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Effect of a wedge on coannular jet noise

K. B. M. Q. Zaman[1]
NASA Glenn Research Center
Cleveland, OH 44135

and

D. Papamoschou[2]
University of California at Irvine
Irvine, CA 92697

Abstract

Directional noise attenuation for a coannular jet, caused by a wedge in the fan stream, is studied with data from three different facilities. The effect, first observed with small-scale convergent nozzles at UCI, involves noise attenuation on the side away from the wedge. The trend is confirmed with data from a large facility. However, several anomalies are noted. In particular, the wedge is found to be ineffective with nozzles having parallel flow lines near the exit. In the latter case, the wedge simply causes a lateral spreading of the flow. In the convergent case, the wedge also diverts the flow downward forming the thicker annular layer underneath that is key to the noise attenuation seen on the ground.

1. Introduction

Over the past several years, substantial noise reduction has been demonstrated for coannular jets in experiments at University of California at Irvine (UCI). The essence of the technique is to offset the annular stream with respect to the primary stream. When this is done, noise on the 'fat' side of the annular stream gets reduced relative to the noise of the concentric case. It is a directional attenuation of noise with obvious practical relevance. In flight if the annular stream could be diverted underneath, noise heard on the ground would be less.

The initial observation of this effect was with inner and outer nozzles placed in an eccentric configuration.[1] The effect with eccentric nozzles was also observed in Ref. 2 and further confirmed in an experiment at NASA Glenn Research Center (GRC).[3] Since in practice the implementation of the eccentric configuration would be difficult, subsequent UCI effort sought alternative means of diverting the annular stream. This included placement of vanes in the outer passage that also produced promising noise reduction.[4-5] Most of these experiments pertained to low bypass ratio nozzles. The effect became more pronounced with increasing jet Mach number in supersonic conditions.

Later, the technique was explored for a high bypass ratio nozzle involving high subsonic and transonic flows. Initially, these tests were conducted in a 'classic' coaxial nozzle with parallel flow lines at the exit and coplanar termination of the inner and outer nozzles. Placement of the vanes again produced significant noise reduction. Another technique involved placing a wedge in the vicinity of the exit of the annular flow. The results were disappointing and the wedge was dropped in favor of the vanes.

However, in later tests with a nozzle having realistic geometry, shaped like the '3BB' nozzle used in previous experiments at GRC,[6] the wedge produced a substantial noise reduction. The reduction in some cases was even more than that achieved by the vanes. Preliminary results from a recently completed test at GRC with the original '3BB' nozzle together with a wedge confirm the overall trend of noise attenuation at shallow angles (Dr. James E. Bridges, private communication). This will be discussed in §3.

[1] Aerospace Engineer, Inlet & Nozzle Branch, Propulsion Systems Division, AIAA Associate Fellow.
[2] Professor, Department of Mechanical and Aerospace Engineering, AIAA Associate Fellow.

The effect of the wedge is the focus of the present paper. The wedge cases tried in the UCI experiment were limited. There could be many variations of the wedge geometry, e.g., half-angle, base width relative to nozzle perimeter, shape of the side walls, etc. Also, there was no explanation why the wedge was not effective with the 'classic' nozzle in the UCI tests. Thus, further explorations and an optimization experiment seemed appropriate.

Such an exploration is attempted in the NASA Glenn open jet facility used in the work of Ref. 3. The nozzles in this facility being about 3 times larger than the UCI hardware offered a more controlled variation of the geometric parameters. The nozzle has parallel flow lines at the exit and does not have a center plug. However, in this same facility and with the same nozzles the effect of eccentricity was verified earlier. So there was the expectation that the wedge would exhibit some noise reduction and permit the desired parametric study. The purpose of this paper is to summarize the results of this experiment as well as further flow field results from UCI to highlight some of the anomalies in the effect of the wedge and provide a discussion and analysis.

2. Experimental Facility

Figure 1 shows the GRC open jet facility.[8] A picture is shown in Fig. 1(a) while Fig. 1(b) shows the essential contours of the coannular nozzle. The primary (inner) nozzle is connected directly to the 30 inch diameter main plenum chamber. Another annular plenum chamber, located just upstream of the nozzles, provides the outer (secondary) flow. The outer flow, supplied by four equally spaced ports, is routed through contoured interior and screens to provide a uniform velocity profile at the exit. For the present experiment, two inner nozzles are used; one is convergent (shown in Fig. 1a) and the other convergent-divergent with a design Mach number of 1.5. Each has an exit diameter of 1.48 inch and a lip thickness of 0.03 inch. The outer annular passage is convergent. The diameter of the outer nozzle (D_f) is 2.1 inch. The nozzles are essentially 'coplanar' with the inner nozzle lip protruding 0.125 inch relative to the exit of the outer nozzle. The ratio of primary-to-annular exit area is 0.92.

In the following, the subscripts '*1*' and '*2*' are used to denote conditions in the inner jet and the outer annular flows, respectively. The subscript '*f*' is used to denote the outer (fan) nozzle diameter. The parameter R ($=M_2/M_1$) denotes the ratio of the two Mach numbers at the exit of the nozzle. All data taken in this facility pertain to 'isothermal' flow, i.e., the total temperature is constant throughout and equal to that of the ambient.

Reference 9 provides a description of the UCI facility. As noted earlier some data from a recently completed test in the GRC Aeroacoustic Propulsion Laboratory ('Dome') will also be discussed; a description of the latter may be found in Ref. 6. The nozzles in the open jet facility (Fig. 1) are about 3 times larger than the UCI nozzles. The nozzles in the 'Dome' are roughly 8 times larger than the UCI nozzles.

Figure 2 shows a schematic of the 3BB-type nozzle fitted with a wedge. All wedges considered in this study are 'internal', filling the annular passage with its base located at the fan nozzle exit. A picture of the small-scale 3BB nozzle used in the UCI experiment is shown in Fig. 3. The original 3BB nozzle was used in the study of noise reduction by chevrons and tabs in the GRC Dome.[6] Figure 2 also shows the definitions of the polar angle (θ) and the azimuthal angle (ϕ) for the noise measurement location.

3. Results

Figure 4 compares overall sound pressure level as a function of θ for the UCI 3BB nozzle with and without a wedge. The data are for simulated hot primary flow (using helium mixture) with an outer-to-inner velocity ratio of 0.73. It can be seen that the noise has decreased dramatically in the entire downstream half. This is significant since most noise reduction devices are known to be effective at shallow angles at the expense of being noisier near θ=90°.

Figure 5 compares power spectral density at indicated microphone locations with and without the wedge. The wedge in both sets of data has a half angle of 11° and its base width is 2.6 times the height of the annular gap. The top figure shows data from the UCI experiment. A large reduction in the noise intensities is observed over the entire bandwidth at both ϕ=0° ('flyover') and ϕ=60° ('sideline') locations. The figure at the bottom shows corresponding data obtained in the recently completed 'offset stream technologies (OST05)' test in the GRC Dome. The two sets of data are plotted in identical format with appropriate conversion. For these data the pressure ratios for core and fan streams are 1.69 and 1.83, respectively; the temperature ratio for the core stream is 2.8. The pressure ratios were the same in the UCI data while temperature effect was simulated by helium-air mixture. The GRC data show a similar trend. However, the attenuation is confined to low frequencies and not observed at high frequencies. Whether the scaled-up integrated noise over the entire radiation field (EPNdB) will exhibit a clear benefit is currently being analyzed and will be reported in the future. Certainly, the general agreement at shallow angular locations (θ) is encouraging. Once again, it should be noted that the noise attenuation is on the 'wedge away' side. In both sets of data the noise intensities are consistently higher on the 'wedge towards' (ϕ=180°) side; these data not shown in Fig. 5 for clarity.

Figure 6 shows a picture of the 'classic' nozzle used in earlier UCI experiments. As indicated before, the main difference with the '3BB' nozzle is in the contours near the exit. Here, the flow lines exiting the nozzle are near parallel. When a wedge (of same geometry as in Fig. 4) was tested with this nozzle the noise attenuation was not as much. This is shown in Fig. 7. The bypass ratio and the exhaust conditions were the same as in Fig. 4. Yet, only marginal noise attenuation occurred at shallow angles at the expense of significant noise increase at larger θ locations.

Before discussing the result on the effect of the wedge in the GRC open jet facility (Fig. 1), it is important to consider the earlier result with the eccentric configuration in the same facility.[3] Note that there is no center plug and the flow goes through a large contraction before exiting with parallel flow lines (Fig. 1b). Figure 8 compares sound pressure level spectra for the eccentric case (on the fat side of the annulus) with the concentric case. The set of data at the top is for a primary jet Mach number of 0.94. A small but clear noise reduction is noted, the overall sound pressure level (OASPL) dropping by 1.4dB. These data are for a convergent inner nozzle. The data at the bottom of Fig. 8 are obtained with the convergent-divergent inner nozzle. It has the same outer contour so that the geometry of the annular passage remained the same. It has a design Mach number of 1.5 and the data are for operation at the design condition. A large decrease in the noise intensity is noted. OASPL has decreased by about 5dB. These data confirmed earlier UCI observations with eccentric nozzles and provided confidence in the offset stream concept for noise reduction.

The effect of a wedge is explored with the same nozzles. The wedge is designed to have approximately the same base-width-to-fan-diameter ratio as one of the cases in the UCI experiment, with 15° half angle. Figure 9 shows data for the wedge case at a primary jet Mach number of 0.94. The upper figure is for outer-to-inner Mach number ratio, $R \approx 0.6$. Here, another set of data is shown with a slightly increased outer flow so that the bypass ratio remained the same as in the no-wedge case. It is clear that there is degradation in the noise characteristics. The wedge has increased OASPL by about one dB, as indicated. The same observation is made for another set of data at $R \approx 1.0$, shown at the bottom of Fig. 9. (The wedge here is shown at the bottom in contrast to Fig. 2 because the microphone location was above.)

Figure 10 shows corresponding data for the primary jet Mach number of 1.5. Recall that a large noise reduction (5 dB) was observed with the eccentric configuration. In contrast no effect is observed with the wedge. While these data are qualitatively similar to the UCI 'classic' case they are in stark contrast with the results from the 3BB nozzle.

A significant difference between the present and the 3BB case is the absence of the center plug. However, the fact that the wedge was also ineffective in the early UCI nozzle (fig. 6) seems to suggest that the center plug may not be the source for the difference. As already alluded to in the introduction the suspicion falls on the flow lines. Here and in the early UCI case, the approach flow lines before the exit are near parallel. For the 3BB case the flow lines are significantly convergent.

Possible flow deflections by the wedge are illustrated in Fig. 11: (a) for the eccentric case, (b) for the wedge in the 'classic' case and (c) for the wedge in the 3BB case. The upshot is that with near parallel flow lines, the wedge merely deflects the flow sideways, as shown in (b). With the convergent flow lines the flow is also diverted downward, as shown in (c). Thus, a thicker annular layer is formed underneath in the 3BB case but not in the classic case.

The postulation appears to be supported by Pitot probe surveys conducted recently at UCI. Normalized velocity distributions on a cross-sectional plane are compared in Figs. 12 and 13 for the classic and the 3BB cases, respectively. Here, the distance x is referred to the tip of the plug. Clearly, the wedge has caused a large lateral spread in the classic case. The core of the jet also appears to be pushed down slightly, below the y=0 plane. The wedge has not caused as much overall spreading in the 3BB case. Note, however, that the baseline cross-section for the latter (Fig. 13, top) is not as large as in the former (Fig. 12, top). The less spreading could be either due to the convergent flow lines in the 3BB case or a relative difference in the plug tip location. However, an increased downward spreading is discernible for the 3BB wedge case. Compared to the baseline (Fig. 13, top) the wedge has resulted in a somewhat thicker shear layer underneath (Fig. 13, bottom). If a layer thickness is defined from the center of the core to the farthest contour in negative z, the thickness ratio between the wedge and no-wedge cases is about 1.07 in Fig. 12. The same ratio turns out to be about 1.2 in the 3BB case in Fig. 13.

4. Conclusions

The phenomenon of directional noise attenuation for a coannular jet, caused by the placement of a wedge in the fan stream, is studied. Data from three different facilities and two different nozzle shapes are analyzed. The basic effect observed with small-scale nozzles at UCI agrees with data from another facility having eight times larger nozzles. However, several anomalies are noted. In the larger jet, the attenuation is not as prominent and also fades away at high frequencies. In particular, the wedge is found to be ineffective with nozzles having parallel flow lines near the exit. Even though an eccentric placement of these same nozzles produce a noise attenuation (on the thicker annulus side), placement of a wedge in fact has a detrimental effect. In contrast the wedge is effective when the flow lines are convergent near the exit. It is thought that in the parallel flow lines case the wedge simply causes a lateral spreading of the flow. In the convergent case, the wedge also diverts the flow downward forming the thicker annular layer underneath that is key to the noise attenuation seen on the ground. Flow field survey results support this notion.

Acknowledgement

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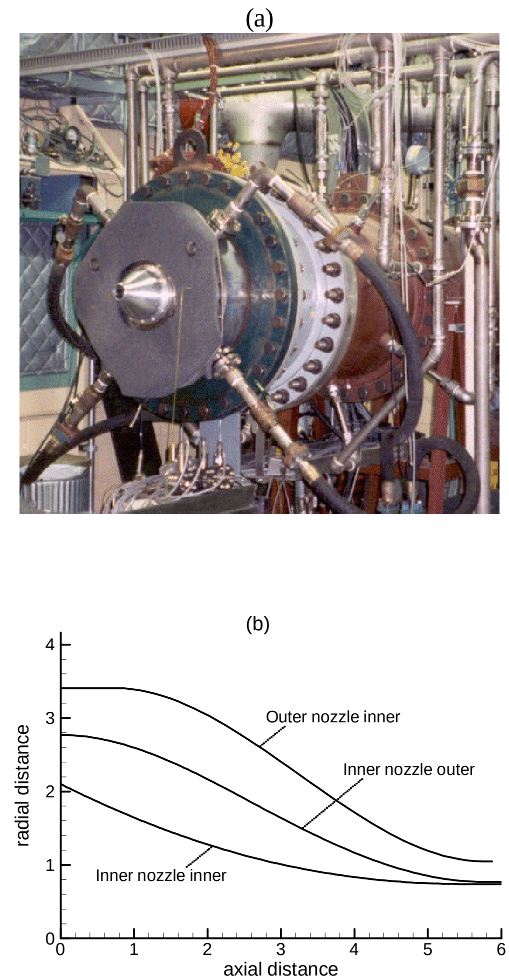

Fig. 1 Coannular jet facility at NASA GRC. (a) Picture of the facility. (b) Contours of the nozzle; dimensions are in inches.

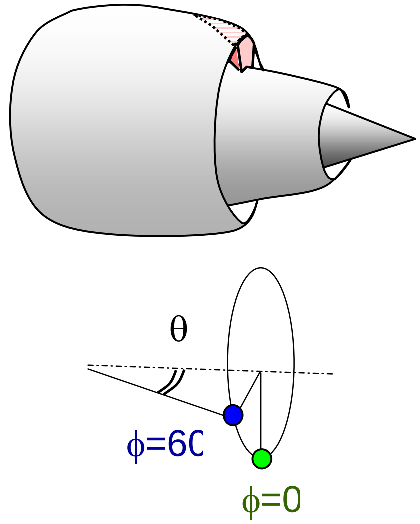

Fig. 2 Schematic of coannular nozzle with center plug and a wedge in the fan stream.

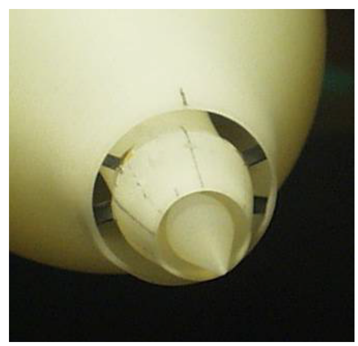

Fig. 3 Picture of UCI '3BB' nozzle.

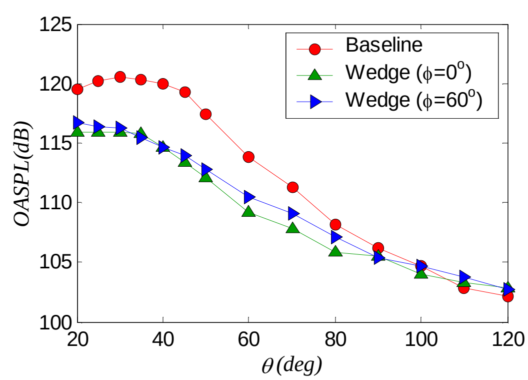

Fig. 4 Overall sound pressure level versus polar angle for the wedge case (UCI '3BB' nozzle). The wedge has 3 mm base and 5 mm length with 17° half-angle.

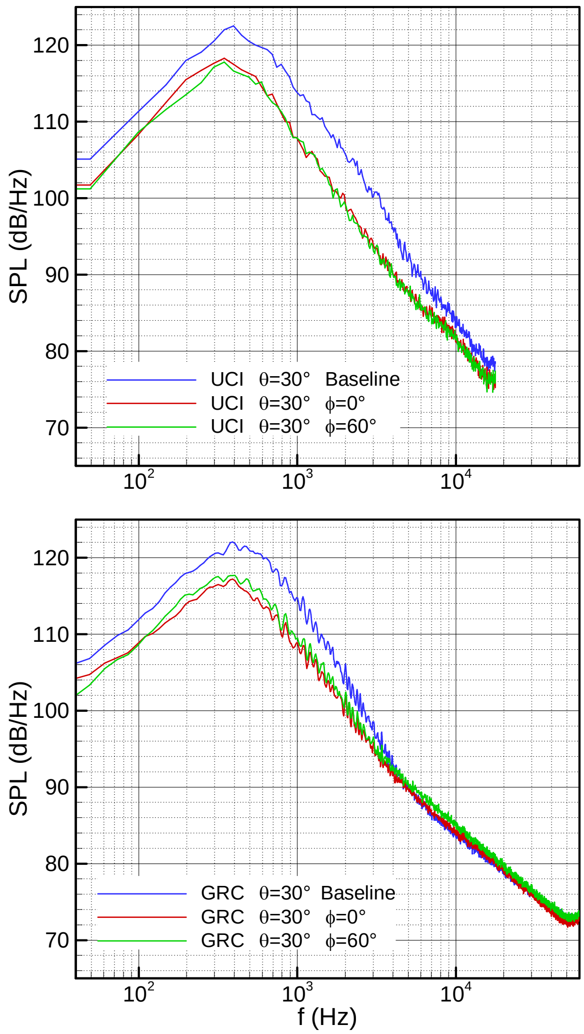

Fig. 5 Sound pressure level spectra showing effect of wedge at indicated microphone locations, for '3BB' nozzle. Upper figure shows data from UCI experiment, lower figure shows data from GRC ('Dome') experiment. Wedges in the two are geometrically similar with 11° half-angle. Data referenced to GRC fan diameter and 1 ft distance.

Fig. 6 Picture of 'classic' nozzle used in early UCI experiments.

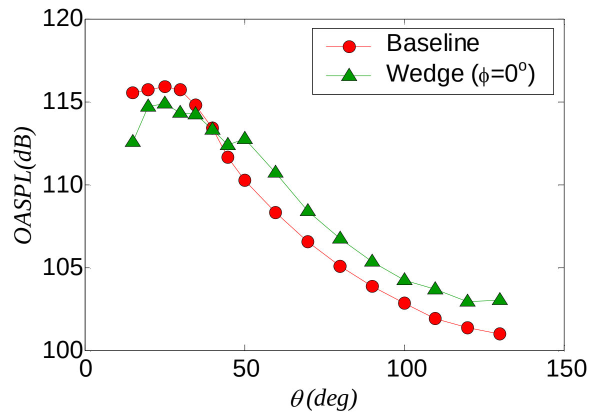

Fig. 7 Overall sound pressure level versus polar angle with and without wedge (UCI 'classic' nozzle). Same wedge geometry as in Fig. 4.

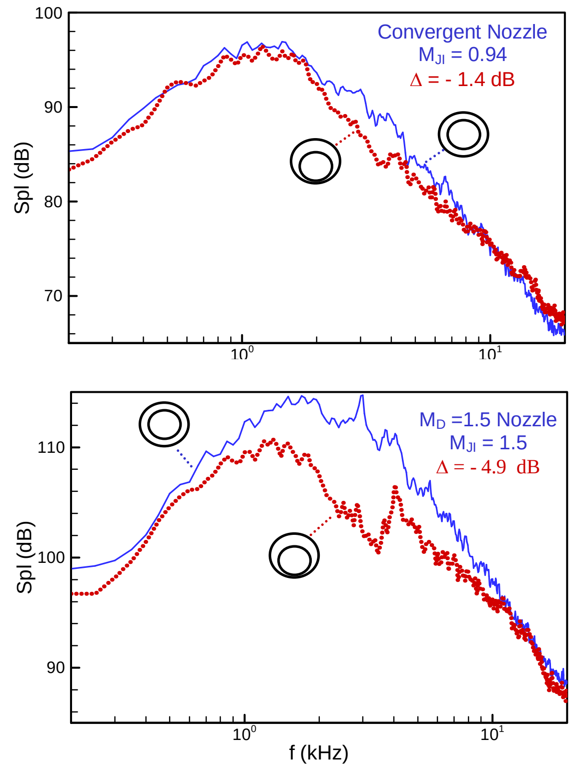

Fig. 8 Comparison of sound pressure level spectra for eccentric and concentric cases at $\theta = 25°$. Data from GRC open jet facility (Fig. 1). Primary jet Mach number in upper figure is 0.94 and that in lower figure is 1.5. Outer-to-inner Mach number ratio, $R \approx 0.5$.

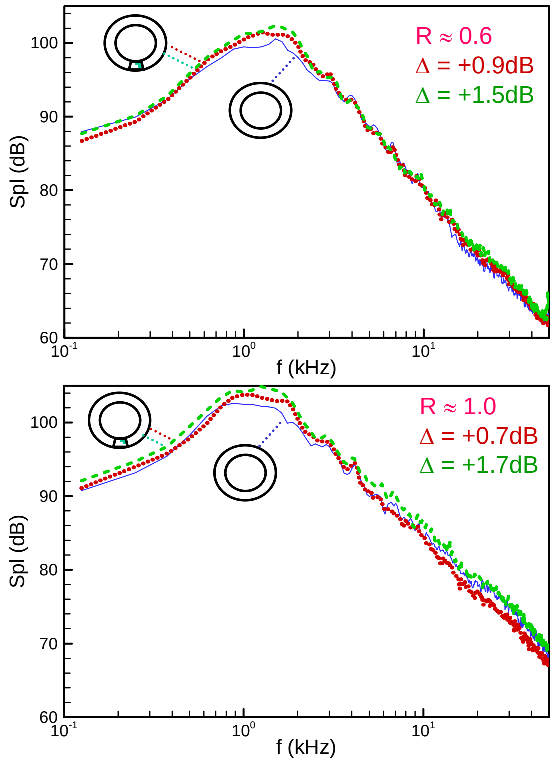

Fig. 9 Sound pressure level spectra with and without wedge, $\theta = 25°$. Primary jet Mach number is 0.94. Upper figure: $R \approx 0.6$, lower figure: $R \approx 1.0$. Green curves are for the wedge case with increased outer flow-rate so that bypass ratio matched that of no-wedge case.

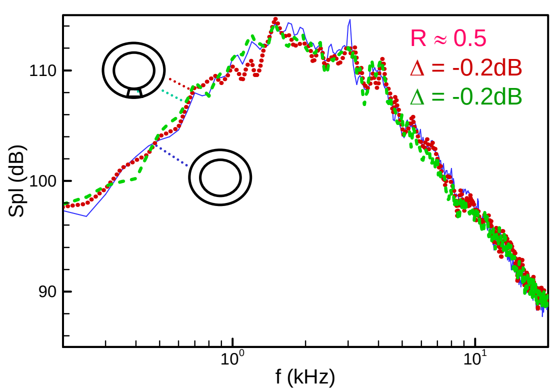

Fig. 10 Sound pressure level spectra with and without wedge as in Fig. 6 for primary jet number 1.5; $\theta = 25°$.

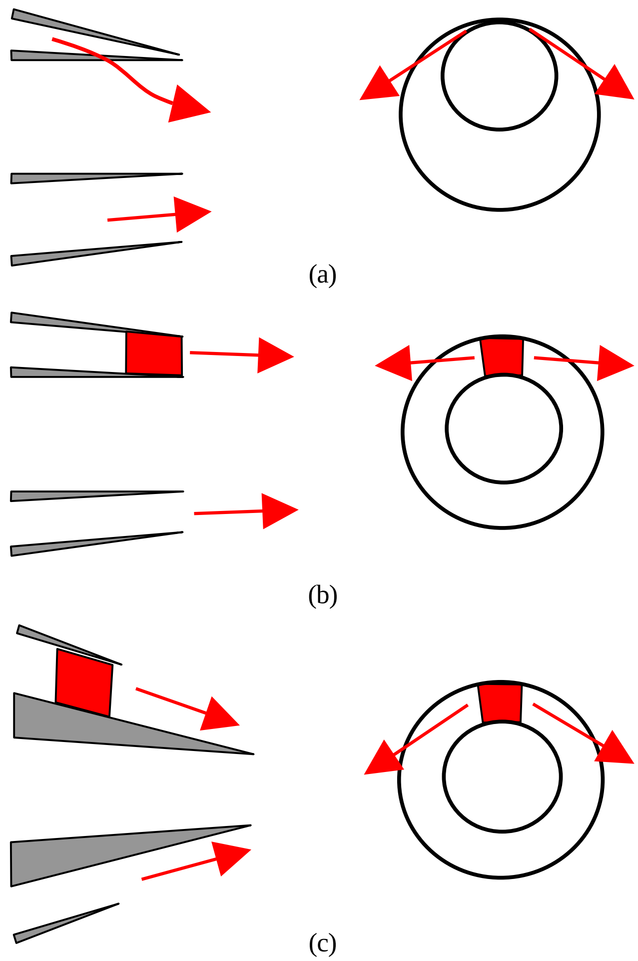

Fig. 11 Possible reason for difference in the effect. Deflection of flow: (a) in the eccentric case, (b) with wedge in the 'classic' case, (c) with wedge in the '3BB' case.

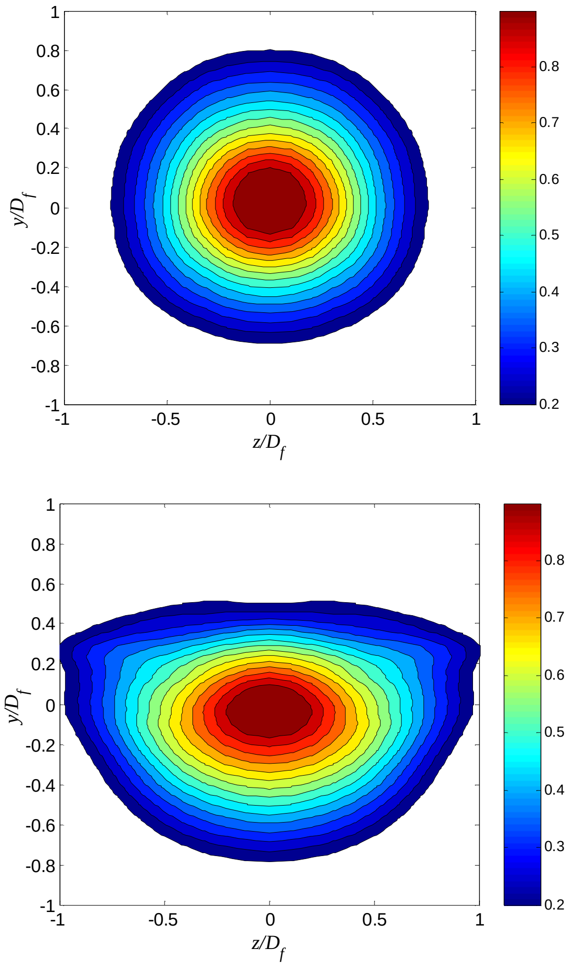

Fig. 12 Contours of streamwise velocity, normalized by local maximum, at $x/D_f = 4$ for UCI 'classic' case. Upper figure is for baseline and lower figure is for wedge case. Same wedge geometry as in Fig. 4.

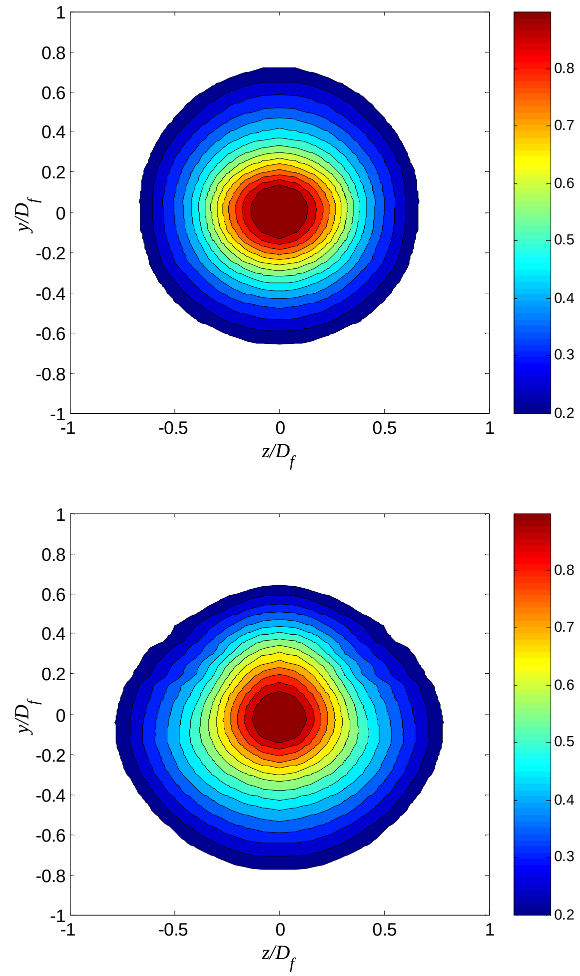

Fig. 13 Contours of streamwise velocity, normalized by local maximum, at $x/D_f = 4$ for UCI '3BB' case. Upper figure is for baseline and lower figure is for wedge case. Same wedge geometry as in Fig. 4.