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Effects of bevelled nozzles on standoff shocks in supersonic impinging jets

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Abstract

Moderately under-expanded jets issuing from a circular baseline and two bevelled circular nozzles impinging upon a perpendicular flat plate were experimentally studied. The effects of nozzle-pressure-ratio and separation distance variations on the standoff shock formations were investigated with schlieren visualizations and a visual hull based three-dimensional (3D) shock reconstruction technique to provide deeper insights into their 3D features. Across all flow configurations arising from the different combinations of these parameters, results indicated that the bevelled nozzles are effective in introducing asymmetry to the standoff shock geometries. Depending on the exact flow configuration, standoff shock locations may also undergo significant upstream displacements. In particular, the single-bevelled nozzle produces highly unsteady standoff shocks with asymmetric oscillation amplitudes along both side of the nozzle lip regions. Changes to the standoff shock key characteristics were observed to be sensitive towards the jet shock structures and reflection point modified by the bevelled nozzle exits. In particular, the strength and relative position of the reflection point are identified as the major contributing factors influencing the upstream static pressure distribution of the standoff shock, hence leading to the observed changes in the standoff shock behaviour.

Keywords: schlieren; standoff shocks; unsteady shocks; shock reconstruction; supersonic jets; impinging jets

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1. Introduction

Impinging jets are directly relevant in applications such as spacecraft launches, gas turbine cooling, cold-spray technologies, aeroacoustics, thrust vectoring systems, among many others [1-5]. Depending on the velocities of the jets used, the resulting impinging flow phenomena can be very different, particularly between subsonic and supersonic jets [6, 7]. Supersonic impinging jets are typically characterized by extremely high flow shear, high levels of aeroacoustics noise, distinct shock structures within the supersonic jet bodies and the formation of standoff shocks. It is now known that the flow field produced by a supersonic impinging jet can be categorized into three main flow regions - (1) the primary jet flow, (2) the impingement zone, and (3) the radial wall jet [6]. The highly complex impingement zone has been the subject of many studies due to their strong influences upon the most important flow characteristics of the supersonic impinging jet [8-10]. It is also in this region where standoff shocks are formed.

In the classical work of Donaldson and Snedeker [6] and Donaldson et al. [7], flow structures and heat transfer properties of a jet impinging under various configurations were investigated using selected experimental techniques such as schlieren photography. Subsequent studies by Kalghatgi and Hunt [10] focused on the impingement zone at small nozzle-to-plate separation distances, where schlieren photography and pressure measurement results indicate a close relationship between the formation of a stagnation bubble and the standoff shocks and jet shock waves. The stagnation bubble, a region of slow recirculating flow under the standoff shock, was observed to exert strong influences upon the impingement surface pressure and heat transfer characteristics. Further impingement studies were also conducted based on normal [11] and inclined flat plates [9] at small separation distances. Through schlieren visualizations and other quantitative results, these studies reaffirmed the complexity of the

interactions between the supersonic jet and standoff shocks, as well as their importance in determining the occurrence of the stagnation bubble. The study by Lamont and Hunt [9] further revealed that the complex shock interactions are able to result in much greater maximum impingement pressures on the inclined flat plates as compared to the normal flat plates.

In addition, Krothapalli et al. [12] revealed that the jet shock structures confer strong influences upon pertinent flow features at small separation distances, based on nonlinear lift loss with nozzle-pressure-ratio (NPR) variation. Furthermore, it was also speculated that the precise geometries of the standoff shock and stagnation bubble both play important roles in the resulting impinging behaviour. The crucial roles played by the supersonic jet shocks and standoff shocks have also been ascertained in the study of impinging jet aeroacoustics [13, 14]. Through the use of conventional and phase-locked schlieren photography alongside acoustics and plate pressure measurements, large plate impulsive tones were detected when the standoff shock was observed to collapse during its oscillation cycle [15]. Furthermore, the occurrence of a Mach disk upstream of the standoff shock was found to contribute towards the tonal production, while tonal mitigation occurs when the first or second jet shock takes on a conical shape. Subsequently, the strength of the standoff shock and the upstream velocity gradients were found to significantly influence jet stability conditions [8], while zones of silence were observed when the standoff shocks were located close to the impingement plate.

Since the primary jet shocks and standoff shocks have been established to have strong influences on the key properties (aeroacoustics, plate pressure and heat transfer) of an impinging jet, appropriate control of the shock structures can lead to desirable impingement

properties in engineering applications. This can be achieved through the use of non-conventional indeterminate-origin (IO) nozzles [16], which involves a systematic circumferential variation of the axial lengths of the nozzle lip. This type of nozzle exit modifications can be classified as a type of passive flow control technique that has the advantage of being practical, easy to implement and has low weight penalty as compared to active flow control techniques. Furthermore, IO nozzles have been shown to be successful in introducing considerable three-dimensional (3D) distortions to these shock structures in supersonic free jet applications. In particular, single-bevelled circular nozzles were observed to introduce thrust/jet vectoring and non-diamond shock cells [17, 18] that were successful in mitigating jet screech [19] and could offer lower noise pollution in an industrial setting such as cold-spraying applications. Double-bevelled circular nozzles were observed to introduce asymmetric shock cells and jet spread rates between the two orthogonal planes, with improved overall mass flux through jet entrainment [20] and potentially favourable impact upon heat transfer levels. Single- and double-bevelled rectangular nozzles [21, 22] have also been investigated and were observed to be effective in shifting the noise directivity upstream, which could further mitigate noise pollution. Spark schlieren images of these jets [23] indicate significant distortions to the overall jet shock structures, and suggest that noise pollution could be reduced by modifying the shock structures. More recently, surface heat transfer characteristics of impinging elliptic jets [24] were investigated, and it was observed that the standoff shock exerts significant influences upon the heat transfer rates.

Despite the possibility of manipulating the flow and shock characteristics associated with the impingement behaviour favourably through the use of non-conventional nozzles, there appears to be very limited research and discussions focusing on the use of such nozzles in supersonic impinging jet conditions. The current paper aims to feature this knowledge in the

field of asymmetric supersonic jet flow impingement by experimentally studying the flow characteristics of moderately under-expanded supersonic impinging IO jets at small nozzle-to-plate separation distances. In addition, while traditional schlieren visualizations of shock structures are commonly used in supersonic impinging jet studies, 3D schlieren techniques could prove to be more appropriate and insightful in cases where the resulting shocks are expected to be non-axisymmetric and highly three-dimensional. A new 3D shock reconstruction approach based on the visual hull image processing technique was recently proposed and demonstrated in an asymmetric free jet application [18]. As such, it will be useful to utilize this technique to shed more light upon the differences between standoff shocks produced by different supersonic impinging IO jets. The current study presents a unique opportunity in extending the scope of application of this novel technique. To the best of the authors' knowledge, it is the first time this technique is used for the study of highly complex supersonic impinging jet flows.

2. Experimental setup and reconstruction procedures

2.1 Supersonic impinging jet setup

The experimental facility consisted of an open-air blow-down cold jet in a temperature and humidity regulated environment [25]. Dehumidified compressed air from air reservoirs capable of storing air at a maximum of 69 bar stagnation pressure was channelled through a series of valves and regulators to the settling chamber of the jet, where standard flow straighteners were employed to improve flow quality. At the outlet of the settling chamber, convergent-divergent circular nozzles of various designs can be attached to produce the supersonic jet flow. For the impingement surface, an aluminium, 6 mm thick, $30D \times 30D$ square plate was mounted on a rigid fixture anchored against the laboratory wall. It was positioned such that the jets impinged upon it perpendicularly and in the centre at two

different separation distances (h) of $h/D=1$ and 1.5 . The use of relatively small separation distances limits the influence of mixing effects, which can generally be ignored at small separation distances since the effects of shock structures interactions are much more dominant [9].

A circular baseline, 30° single- and double-bevelled nozzles were used and their design details can be found in earlier studies [17, 20]. These nozzles were designed with a circular-to-circular contraction section with a contraction-ratio of 10.5, nozzle exit inner diameter of $D=12.7$ mm and lip thickness of 0.5 mm. The design Mach number was $M_d=1.45$ for a perfectly-expanded NPR of 3.4. Throughout the present study, the jet was operated at two different moderately under-expanded conditions of NPR=4 and 5. By keeping the bevel angle similar between the two IO nozzles, influences upon the flow imposed by different number of bevels can be explored here. For the sake of consistency, they were designed such that their mean heights (i.e. average of the longest and shortest nozzle axial lengths) were the same, with that particular location designated as the jet origin or $x/D=0$ location. Details of the baseline nozzle design schematics are illustrated in Fig. 1(a), and the straightening section of the two bevelled nozzles are shown in Figs. 1(b) and 1(c). The cylindrical coordinate system, (r, θ, x) , is also defined in the schematic.

2.2 Schlieren system setup

The experimental setup for schlieren visualization was based on the modified single-pass Z-type schlieren setup adopted in an earlier study [18], hence its description will only be briefly covered here. A 200 W white light emitting diode (LED) was used to provide broadband illumination, with two 3 m focal length and 300 mm diameter parabolic mirrors reflecting the light into the test section and onto the knife-edge. The knife-edge was placed in the vertical

Fig. 1 Detailed design schematics of (a) the baseline nozzle and the straightening sections of the (b) single-bevelled and (c) double-bevelled nozzles

configuration normal to the jet flow and adjusted to about 80% cut-off to over-range the schlieren system and better highlight the shock structures. An IDT NX4-S1 camera with a Nikon AF Micro-Nikkor 200 mm f/4D IF-ED lens was used to capture the schlieren images. To compensate for the image brightness levels and reduce turbulence effects, a relatively long frame exposure time of $200 \mu\text{s}$ was used for the impinging jets and over $400 \mu\text{s}$ was used for the free jets, unless otherwise stated. All images were captured at 1000 frames-per-second (FPS).

2.3 3D shock reconstruction procedures

The 3D shock reconstruction principle and procedures have been described in great detail in an earlier work [18], hence this section will only highlight the most important features of the

Fig. 2 Flowchart of the 3D shock reconstruction procedures

reconstruction procedures adopted in the present study. For reference, a flowchart which highlights the key reconstruction procedures is presented in Fig. 2. To perform the reconstruction on the standoff shocks, two pieces of information are required – Firstly, the silhouette images of the standoff shock and secondly, the corresponding camera matrices which defines the position and orientation of the cameras capturing the images. Ideally, an infinite number of silhouette images with its corresponding camera matrices (i.e. images of the standoff shock and the corresponding camera information at infinite number of different viewing angles) is required. Clearly, this is not possible in practice. Instead, the bevelled nozzles were rotated at 10° intervals such that schlieren images were captured at 10 different viewing angles for the range of $\theta=[0^\circ, 90^\circ]$. Image post-processing was subsequently performed to convert these images into silhouette images necessary for the shock reconstructions.

In accordance to the procedures described by Lim et al. [18], the image post-processing mainly consists of binary decisions performed at the location of the standoff shocks, which classifies the image pixels as part of the standoff shock silhouettes or not. For the current study, since the standoff shocks display excellent image intensity contrast with the background, the acceptance criterion is based on a pre-defined image intensity threshold. The camera matrices were obtained through a combination of standard external camera calibration procedure and synthetically generated camera parameters, which followed the processes described in Lim et al. [18]. Through the preceding steps, the two important pieces of information necessary for the shock reconstruction were obtained. With this information, volume carving operation was performed on a pre-defined tessellation of cubic voxels, and the reconstructed 3D shock structures were extracted for subsequent analysis.

3. Results and discussions

3.1 Free-jet configurations

Comparisons between impinging jets and their corresponding free-jet counterparts are often performed in earlier studies [6, 8] as a starting point of discussion. Similarly, shock patterns associated with $M_d=1.45$ freely-exhausting supersonic jets from the baseline and two IO nozzles at $NPR=5$ and 4 are presented in Figs. 3 and 4 respectively. Since detailed discussions of these freely-exhausting supersonic jets had been covered in earlier studies [17, 20], only the most important and relevant features will be highlighted here. It should be noted that both NPRs produce qualitatively similar shock structures under free-jet configurations. Discrepancies of interest exist only in terms of quantitative characteristics such as shock cell lengths and locations of the reflection point, which will be discussed later.

With reference to both figures, high-speed schlieren imaging results show that all test nozzles

Fig. 3 Schlieren images of $M_d=1.45$ freely-exhausting jets at $NPR=5$ for (a) baseline, (b) single-bevelled ($\theta=0^\circ$), (c) single-bevelled ($\theta=90^\circ$), (d) double-bevelled ($\theta=0^\circ$) and (e) double-bevelled ($\theta=90^\circ$) nozzles

Fig. 4 Schlieren images of $M_d=1.45$ freely-exhausting jets at $NPR=4$ for (a) baseline, (b) single-bevelled ($\theta=0^\circ$), (c) single-bevelled ($\theta=90^\circ$), (d) double-bevelled ($\theta=0^\circ$) and (e) double-bevelled ($\theta=90^\circ$) nozzles. Note that the brightness of these images has been enhanced.

produce quasi-steady shock systems. In Fig. 3(a), intercepting oblique shocks emanating from the baseline nozzle lip can be seen to reflect off each other at the reflection point to form two reflected shocks that end at the terminating line of the first shock cell. No Mach disk is present at the reflection point due to the conservative under-expansion exhaust

conditions used here. For the single-bevelled nozzle, image captured with respect to the $\theta=0^\circ$ viewpoint of the jet is shown in Fig. 3(b) while that of the $\theta=90^\circ$ viewpoint is shown in Fig. 3(c). As compared to the baseline test case shown in Fig. 3(a), the first shock cell has undergone significant changes, with what appears to be a slight upward vectoring of the jet body and shocks in the direction of the shorter nozzle lips. The reflection point has also shifted away from the jet axis and towards the longer nozzle lips region. This could be due to the intercepting shocks originating from different axial positions but with similar intercepting shock angles – which is not too surprising since it is still a circular nozzle. Indeed, it can be observed that when the intercepting shock starts to form at the longer nozzle lip, the intercepting shock from the shorter nozzle lip has already almost reached the jet centreline. A 3D representation and geometrical information of this shock system can be found in Lim et al. [18]. For the double-bevelled nozzle depicted in Figs. 3(d) and 3(e), the reflection point appears clearly in Fig. 3(e) but less so in Fig. 3(d), due to the existence of numerous weak shocks in the latter. In this case where the double-bevelled nozzle was designed such that it is symmetrical about the jet axis along both $\theta=0^\circ$ and 90° viewpoints, the reflection point maintains its location along the jet axis, with no vectoring of the shock systems observed.

Table 1 summarizes the shock cell lengths and reflection point locations with respect to the jet origin, as well as the shock stability conditions determined from the high-speed schlieren images and will be relevant to the discussions later. All values were normalized by the jet inner diameter (D) and averaged across $\theta=0^\circ$ and 90° image viewpoints for the single- and double-bevelled test nozzles, except for the reflection point of the double-bevelled nozzle whereby only the $\theta=90^\circ$ viewpoint (see Figs. 3(e) and 4(e)) information was considered. Shock systems are deemed to be quasi-steady since there is no image blurring in the schlieren images, and there is less than $0.05D$ change in the position of the shock systems across the

Table 1 Non-dimensional parameters of $M_d=1.45$ freely-exhausting supersonic jets

Nozzle type	Shock cell length (x/D_{sc})	Reflection point axial location (x/D_{RP})	Reflection point radial location (r/D_{RP})	Quasi-steady
NPR=5				
Baseline	1.86	1.19	0	Yes
Single-bevelled	1.79	1.14	0.11 ($\theta=270^\circ$, towards longer lips)	Yes
Double-bevelled	1.83	1.17	0	Yes
NPR=4				
Baseline	1.34	0.71	0	Yes
Single-bevelled	1.35	0.76	0.21 ($\theta=270^\circ$, towards longer lips)	Yes
Double-bevelled	1.28	0.91	0	Yes

time-series images captured at 1000 FPS (shown in Appendix A). This observation is also consistent with the results in past studies [17, 20]. The error of the parameters in Table 1 is estimated to be $\pm 0.05D$.

3.2 Impinging jet – Effects of NPR

3.2.1 Configuration 1: $h/D=1$ and NPR=5

Schlieren images of under-expanded jets at NPR=5 impinging upon the impingement surface at a separation distance of $h/D=1$ are presented in Fig. 5. Based on Table 1, it can be discerned that the separation distance is shorter than the first shock cell length for all test nozzles, with the *impingement surface upstream of the free jet's reflection point location*. For the baseline nozzle shown in Fig. 5(a), the standoff shock resembles that of a convex disk with a Mach disk on the top surface. Note that similar standoff shocks had been observed in past studies [26, 27] despite some differences in the test conditions. This unique disk

Fig. 5 Schlieren images of $M_d=1.45$ impinging jets at $h/D=1$ and $NPR=5$ (configuration 1) for (a) baseline, (b) single-bevelled ($\theta=0^\circ$), (c) single-bevelled ($\theta=90^\circ$), (d) double-bevelled ($\theta=0^\circ$) and (e) double-bevelled ($\theta=90^\circ$) nozzles

geometry has been observed to manifest when standoff shocks are located within the initial expansion region near the nozzle lips [9], which is certainly the case for the present test configuration. The apparent finite “thickness” of the standoff shock can be attributed to its inherent 3D geometry and the integrative nature of schlieren photography. Additionally, it should also be mentioned that the region of intense bright white pixel intensity adjacent to the impingement surface represents the radial wall jet region ([see Appendix B](#)), where a series of compression and expansion waves extend away from the impingement point. However, the most important aspect of the baseline nozzle standoff shock is that its features and outlines are invariant even if the nozzle were to be rotated to another angle during the high-speed schlieren imaging.

For the single-bevelled nozzle shown in Figs. 5(b) and 5(c), the overall geometry and position of the standoff shock remains very similar to the baseline test case; a convex disk. Possibly, the standoff shock is located too far upstream within the initial expansion region near the nozzle lips and is hence comparatively invariant to the influence of the nozzle exit geometry. Nonetheless, minute changes in the form of a concavity (slight depression) along the top surface of the standoff shock can still be observed due to the asymmetric nozzle design. Along $\theta=0^\circ$ viewpoint, the asymmetric intercepting oblique shocks produced a small concavity that is tilted slightly towards the longer nozzle lip region (i.e. towards the left of the jet axis in Fig. 5(b)). In contrast, they remain symmetric along the $\theta=90^\circ$ viewpoint. Clearly, the original standoff shock geometry from the baseline nozzle has been modified in an asymmetric fashion by the use of a single-bevelled nozzle.

As for the double-bevelled nozzle, even though the overall geometry takes on the shape of a convex disk, the outlines of the top surface of the standoff shock differ greatly between $\theta=0^\circ$ and 90° viewpoints. There appears to be no clear pair of intercepting shocks in the $\theta=0^\circ$ viewpoint, in contrast to the symmetrical intercepting shocks observed to clearly intersect the standoff shock in the $\theta=90^\circ$ viewpoint. The result is the formation of a small flat plateau and a significantly large concavity on top of the standoff shock along $\theta=0^\circ$ and 90° viewpoints respectively, as shown in Figs. 5(d) and 5(e). Like the previous test cases, the concavity is always bounded by the intercepting oblique shocks. While it is convenient to regard the geometry on the top surface here as a Mach disk, it will be erroneous to do so since the concavity in the $\theta=90^\circ$ viewpoint is depressed downward instead of taking on a flat plateau geometry like the $\theta=0^\circ$ viewpoint. In addition, a small dome can be observed at the base of the standoff shock in Fig. 5(d). Since the standoff shock thickness represents the three-dimensionality of the shock, the dome is likely to exist at the peripheral of the base of the

Table 2 Non-dimensional geometric parameters and characteristics of standoff shocks at $h/D=1$ and $NPR=5$ (configuration 1)

Nozzle type	Standoff shock distance (s/D)	Standoff shock thickness (t/D)	Standoff shock geometry
Baseline	0.33	0.08	Axisymmetric convex disk with Mach disk in the centre.
Single-bevelled	0.31	0.08	Convex disk with concavity shifted and tilted towards longer nozzle lip.
Double-bevelled	0.35	0.08	Disk with “saddle point” geometry along top surface. Two small domes in the same plane as the nozzle longer lips.

standoff shock. The standoff shock geometries across the two viewpoints are very different, indicating that the double-bevelled nozzle is effective in introducing asymmetry to the geometry of the standoff shock.

Based on the high-speed schlieren imaging experiments, the standoff shocks produced by all three nozzles were observed to be quasi-steady, where qualitatively the positions of the standoff shocks remain relatively invariant between the different nozzle designs. The standoff shock thicknesses, indication of its overall three-dimensionality, do not differ too drastically among the three different nozzles. A summary of the state and geometrical information of the standoff shocks is provided in Table 2, whereby the standoff shock distance (s) is defined to be the distance between the impingement surface and top-most point on the standoff shock, and the standoff shock thickness (t) is defined as the distance between the top-most and bottom-most points of the standoff shock. The estimated uncertainty of these parameters is below 2% of the jet diameter.

Fig. 6 Schlieren images of $M_d=1.45$ impinging jets at $h/D=1$ and $NPR=4$ (configuration 2) for (a) baseline, (b) single-bevelled ($\theta=0^\circ$), (c) single-bevelled ($\theta=90^\circ$), (d) double-bevelled ($\theta=0^\circ$) and (e) double-bevelled ($\theta=90^\circ$) nozzles

3.2.2 Configuration 2: $h/D=1$ and $NPR=4$

To look into the effects of NPR upon the structure of the standoff shocks, $NPR=4$ was used while maintaining the same separation distance of $h/D=1$ and the corresponding schlieren images are shown in Fig. 6. Based on Table 1, the primary difference between the flow scenarios at $NPR=5$ and 4 (i.e. configuration 1 and 2 respectively) is that the *impingement surface is now situated downstream of the free jet's reflection point location* but still within the first jet shock cell in all three test cases. Since the under-expansion is more conservative, the adverse pressure gradient across the reflection point is also expected to be weaker. For the baseline nozzle as shown in Fig. 6(a), the standoff shock has a small flat plateau (i.e. Mach disk) along its top surface. The diameter of the Mach disk is also significantly smaller as compared to the one in Fig. 5(a) and could possibly be due to the intercepting oblique shocks meeting the standoff shock much closer to the jet axis at $NPR=4$. The overall standoff

shock thickness is also visibly greater than its NPR=5 counterpart in configuration 1 (as shown in Fig. 5(a)), signifying a greater extent of three-dimensionality present in the overall geometry.

For the single-bevelled nozzle, the standoff shock along $\theta=0^\circ$ viewpoint as depicted in Fig. 6(b) has a sharp tip pointing towards the longer nozzle lip, which coincides with the position of the reflection point formed by the intercepting oblique shocks. The concavity interestingly remains approximately at the centre but tilted towards the shorter nozzle lip. Hence, the tilt of the concavity is opposite to that observed at NPR=5 condition. Along $\theta=90^\circ$ viewpoint shown in Fig. 6(c), the standoff shock resembles that of the baseline nozzle in Fig. 6(a), except that it is thinner. Comparing with its NPR=5 counterpart in configuration 1 (see Fig. 5(c)), the concavity does not appear to exist anymore. Finally, for the double-bevelled nozzle presented in Figs. 6(d) and 6(e), the standoff shocks are symmetrical about the jet axis. Along $\theta=0^\circ$ viewpoint, the standoff shock takes on the geometry of a convex disk and the top surface does not appear to form any concavity or flat plateau. This is likely because there are numerous weak shocks emanating from the nozzle instead of a pair of strong intercepting oblique shocks forming the reflection point. On the other hand, a flat plateau bounded by the intercepting oblique shocks exists on the top surface of the standoff shock along the $\theta=90^\circ$ viewpoint. As compared to its NPR=5 counterpart in configuration 1 (see Fig. 5(e)), the decrease in concavity/plateau diameter is likely caused by the intercepting oblique shocks meeting the standoff shock closer to the jet axis. Similar to the NPR=5 counterpart, a small dome can once again be observed at the base of the standoff shock, as shown in Fig. 6(d). A summary of the standoff shock characteristics for $h/D=1$ and NPR=4 (configuration 2) is presented in Table 3.

Table 3 Non-dimensional geometric parameters and characteristics of standoff shocks at $h/D=1$ and $NPR=4$ (configuration 2)

Nozzle type	Standoff shock distance (s/D)	Standoff shock thickness (t/D)	Standoff shock geometry
Baseline	0.38	0.12	Axisymmetric convex disk with Mach disk in the centre.
Single-bevelled	0.33	0.09	Convex disk with an “edge” feature tilted towards longer nozzle lip, coinciding with intercepting shocks. Concavity shifted towards jet axis and tilted towards shorter nozzle lip.
Double-bevelled	0.36	0.09	Disk resembling a “2D bow shock” along top surface. Two small domes in the same plane as the nozzle longer lips.

Fig. 7 Schematics of the standoff shock at the impingement condition of $h/D=1$ and $NPR=5$ (configuration 1) for (a) baseline, (b) single-bevelled and (c) double-bevelled nozzles. *Note that the key features are not drawn to scale.*

Throughout both test configurations, the IO jet nozzles have demonstrated their capabilities in influencing the standoff shock geometry. In view of the high degree of asymmetry in the standoff shocks, 3D shock wave reconstruction was applied to all the preceding test cases to

Fig. 8 Schematics of the standoff shock at the impingement condition of $h/D=1$ and $NPR=4$ (configuration 2) for (a) baseline, (b) single-bevelled and (c) double-bevelled nozzles. *Note that the key features are not drawn to scale.*

shed more light on the standoff shocks' geometry. Nonetheless, as the geometrical difference was small to begin with, the results also reflected as such and it was not meaningful to present the reconstruction results directly. In order to allow the reader to better discern the key shock structure differences, the results were carefully analysed and schematics of the standoff shock with exaggerated key features are presented in Figs. 7 and 8.

Based on the results, it becomes very clear how the standoff shock has changed its 3D geometry as the NPR was reduced across the two test configurations. For the baseline test case, while the features remain axisymmetric, the Mach disk has reduced its diameter from what is shown in Fig. 7(a) to that of Fig. 8(a). For the single-bevelled test case, the concavity in Fig. 7(b) was initially pointing towards the longer lips of the nozzle but shifted towards the jet axis and pointed towards the shorter nozzle lips with the decrease in NPR as shown in Fig. 8(b). The sharp tip that was observed in Fig. 6(b) is now highlighted in Fig. 8(b) and appears

to belong to an “edge” that coincides with the intercepting shocks. Note that this edge feature manifested as the tip of the standoff shock bounded by the intercepting shocks in Fig. 6(c). For the double-bevelled test case, the standoff shock in configuration 1 resembles that of a “saddle point” geometry as shown in Fig. 7(c). The small dome at the base of the standoff shock observed in Fig. 5(d) appears to be in the same plane as the nozzle longer lips, as indicated in Fig. 7(c). For the same test case in configuration 2, the standoff shock appears to look more like a 2D bow shock instead, due to the combination of the convex disk and flat plateau in the $\theta=0^\circ$ and 90° viewpoints respectively.

3.3 Impinging jet – Effects of separation distance

3.3.1 Configuration 3: $h/D=1.5$ and $NPR=5$

To look into the effects of separation distance, the nozzle-to-plate distance was increased to $h/D=1.5$ while maintaining $NPR=5$. This allows direct comparisons with the $h/D=1$ and $NPR=5$ configuration (configuration 1) presented earlier. Based on Table 1, this configuration also ensures that the *impingement surface is situated downstream of the free jet’s reflection point location* but still within the first jet shock cell in all three test cases. The schlieren results of all three test cases for test configuration 3 are shown in Fig. 9. As compared to the results in the previous two test configurations, much more significant changes to the location and geometry of the standoff shocks can now be observed. For the baseline test case shown in Fig. 9(a), the standoff shock thickness has increased from $t/D=0.08$ in configuration 1 and $t/D=0.12$ in configuration 2 (see Tables 2 and 3) to $t/D=0.23$ in the current test configuration, indicating a significant increase in the three-dimensionality of the shock. There is also a drastic increase in standoff shock distance, from $s/D=0.33$ in configuration 1 and $s/D=0.38$ in configuration 2, to $s/D=0.59$ in the current test configuration.

Fig. 9 Schlieren images of $M_d=1.45$ impinging jets at $h/D=1.5$ and $NPR=5$ (configuration 3) for (a) baseline, (b) single-bevelled ($\theta=0^\circ$), (c) single-bevelled ($\theta=90^\circ$), (d) double-bevelled ($\theta=0^\circ$) and (e) double-bevelled ($\theta=90^\circ$) nozzles

The increase in standoff shock distance is closely related to its thickness. The underlying mechanism is likely to be related to the instability mechanism proposed by Ginzburg et al. [28], and is closely relevant to the interaction between the jet shock structures and the standoff shock. In Fig. 9(a), a Mach disk has now clearly appeared at the centre of the standoff shock, and together with the nozzle intercepting oblique shocks as well as the tail shocks on the outer edge of the standoff shock, the three-shock confluence point is produced. According to Ginzburg et al. [28] and Kalghatgi and Hunt [10], a shear layer forms along the slip-line originating from the three-shock confluence point. As this approaches the subsonic plate boundary layer, it causes an increase in the flow pressure, leading to the occurrence of

plate boundary layer separation and the formation of the stagnation bubble. Occurrence of a peripheral static pressure maximum often associated with the formation of a stagnation bubble leads to a static pressure build up behind the Mach disk when the flow in the central domain is trapped and cannot enter the mixing zone. As the pressure behind the Mach disk rises, upstream displacement of the standoff shock occurs. This motion is counteracted by the primary jet momentum and static pressure upstream of the Mach disk until a dynamic equilibrium is attained. The pressure in the central domain does not rise above the peripheral maximum, hence flow in the central domain cannot enter the mixing zone and the standoff shock remains displaced upstream.

In the case of the **single**-bevelled nozzle, the schlieren images in Fig. 9(b) and 9(c) capture two prominent flow features not observed in any of the other test cases. Firstly, modification of the nozzle exit appears to have a much stronger and pronounced effect in influencing the geometry of the standoff shock as compared to the previous two configurations. The standoff shock appears to be severely distorted, with the tip of the standoff shock attracted to the reflection point located nearer to the longer lips of the asymmetric nozzle. Similar to the shock structures observed in the baseline case, formation of the three-shock confluence point connecting the nozzle intercepting oblique shocks, Mach disk, and tail shock can be observed. Though, it must be noted that due to considerable standoff shock instabilities, it was difficult to accurately determine if the tip of the standoff shock actually constitutes the geometry of a Mach disk. Secondly, the schlieren images captured highly unsteady behaviour of the standoff shock at multiple positions throughout its oscillation cycle. While minor oscillations or instabilities can be expected due to the local influence of turbulence, jet mixing layer, or the wall jet, this was the only test case in the entire study whereby the standoff shock waves were unstable with such a large oscillation amplitude. In terms of

oscillation amplitude, the axial displacement was observed to be much greater on the segment of the standoff shock that is nearer to the longer nozzle lip. For the same segment of the oscillating standoff shock, it does not oscillate at the same amplitude across the observed oscillation cycles. Specifically, the oscillation amplitude appears to fluctuate between low and high amplitudes between different oscillation cycles. This could also be due to the relatively low 1000 Hz image acquisition rate used here, where the camera framerate was unable to fully resolve the oscillation amplitudes. Due to the hardware constraint, it was not possible to accurately determine the oscillation amplitude and frequency in the current study. The intercepting oblique shocks were observed to be steady throughout this entire process and did not appear to have any correlation with the motions of the standoff shock.

There could be a few possible causes of the shock instability. Unsteadiness with frequencies below 10 Hz can occur if the stagnation bubble is repeatedly formed and swept away [10]. This does not appear to be the case in the present study, as instantaneous schlieren images with an image exposure time of 10 μ s and an image acquisition rate of 1000 Hz proved insufficient in capturing time-resolved information on the oscillations (see [Appendix C](#)). Lamont and Hunt [9] reported on the possibility of acoustic standing waves set up between the plate and any parallel surface near the nozzle, which can lead to higher frequency unsteadiness. This also does not appear to be the case as the experimental rig used in the present study did not have any parallel plates near the nozzle vicinity. Finally, the instability mechanism proposed by Ginzburg et al. [28] seemed the most likely based on similar smudged features in the schlieren images as well as the observation of strong acoustics in the surrounding space [29] during the course of the experiments in this study.

Displacement of the standoff shock is likely to be due to the occurrence of a peripheral static pressure maximum often associated with the formation of a stagnation bubble, which leads to a static pressure build up behind the Mach disk when the flow in the central domain is trapped and cannot enter the mixing zone. As the pressure behind the Mach disk rises, upstream displacement of the standoff shock occurs until the pressure in the central domain has risen to greater than the peripheral maximum. Flow in the central domain may then enter the mixing zone, thus leading to pressure relief in the central domain and the standoff shock displaces downstream back to its original position. The entire process repeats itself, leading to the observed oscillations. Keeping in mind that all three nozzles were designed with a circumferential variation of the axial length of the nozzle lips, the pressure relief that occurs when the flow exits the nozzle is expected to be different for all three nozzles. This affects the pressure field near the standoff shock, which is closely linked to the physical mechanism involved in the upstream displacement/instability characteristics of the standoff shock. Hence, it is unsurprising that the shock instability was observed only for the single-bevelled nozzle.

For the double-bevelled nozzle as shown in Fig. 9(d) and 9(e), the standoff shock in both viewpoints clearly exhibits differing geometries which are much more pronounced than the previous two configurations. At the top surface of the standoff shock, a dome geometry and a flat plateau can be observed in the $\theta=0^\circ$ and 90° viewpoint respectively. This observation is reminiscent of the double-bevelled configuration 2 test case, and the top of the standoff shock should resemble the geometry shown in Fig. 8(c), that of a 2D bow shock. At the base of the standoff shock, a smaller dome can be observed in the $\theta=0^\circ$ viewpoint as shown in Fig. 9(d). While domes at a similar position have been observed in both configuration 1 and 2, the current configuration has the largest and most distinct dome formation. In the $\theta=90^\circ$

Table 4 Non-dimensional geometric parameters and characteristics of standoff shocks at $h/D=1.5$ and $NPR=5$ (configuration 3)

Nozzle type	Standoff shock distance (s/D)	Standoff shock thickness (t/D)	Standoff shock geometry
Baseline	0.59	0.23	Quasi-steady. Significant upstream displacement with formation of a distinct Mach disk and the three-shock confluence point.
Single-bevelled	N.A.	N.A.	Highly unsteady behaviour. Largest displacement observed at the longer nozzle lips.
Double-bevelled	0.52	0.23	Quasi-steady. Significant upstream displacement with narrower shock structures on the plane of the longer nozzle lips ($\theta=90^\circ$ plane).

viewpoint shown in Fig. 9(e), the three-shock confluence point is observed although this was not the case for the $\theta=0^\circ$ viewpoint in Fig. 9(d). Similar to configuration 1 and 2, this is likely to be due to a lack of well-defined intercepting shocks in the $\theta=0^\circ$ viewpoint. Nonetheless, drastic displacement of the standoff shock has occurred with the standoff shock distance increasing from $s/D=0.35$ and 0.36 in configuration 1 and 2 respectively (see Tables 2 and 3) to $s/D=0.52$ in the current test configuration. The thickness of the standoff shock has also drastically increased from $t/D=0.08$ and 0.09 in configuration 1 and 2 respectively to $t/D=0.23$ in the current test configuration. Based on the mechanism in which the shock upstream displacement occurred, it is highly likely that a stagnation bubble has formed in the current test case, although the cross-section of the stagnation bubble is unlikely to be axisymmetric. Table 4 summarizes the geometrical information of the standoff shock across the three test cases in the current configuration.

Since the standoff shock in the double-bevelled test case has been observed to take on a much different 3D geometry, the 3D reconstruction procedure [18] was again performed to ascertain the geometry of the standoff shock. The results from the reconstruction are shown

Fig. 10 Reconstructed standoff shock geometries associated with (a) baseline and (b) double-bevelled nozzles in isometric view, as well as (c) baseline and (d) double-bevelled nozzle cross-sections, for $h/D=1.5$ and $NPR=5$ (configuration 3).

in Fig. 10. Some spurious surfaces at the peripheral of the reconstruction can be observed for the double-bevelled test case in Fig. 10(b) and at the bottom of Fig. 10(d). This is an artefact of the image-processing approach adopted in the reconstruction algorithm and is not part of the shock structures. Interested readers are encouraged to refer to the earlier study [18] for detailed discussions on the associated reconstruction errors.

Based on the 3D reconstruction results, there is an obvious eccentricity in the cross-section of the double-bevelled standoff shock, with much narrower shock structures in the $\theta=90^\circ$ plane as compared to the $\theta=0^\circ$ plane. The narrow shock structures did not even reach the nozzle throat diameter and manifested itself in Fig. 10(b) as the small dome at the base of the

standoff shock. Upon closer inspection of Fig. 9(e), the constant pressure streamlines which bound the formation of the tail shock in the $\theta=90^\circ$ viewpoint appears to form inward towards the jet axis as compared to that in Fig. 9(d) which forms outwards away from the jet axis. This behaviour can also be observed in the freely-exhausting jet shock structures shown in Fig. 2. The elliptical cross-section of the constant pressure streamlines was produced due to the asymmetrical nozzle design and likely led to the asymmetric cross-section geometry of the standoff shock. Possibly, the nozzle asymmetry led to an earlier flow expansion in the $\theta=0^\circ$ plane as compared to the in the $\theta=90^\circ$ plane. Hence, at any axial distance before the occurrence of the reflection point in the first shock cell, flow in the $\theta=0^\circ$ plane should have a higher Mach number and lower static pressure than those along the $\theta=90^\circ$ plane. This implies that the tail shock in the $\theta=90^\circ$ plane should be weaker than in the $\theta=0^\circ$ plane, which can be achieved by either decreasing the oblique shock angle with respect to the flow, or in this case by reducing the cross-section area of the tail shock. With the standoff shock's cross-section as shown in Fig. 10(d), it is likely that the formation and cross-section of the stagnation bubble under the standoff shock is also affected, though there is currently no pressure data to confirm this postulation.

3.4 Reflection point and standoff shock relationship

Thus far, the standoff shock had been investigated by varying the independent variables; namely NPR, nozzle exit geometry and separation distance. Varying the NPR has the effect of shifting the axial position of the reflection point relative to the impingement surface and standoff shock, leading to a change in the static pressure distribution at the position of the standoff shock. The use of IO jet nozzles directly affects the overall jet shock structures emanating from the nozzles and can introduce significant variations particularly to the radial position of the reflection point. Separation distance dictates the relative distance of the

Fig. 11 Flow schematics of an under-expanded jet under (a) freely-exhausting condition, (b) configuration 1, (c) configuration 2 and (d) configuration 3. *Not drawn to exact scale.*

standoff shocks with respect to the reflection point. Evidently, the reflection point is the dependent variable with its characteristics determined by the aforementioned independent variables. To better understand changes observed in the standoff shock properties, it is necessary to consider from the perspective of the reflection point.

In an under-expanded freely-exhausting jet as illustrated in Fig. 11(a), the exit pressure (P_1) is higher than that of the back pressure (P_{atm}). For the flow to correct itself, it undergoes expansion through a series of Prandtl-Meyer expansion waves to achieve an increase in Mach number and a reduction in static pressure to P_2 . Since the flow in region 2 is turned away from the jet centreline, and the normal velocity component must be zero at the jet centreline, a second set of expansion wave occurs which turns the flow towards the jet centreline, resulting in further reduction of the static pressure to P_3 . Since P_3 is now lower than the

ambient pressure, the expansion waves reflect on the constant pressure line as compression waves and coalesce to form the intercepting oblique shocks, which then reflect off at the reflection point to form the reflected shocks farther downstream. Flow in region 3 continually undergoes expansion as it travels downstream, until it passes through the intercepting and reflected shocks to arrive at region 4 and 5 with higher static pressures of P_4 and P_5 respectively. The pressure jump across the intercepting and reflected shock is dependent on the shock angle with respect to the local flow direction. Based on this flow schematic, it becomes clear that there is an adverse pressure gradient across the reflection point, and the location of the lowest static pressure lies just upstream of the reflection point. To facilitate discussions, hereinafter, the magnitude of this adverse pressure gradient will simply be referred to as the “strength” of the reflection point.

In an impinging jet, a standoff shock forms ahead of the impingement surface, leading to a change in flow direction away from the central region of the impingement surface. This is illustrated in Figs. 11(b), 11(c) and 11(d), which correspond to flow configuration 1, 2 and 3 respectively. Since the position and strength of the reflection point determines the static pressure distribution upstream of the standoff shock, it is unsurprising that the standoff shock characteristics are dependent on it. The effects of varying the axial position, radial position, and strength of the reflection point on the standoff shock are further discussed based on the results of the three flow configurations presented in Figs. 5, 6 and 9.

3.4.1 Effects of reflection point position

In terms of the axial position of the reflection point, configurations 1 and 3 as illustrated in Figs. 11(b) and 11(d) may be considered, which consist of the same jet exhausting at $NPR=5$ but with different relative axial position of the reflection point with respect to the

impingement surface and standoff shock. For the baseline impinging jet in configuration 1, the free jet's reflection point is *downstream* of the impingement surface as illustrated in Fig. 11(b). In this situation, a comparatively large diameter at the centre of the standoff shock is subjected to a lower static pressure (P_3) than its peripheral (P_4), hence leading to a stronger upstream “suction” effect in the central region of the standoff shock. The geometry of the standoff shock is affected by this pressure distribution, resulting in the convex disk geometry as observed in Fig. 5(a). The standoff shock tapers off at the constant pressure line where the static pressure equals the ambient pressure.

In comparison, although configuration 3 has the jet exhausting at the same NPR, the reflection point is now *upstream* of the impingement surface as illustrated in Fig. 11(d). The change in the relative position of the reflection point with the impingement surface (and standoff shock) led to very significant differences in the standoff shock's geometry and position. A smaller diameter of the standoff shock is now subjected to the low static pressure region 3, resulting in the formation of a smaller diameter flat plateau (i.e. Mach disk) as shown in Fig. 9(a). Furthermore, since the relative position of the standoff shock is now much closer to the position of the reflection point, and that the static pressure P_3 is at its lowest just upstream of the reflection point, the standoff shock in configuration 3 is subjected to a stronger upstream suction effect as compared to the flow scenario in configuration 1. This led to a greater degree of three-dimensionality in the standoff shock as previously discussed, with particularly distinct observations of the Mach disk, tail shocks and three-shock confluence point. The stronger upstream suction effect along with the build-up of static pressure behind the standoff shock as discussed earlier both contributed to the observation of a significant upstream displacement of the standoff shock.

Similar characteristics of the standoff shock in terms of upstream displacement, three-dimensionality and localized distortions to the geometry were also observed in the IO jet test cases. For the double-bevelled jet in configuration 3 as shown in Figs. 9(d) and 9(e), the standoff shock has undergone upstream displacement with a greater degree of three-dimensionality relative to its counterpart in configuration 1 (see Figs. 5(d) and 5(e)). Furthermore, in the $\theta=90^\circ$ viewpoint as shown in both Figs. 5(e) and 9(e), the most upstream position of the standoff shock is always bounded by the intercepting oblique shocks at the three-shock confluence point, consistent with the hypothesis of a lower static pressure and stronger upstream suction effect in the central region of the jet as compared to its peripheral when a reflection point is present. In contrast, the $\theta=0^\circ$ viewpoint shown in both Figs. 5(d) and 9(d) has no clear pair of intercepting shock, resulting in a much more gradual radial variation of the static pressure upstream of the standoff shock. The effects on the standoff shock are reflected by the formation of a smooth convex disk geometry with no sharp kinks that is indicative of the three-shock confluence point.

In terms of the radial position of the reflection point and its influence on the standoff shock, this is best exemplified by the $\theta=0^\circ$ viewpoint of the single-bevelled nozzle. Results from all three configurations indicated a shift of the standoff shock in the direction of the longer nozzle lip towards where the reflection point is biased. From the results presented in Figs. 5(b) and 6(b), the shift in standoff shock appears to be greater and much more apparent in configuration 2 than in configuration 1. This agrees well with the non-dimensional parameters provided in Table 1, which indicates that the NPR=4 jet used in configuration 2 possessed a greater radial shift of the reflection point away from the jet axis as compared to the NPR=5 jet used in configuration 1. The part of the standoff shock that is exposed to the low-pressure region upstream of the reflection point is always at the most upstream position

Fig. 12 Time-sequenced images of $M_d=1.45$ baseline impinging jet at $h/D=1.5$, (a) just before (b) just after shock jump

and bounded by the intercepting shock, which is again consistent with what is to be expected to occur from the upstream suction effect of the reflection point. The preceding arguments indicate that the effects of the reflection point location on the standoff shock are applicable across all test nozzles investigated in this study.

Schlieren videos were taken at 1000 FPS to further understand the exact process in which upstream displacement of the standoff shock occurred. At the separation distance of $h/D=1.5$, the NPR was gradually increased from $NPR=4$ to $NPR=5$, which has the effect of gradually shifting the reflection point downstream, towards the standoff shock. In the baseline nozzle, changes to both geometry and position of the standoff shock was gradual as the NPR was increased. At approximately $NPR=4.7$, the thickness and position of the standoff shock undergo a very sudden and abrupt jump. The reflection point was observed to be just upstream and about to intersect with the standoff shock when the jump occurred, as shown in Fig. 12. Interestingly, when the experiments were repeated in reverse order by decreasing the NPR starting from $NPR=5$, a sudden and abrupt decrease in standoff shock thickness and distance occurred at $NPR=4.5$ instead. Below this value, the standoff shock thickness and distance slowly decreased with the NPR. This observation suggests the presence of a

Fig. 13 Time-sequenced images of $M_d=1.45$ single-bevelled impinging jet at $h/D=1.5$ for $\theta=0^\circ$, (a) minimal position of small amplitude and low frequency oscillations (b) maximal position of small amplitude and low frequency oscillations, also just before large amplitude and high frequency oscillations (c) large amplitude and high frequency oscillations.

hysteresis effect associated with the standoff shock, although the underlying physical mechanism is still unclear at this point.

For the single-bevelled nozzle, the instability started to occur between $NPR=4.8$ to 4.85 as the NPR was increased, with the frequency and amplitude of the oscillations visually observed to increase at higher NPR s. The reflection point was approximately $0.12D$ upstream of the tip of the standoff shock (see Fig. 13(a)) when low frequency and small amplitude instabilities started occurring. Figures 13(a) and 13(b) show the approximate minimal and maximal positions of the small amplitude oscillations. As the NPR further increases from $NPR=4.8$ to 4.85 , large amplitude oscillations at much higher frequencies were observed, based on significant image blurring as shown in Fig. 13(c). Note that Fig. 13(b) illustrates the reflection point just upstream of the tip of the standoff shock and is also just before the onset of the large amplitude and high frequency oscillations. When the experiments were carried out in reverse order by reducing the NPR from 5 , the unstable standoff shock became stable again in approximately the same NPR range of 4.8 to 4.85 .

Fig. 14 Time-sequenced images of $M_d=1.45$ double-bevelled impinging jet at $h/D=1.5$ for $\theta=90^\circ$, (a) just before (b) just after shock jump

For the double-bevelled nozzle, the sudden and abrupt increase in standoff shock thickness and distance occurred at $NPR=4.92$ as the NPR was increased, and similar to the baseline test case, the reflection point was just upstream and about to intersect the standoff shock when it occurred (see Fig. 14(a)). The abrupt decrement was observed at $NPR=4.8$ when the experiments were conducted in reverse order. Similar to the baseline test case, there appears to be a hysteresis effect associated with the standoff shock jump phenomenon. In all test cases, the reflection points clearly had a significant role leading up to the onset of standoff shock thicknesses and distances jump in the baseline and double-bevelled test cases, and standoff shock instabilities for the single-bevelled test case. Since just upstream of the reflection point there is a region of low static pressure, it is perhaps unsurprising for the observed changes to occur when the reflection point approaches very close to the standoff shock. Nonetheless, the manner in which it occurred remains very intriguing, particularly for the observation of the hysteresis effect associated with the baseline and double-bevelled standoff shocks, as well as a change in the oscillatory behaviour of the single-bevelled standoff shock when the NPR was further increased. Note that orthogonal views for the IO

jets did not reveal additional information and were therefore not included in the discussions of the results.

3.4.2 Effects of reflection point strength

The strength of the reflection point is influenced through variation of the NPR. Since the axial position of the reflection point can also lead to different pressure distributions in front of the standoff shock, it is necessary to compare two configurations that have a similar reflection point axial location with respect to the standoff shock, but with differing pressure gradients across the reflection point. Configurations 2 and 3 both ensures that the impingement surface is situated downstream of the reflection point location but still within the first jet shock cell in all three test cases, as seen in the flow schematics presented in Figs. 11(c) and 11(d). This was intentionally designed based on the available geometric information in Tables 1 to 3. Since the higher under-expansion exhaust condition of the jet in configuration 3 will create a stronger reflection point, the strength of the reflection point may then be investigated.

Results presented in Sections 3.2.2 and 3.3.1 (see Figs. 6 and 9) have already demonstrated significant changes in the standoff shock properties across configuration 2 and 3. In particular, the baseline test cases display qualitatively similar standoff shock structures with the formation of a Mach disk, tail shocks and the three-shock confluence point observed, albeit with configuration 3 having much more distinct shock features than configuration 2. Based on Ginzburg et al. [28] and Kalghatgi and Hunt [10], the flow dynamics behind the standoff shock should be very similar, where the shear layer originating from the three-shock confluence point eventually leads to a build-up of static pressure behind the standoff shock. Nonetheless, the standoff shock features in configuration 3 were much more accentuated,

with a significantly higher standoff shock thickness and distance as compared to configuration 2. With similar flow dynamics occurring behind the standoff shock, it is very likely that the static pressure in front of the standoff shock played a significant role in leading up to the observed key differences of the flow features between configurations 2 and 3. The same argument can be made for the double-bevelled test case, where the standoff shock in configuration 3 had larger standoff shock thickness and distance as compared to that in configuration 2.

For the single-bevelled nozzle, the standoff shock in configuration 3 (Figs. 9(b) and 9(c)) was highly unsteady and displays large amplitude oscillations near the longer nozzle lip with relatively smaller amplitude oscillations on the shorter nozzle lip side. It may be possible that the difference in upstream static pressure distribution contributed to the difference in oscillation amplitude on the two sides of the nozzle lips. Overall, due to very significant changes in the properties of the standoff shock when comparing across configuration 2 and 3, it is likely that the behaviour of the standoff shock is highly dependent on the strength of the reflection point, whereby a stronger reflection point is expected to lead to more significant changes in terms of standoff shock geometry, position and stability conditions.

4. Conclusions

Schlieren visualizations and 3D shock reconstruction technique were performed on moderately under-expanded IO jets impinging normally upon a flat plate at small separation distances. Detailed results demonstrate strong evidences that the standoff shock is also sensitive to the nozzle exit geometry, other than the NPR and separation distance. Specifically, eccentric cross-section of the standoff shock was observed for the double-bevelled nozzle, while large amplitude and asymmetric standoff shock oscillation was

observed for the single-bevelled nozzle under certain conditions. The strength and location of the reflection point were identified as the major contributing factors leading to the above observations. Results suggest that the reflection point formed by the intercepting oblique shocks produces an adverse pressure gradient across it, such that a low static pressure region exists immediately upstream of the reflection point. This leads to a localized suction effect upstream of the reflection point and would agree well with the schlieren images where the standoff shocks were observed to be attracted towards the reflection point. In the case of the IO jet nozzles, this leads to asymmetric distortions of the standoff shock, and they become more pronounced when a stronger reflection point was present.

At the separation distance of $h/D=1.5$, schlieren videos of the standoff shock were taken as the NPR was slowly increased from $NPR=4$ to $NPR=5$. When the reflection point was initially far from the standoff shock but gradually moving towards it, the standoff shock from all three nozzles revealed gradual upstream displacement and geometrical modifications. As the NPR increases further, the reflection point approaches the standoff shock until it is just upstream of it, and a sudden and abrupt jump in both the position and geometry of the standoff shock was observed for the baseline and double-bevelled nozzle. For the single-bevelled nozzle, small amplitude oscillations were found to occur when the reflection point was about $0.12D$ from the standoff shock, and as the reflection point approaches even closer, large amplitude oscillations start to occur. These observations strongly suggest the importance of the reflection point in determining the characteristics of the standoff shock. Future studies on the impingement zone based on surface plate pressure and 3D-3C PIV measurements could shed more light on the above observations.

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Appendix

A. Schlieren images of the freely-exhausting jets

Table A: Imaging parameters for the freely-exhausting jets at NPR=5 and 4

	Nozzle type	Image exposure time	LED power	Knife-edge cut-off and orientation	Framing rate
NPR=5 (Figure A1)	Baseline	494 μ s	Maximum	~80% vertical	1000 FPS
	Single-bevelled	494 μ s	Maximum	~80% vertical	1000 FPS
	Double-bevelled	494 μ s	Maximum	~80% vertical	1000 FPS
NPR=4 (Figure A2)	Baseline	462 μ s	Maximum	~90% vertical	1000 FPS
	Single-bevelled	678 μ s	Maximum	~90% vertical	1000 FPS
	Double-bevelled	678 μ s	Maximum	~90% vertical	1000 FPS

Figure A1: Time-series of schlieren images of $M_d=1.45$ freely-exhausting jets at NPR=5 for the (a) baseline, (b) single-bevelled and (c) double-bevelled nozzles.

Figure A2: Time-series of schlieren images of $M_d=1.45$ freely-exhausting jets at $NPR=4$ for the (a) baseline, (b) single-bevelled and (c) double-bevelled nozzles.
Note that the brightness of these images has been enhanced.

B. Test images of the impinging jet under various imaging conditions

(a)

(b)

Figure B1: Instantaneous schlieren images of $M_d=1.45$ impinging jets for the baseline nozzle. Images captured with $10\ \mu\text{s}$ image exposure time using the (a) horizontal knife-edge and (b) vertical knife-edge configuration (normal to the primary jet flow).

C. Test images of the unsteady single-bevelled standoff shock

Figure C1: Instantaneous schlieren images of $M_d=1.45$ impinging jets at $h/D=1.25$ and $NPR=5$ for the single-bevelled nozzle. Images captured with 1000 FPS and $10\ \mu\text{s}$ image exposure time.