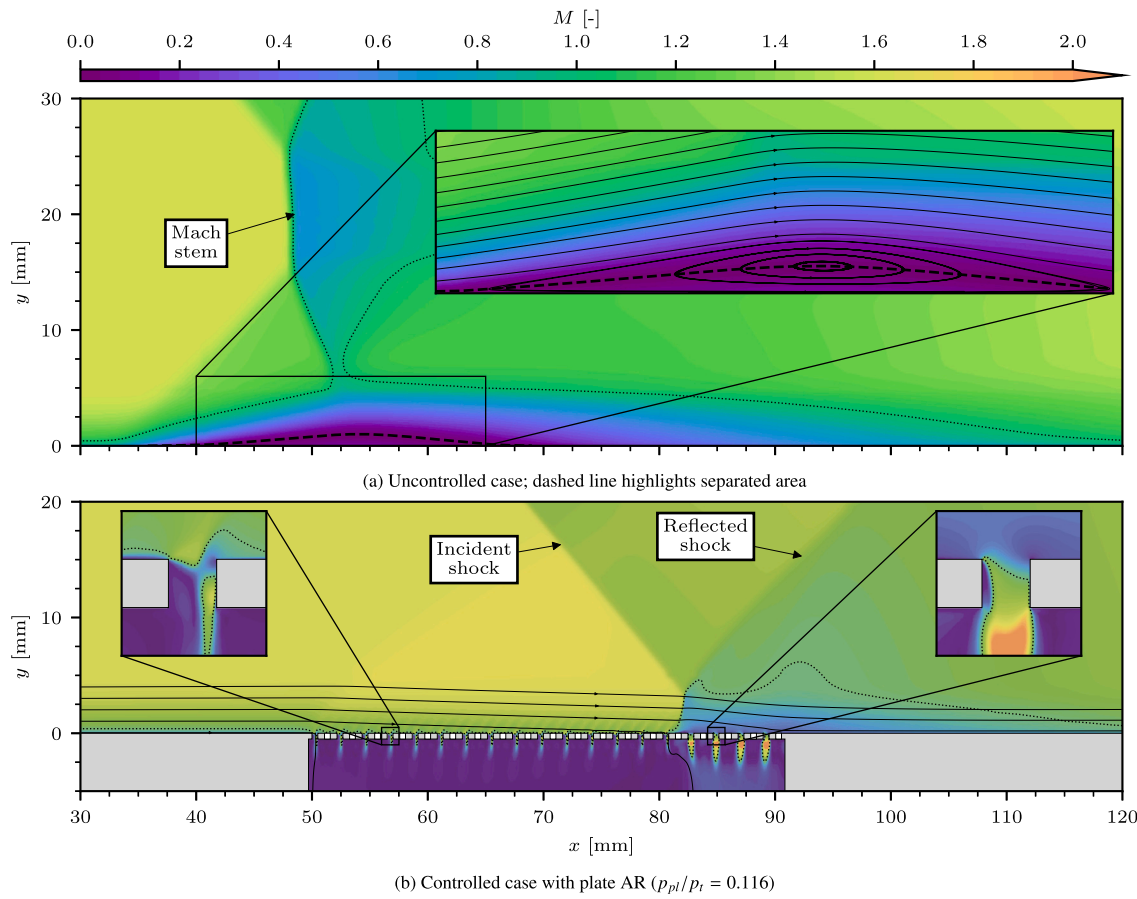


Fig. 19. Mach contours for shock-wave/boundary-layer interaction in controlled and uncontrolled case; dotted lines highlight sonic line.

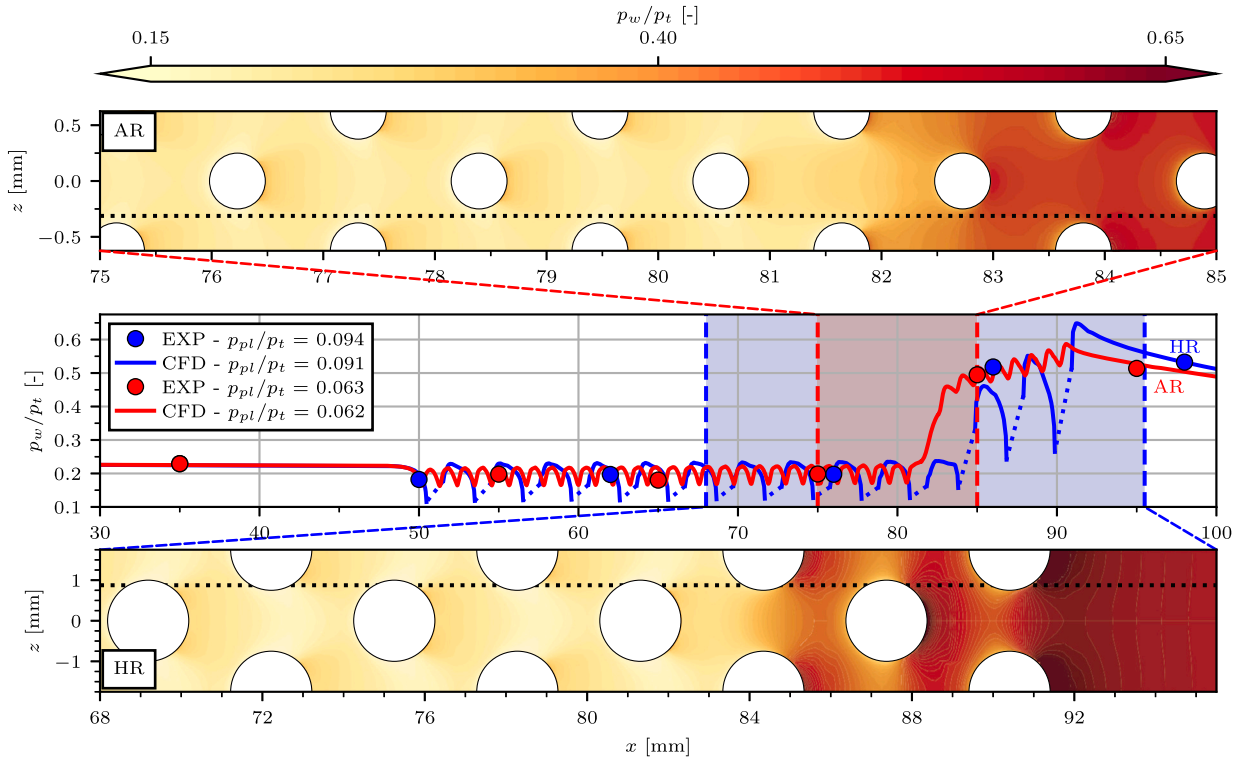


Fig. 20. Static wall pressure along the bleed region.

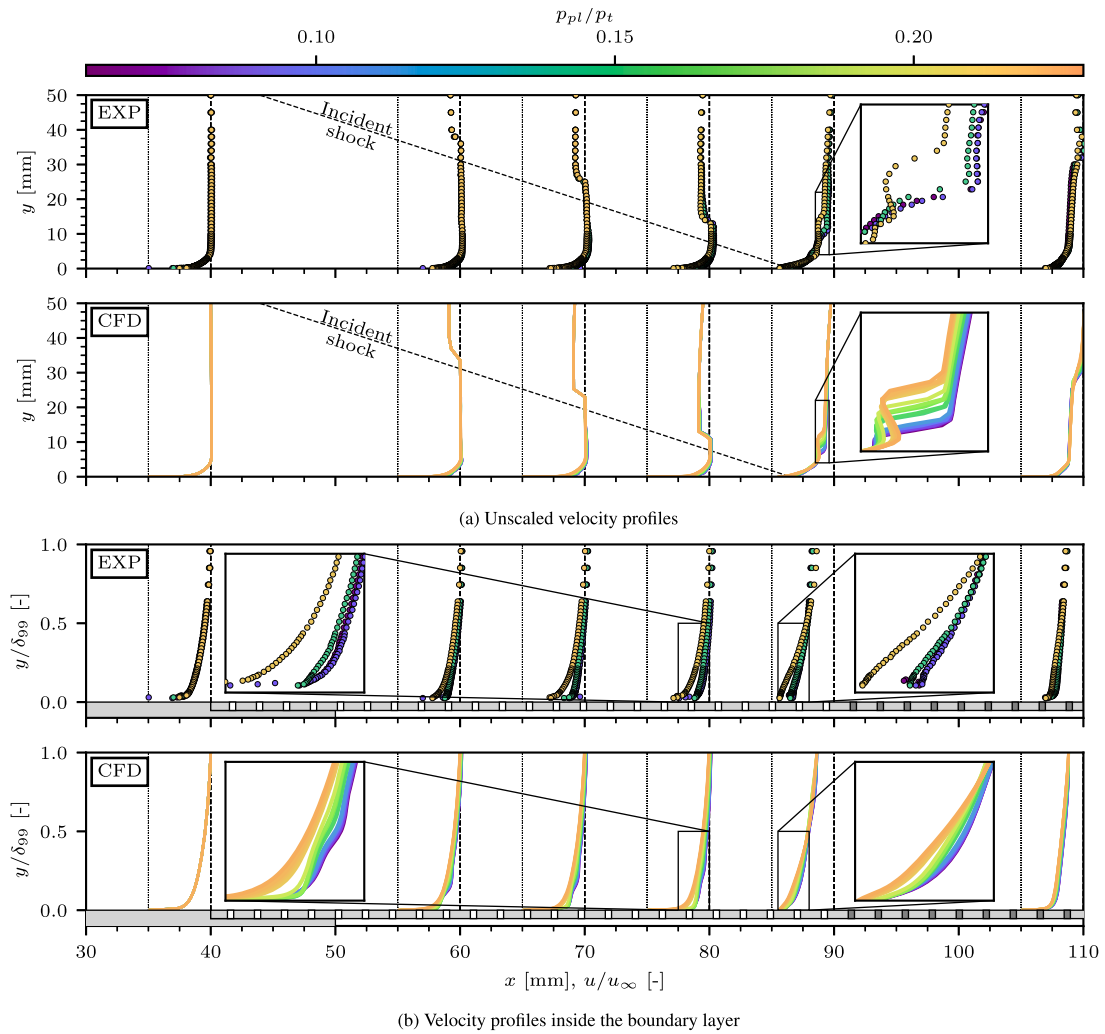


Fig. 21. Velocity profiles along the bleed region for plate AR.

the reflected shock is located closer to the wall for the further downstream positions. The zoom-view demonstrates the effect of the bleed rate on the velocity profiles. The agreement between experiments and simulations is very good.

For the observation of the near-wall region inside the boundary layer, the profiles are scaled by the incoming boundary-layer thickness (see Fig. 21b). The profiles upstream of the incident shock, which is located between $x = 80$ mm and 85 mm, show the increase of the momentum inside the boundary layer dependent of the bleed rate. The higher the bleed rate, the fuller the boundary-layer profile, as visible in the zoom-view on the left. Please note that the knees in the numerical profiles are caused by the relative position to the bleed holes and the resulting passing of shocks and expansion waves. In the experiments, these effects are more smeared because of the size of the measurement volume.

Downstream of the shock, artifacts of the supersonic control are notable. The higher the momentum in the boundary layer upstream of the shock the higher the momentum downstream of the shock. However, a higher momentum downstream of the shock is expected to result in a lower bleed efficiency as the flow separation inside the holes increases, and hence, the vena contracta area decreases. Since the adverse pressure gradient along the plate below the shock foot leads to lower pressure ratios p_{pl}/p_w , the relative difference between the cases becomes smaller, and the bleed works close to, or under choked conditions ($p_{pl}/p_w \leq 0.528$). Thus, a lower bleed efficiency results in lower bleed rates, and a lower increase of flow momentum near the wall. Conse-

quently, the differences between the cases are found to be smaller than upstream of the shock, as illustrated in the zoom-view on the right. Downstream of the bleed region, the variations in the boundary-layer profiles are even smaller compared to the differences upstream of the shock.

In the last step, the wind tunnel half-span simulations are compared to the flow visualization for the plate HR. Fig. 22 gives an overview of the flow topology inside the wind tunnel. In Fig. 22a, the wall shear stress as well as the flow field downstream of the bleed region are shown. Moreover, an iso-contour of the density gradient is added to visualize the incident as well as the reflected shock. Directly at the first glance, a significant three-dimensionality of the flow is observable. The curvature of the shock is used as a measure to evaluate the variation of the flow along the span. Therefore, the iso-contour of the density gradient is closer observed in Fig. 22b. The darker the color of the iso-contour, the closer the location with regard to the wind tunnel side wall. The incident shock has only a small variation along the span and is only slightly curved in the upstream direction towards the side wall. On the contrary, the reflected shock is strongly curved. The low flow momentum of the corner flow increases the upstream influence of the incident shock, moving the shock foot and the reflected shock upstream. Interestingly, the reflected shock merges with the trailing shock at the center of the test section.

The footprint of the shock is visible in Fig. 22c which shows the wall shear stress. The positive pressure gradient induces a local flow separation, visualized by the blue color range and surrounded by the dashed

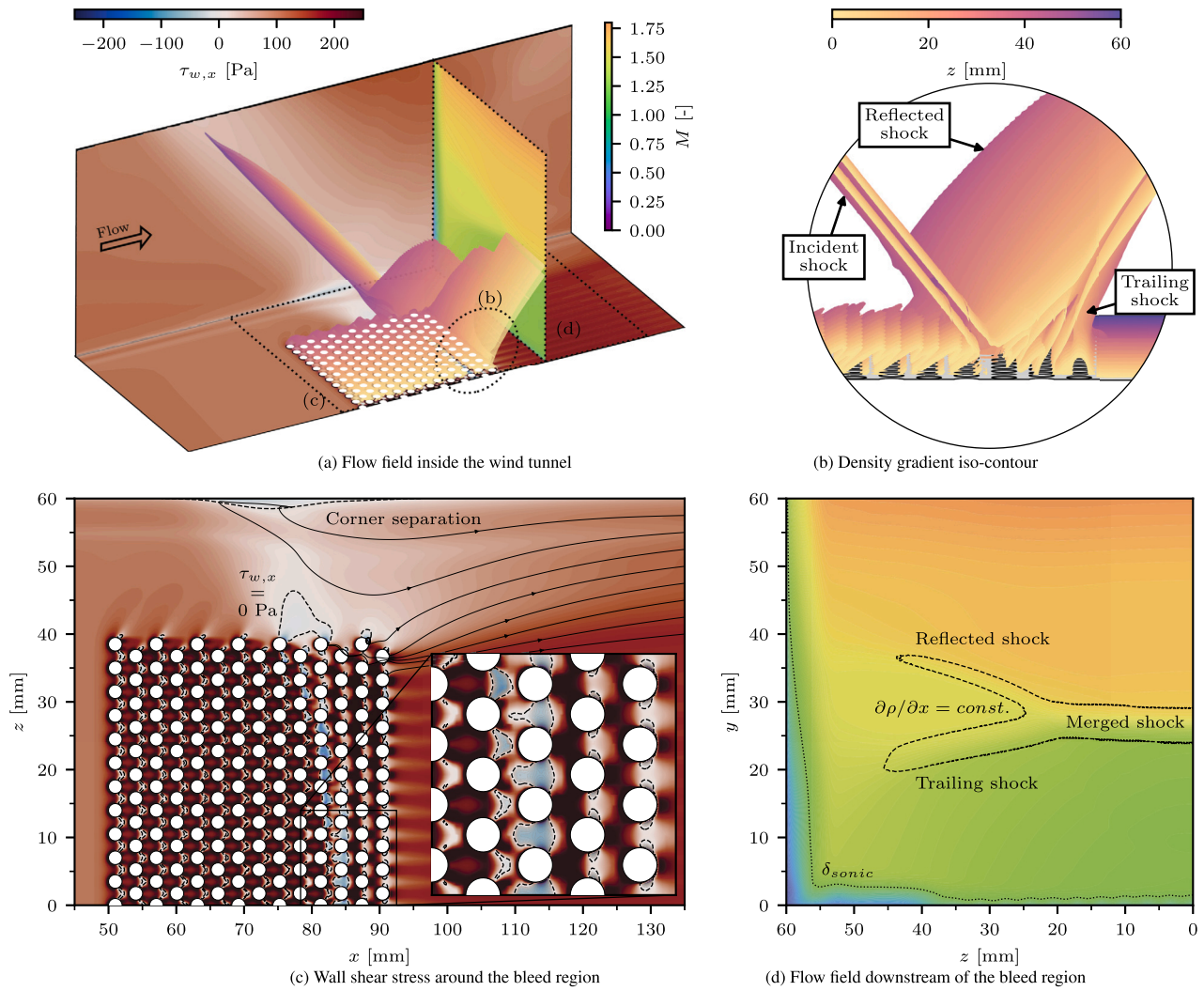


Fig. 22. Flow topology with shock-wave/boundary-layer interaction inside the wind tunnel from simulation ($p_{pl}/p_t = 0.095$).

line. The size of the separation is limited to the area between the holes, as the suction leads to a fast reattachment of the flow. At the center of the test section, the shock can be located at $x \approx 83$ mm since the flow starts to separate even between the holes at this station. Along the span, the incident flow separation moves upstream. Alongside the bleed region, a small area of separated flow is apparent, as well as a separation of the corner flow. However, the flow separation does not cover the entire span of the wind tunnel as the bleed energizes the flow at the center. The streamlines demonstrate how the suction confines the width of the stream tube. Similar effects were found in earlier investigations with vortex generators controlling the center flow [32,33].

The flow field on a slice downstream of the bleed region is shown in Fig. 22d. In the upper part, the Mach number is found to be higher as the reflected shock has not passed the flow at this location, while the Mach number is significantly reduced in the lower part of the test section. The iso-line of the density gradient pinpoints the approximate position of the reflected shock. Here again, the merging of trailing and reflected shock is observed in the center of the test section. With further distance from the center, the two shocks divide. Near the side walls, the intensity of the shocks decreases as they merge with the expansion waves caused by the bleed and the rear edge of the shock generator. Particularly the expansion fan caused by the shock generator results in a smearing of the density gradient and leads to a re-acceleration of the flow.

Furthermore, the sonic height is extracted and highlighted by the dotted line. Its high amount at the side walls near the corner illustrates the thickening of the boundary layer caused by the adverse pressure gradient of the shock. Thus, the sonic height is larger at the top before passing the shock and increases against the corner. In the area downstream of the bleed, the sonic height is smaller as the suction increases the momentum inside the boundary layer. The lowest sonic height is found around $x = 30$ mm with its value slightly increasing towards the center of the test section. As the shock position is further upstream towards the side wall, the area with a subsonic working regime of the bleed is larger. Hence, the effect of the flow control is increased in this area and the momentum is higher in the wall vicinity. However, no significant effect of the bleed on the corner flow is apparent. The presence of an expansion fan caused by the rear edge of the shock generator leads to a reattachment of the flow and counteracts the negative effect of the porous bleed.

BOS visualizations of the experiments with the high-porosity plate HR are shown in Fig. 23. At the top, the flow field is illustrated from a distance, showing almost the entire test section including the shock generator. The generated oblique shock is seemingly regularly reflected at the bottom wall. Faintly visible is the expansion fan created by the bleed region, as well as the expansion fan generated by the rear edge of the shock generator. A closer look at the interaction is shown in Fig. 23b, where the camera was positioned closer to the test section focusing on the impingement point of the shock, revealing more information about

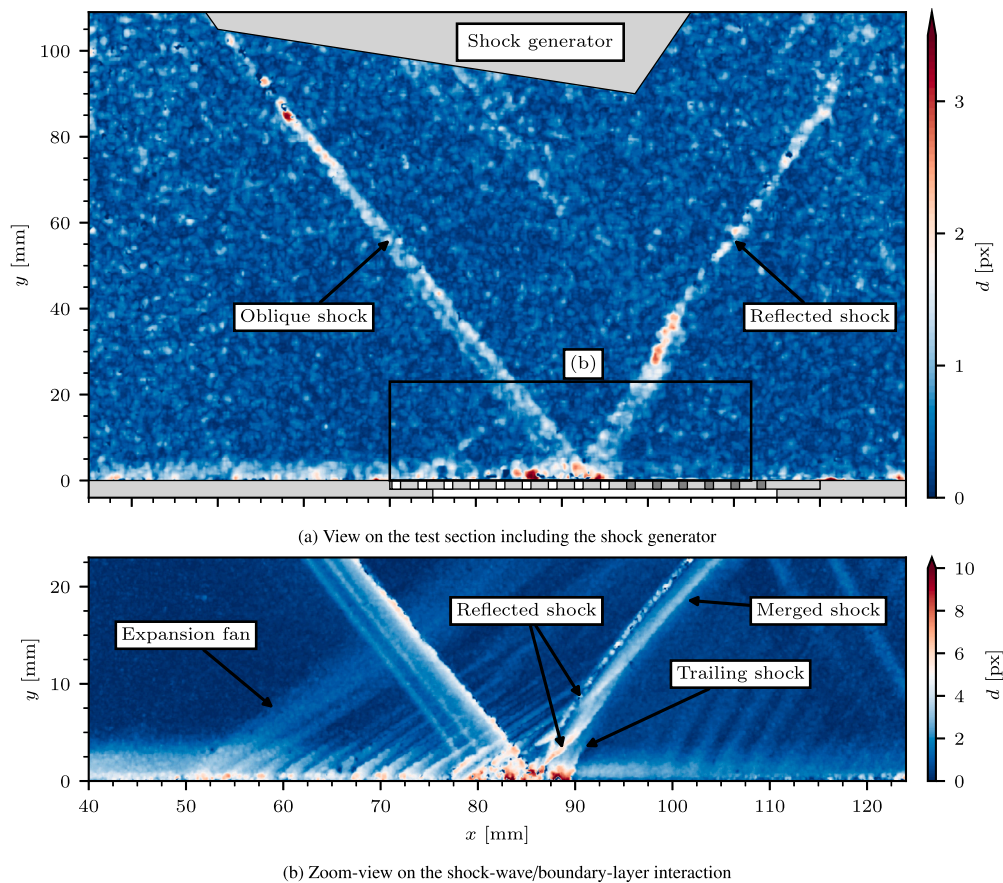


Fig. 23. BOS visualization of the shock-wave/boundary-layer interaction control for $p_{pl}/p_t = 0.094$.

the shock structure. A distinct incident shock is visible with its impingement point located at $x \approx 85$ mm. The reflected shock is divided in two distinct parts and smeared between. One part of the shock has a significantly lower shock angle and is located further downstream, where it merges with the trailing shock. The second distinct part is located further upstream and forms a shock wave located with an offset to the merged shock. Since the BOS visualization is an integration of the density gradient along the visual axis of the camera, it is expected that the first part of the reflected shock is located close to the center of the wind tunnel, while the second part is found near to the side walls. Thus, the structure of the shock system is in line with the numerical findings.

4. Conclusion

This paper studied experimentally and numerically the control of boundary layer by porous bleed systems. We have presented the effect of the porous bleed on a shock-wave/boundary-layer interaction after simplifying the complex problem into two separate problems: super- and subsonic boundary-layer control by porous bleed. The findings support the idea to separately characterize the working principle of porous bleed systems for both flow regimes as the flow topology inside the bleed holes significantly differs, resulting in different effects on the boundary layer and interaction with an incident shock.

In the supersonic flow case, we have found a good agreement between experimental and numerical results. The effect of the porous bleed on the boundary layer is well resolved by the numerical simulations, as proven by the LDV-obtained velocity fields, boundary-layer profiles, and static wall pressure measurements. Moreover, three-dimensional effects resulting in variations of the boundary-layer profiles along the span for the use of large bleed holes were proven for the first time in experiments. Furthermore, the effect on the corner flow and the

impact of the corner flow on the two-dimensionality of the center flow was illustrated.

In addition, the effect of the porous bleed on a subsonic flow was determined in the same experimental and numerical setup. For the first time, one study described the working principle of porous bleeds in both super- and subsonic conditions by means of experiments and RANS simulations. Like in the supersonic regime, the boundary-layer bleeding leads to an increase of the flow momentum in the wall vicinity. However, the removal of mass results in a decrease of the flow momentum in the outer region of the boundary layer as well as of the external flow.

Finally, the shock-wave/boundary-layer interaction control was studied. Even for this complex flow topology, a very good agreement between simulations and experiments was achieved. The effect on the boundary layer along the bleed region was well replicated by the experiments. Also, three-dimensional simulations of the wind tunnel half-span were performed to study the impact of the corner flow on the interaction of shock, boundary layer, and porous bleed. Like in previous studies, a reinforcement of the corner flow was observed. In both experiments and simulations, the same structure of the shock topology was found.

The findings of this study legitimate the use of RANS simulations to investigate the effect of porous bleed systems in subsonic and supersonic flows with and without shock-wave/boundary-layer interactions. As experiments are time- and cost-intensive to examine comprehensive parametric studies, numerical simulations can help to deepen the knowledge about the working principle of bleed systems to improve bleed models. Moreover, the findings endorse a separate consideration of super- and subsonic bleeds, especially with regard to bleed models that are required to work in the case of normal shock-wave/boundary-layer interactions.

CRedit authorship contribution statement

Julian Giehler: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Thibault Leudiere:** Resources, Methodology, Investigation. **Robert Soares Morgadinho:** Resources, Methodology, Investigation. **Pierre Grenson:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Conceptualization. **Reynald Bur:** Writing – review & editing, Supervision, Project administration, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Julian Giehler reports financial support was provided by European Commission Marie Skłodowska-Curie Actions. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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