MIXING CONTROL IN SUPERSONIC JET VIA STREAMWISE VORTICES

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ABSTRACT

A Mach 2 rectangular nozzle with an aspect ratio 3 was used to investigate the effects of trailing edge modifications, which generate streamwise vorticity, on mixing enhancement at the fully expanded jet Mach numbers of 1.75, 2.0, and 2.5. The jet cross-sectional image was acquired by the laser sheet illumination technique. Surface flow visualizations and wall pressure measurements were used to investigate the major source of streamwise vorticity. Substantial mixing enhancement was achieved in the underexpanded flow condition. In this flow regime, the major source of streamwise vorticity was determined to be the spanwise surface pressure gradient on the modification. In the overexpanded flow regime, mixing enhancement was not substantial and the role of streamwise vorticity in mixing and the source of streamwise vorticity were unclear.

INTRODUCTION

It has been known for sometimes that it is difficult to control mixing by using spanwise or ring-like vortical structures in highly compressible supersonic mixing layers because of their three-dimensionality and lack of organization (see for example Samimy et al. 1998). In contrast to these large-scale structures, streamwise vortices do not seem to be much affected by compressibility (Elliott et al., 1992; Samimy et al., 1993; Zaman et al., 1994; Reeder and Samimy, 1996). Thus, generating streamwise vortices appears to be an effective way to enhance mixing in supersonic jets.

Several techniques have been explored to generate streamwise vortices and to enhance mixing. Tabs, as streamwise vortex generators, were found to be an effective device in reducing jet noise and enhancing mixing in both subsonic and supersonic axisymmetric jets (Ahuja and Brown, 1989; Samimy et al., 1993; Zaman et al., 1994) with some thrust penalty (Zaman et al., 1994). The streamwise vortices generated by half delta-wings resulted in significantly enhanced mixing in Mach number 0.6 circular (Surks et al., 1994) and rectangular (Rogers and Parekh, 1994) jets.

Martens et al. (1996) showed that mixing in a rectangular supersonic jet can be significantly enhanced in the underexpanded flow regime by trailing edge modifications. Samimy et al. (1997a, 1997b, 1998) furthered the experiments and found that the use of trailing edge modifications enhanced mixing significantly and moderately in the underexpanded and overexpanded cases, respectively. The enhanced mixing is was attributed to the generated streamwise vortices (Samimy et al., 1997b, 1998). However, the modifications did not significantly enhance mixing in the ideally expanded case.

The purposes of the present experiments are to investigate the development of streamwise vortices with downstream locations and to identify the major source(s) of streamwise vorticity.

EXPERIMENTAL FACILITY AND TECHNIQUES

All experiments were conducted at the Aeronautical and Astronautical Research Laboratory at the Ohio State University. The air supply system and jet facility used in the present experiments are the same as those used in previous experiments (Samimy et al., 1998).

A full nozzle with an aspect ratio 3 was used in the present experiments. Since the nozzle is smaller than the one used in the previous experiments (Samimy et al., 1998), it will be referred to as smaller nozzle from this point on. The exit dimensions of the smaller nozzle are 2.86 cm wide and 0.95 cm high, with an equivalent diameter ($D_{eq}=(4A_{exit}/\pi)^{½}$) of 1.86 cm. The schematic of the baseline nozzle and the trailing edge modified nozzles and modification types are shown in Fig. 1. The modification is a simple cut-out on the trailing edge. Based on previous results (Samimy et al., 1998), four types of modifications, OS (Oblique Side cut-out), OC (Oblique Central cut-out), RS (Rectangular Side cut-out), and RC (Rectangular Central cut-out), were selected due to their

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superior mixing performance. By combining any two types of modifications, six double trailing edge modified nozzles, nozzle OS-OS (N33), OC-OS (N43), OC-OC (N44), RS-RS (N55), RC-RS (N65), and RC-RC (N66), were formed. The nozzle names in the parenthesis are those used in Kim et al. (1998).

The larger nozzles (Samimy et al., 1998), whose exit dimensions are 7.6 cm wide and 2.5 cm high, were used for surface flow visualizations and wall pressure measurements.

The instantaneous cross-sectional images were acquired by the laser sheet illumination technique as in previous experiments (Samimy et al., 1998). Water particles, with a diameter on the order of 50-100 nm, are formed when the cold and dry jet air mixes with the humid and warm ambient air that is entrained into the jet plume. These particles scatters laser light in the flow visualization experiments. The visualizations of the jet cross-section were performed at four downstream locations, i.e., x/D_{eq}=1, 2, 4, and 8. The jet was operated at three fully expanded jet Mach numbers of 1.75 (overexpanded), 2.0 (design Mach number), and 2.5 (underexpanded). Two additional Mach numbers, M_j=1.5 and 2.2, were also used in surface flow visualizations. Mach numbers for the small nozzles are nominal values since the measured design Mach number is 1.93.

Surface flow visualizations were performed for the baseline nozzle and nozzles OS, OC, RS, and RC (denoted as nozzle N3, N4, N5, and N6, in Samimy et al. (1998)) by using the kerosene-lampblack surface streak method (Settles and Teng, 1983). The wall pressure distribution on the modifications was measured by spanwise and streamwise arrays of pressure taps, as shown in Fig. 2, for one of the two cases investigated.

RESULTS

The present experiments were focused on the identification of the major source of streamwise vorticity, and on the investigation of the development and role of streamwise vortices in mixing processes. The results presented here complement those reported in previous experiments (Samimy et al., 1998) and further advance our understanding of these complex flows.

Effects of cut-outs on the jet development

Figures 3-5 show average images of the cross section of the jet at x/D_{eq} = 1, 4, and 8 at the fully expanded jet Mach number of M_j = 1.75, 2.0, and 2.5. These images are obtained by averaging 50 instantaneous images. The average images at x/D_{eq}=2 are similar to those at x/D_{eq}=1, thus are not presented here, but can be found in Kim et al. (1998).

As observed in previous work (Samimy et al., 1998), the cut-outs do not seem to affect the jet cross section in any significant fashion in the ideally expanded case. This is due to the lack of the main streamwise vorticity source of wall pressure gradients in the zone of upstream influences, as will be discussed.

For the underexpanded case, M_j=2.5, the streamwise structures due to the RS and RC type cut-outs are very clearly shown at x/D_{eq} = 1. The streamwise structures due to the OS and OC type cut-outs can only be inferred from the jet cross-sectional deformation. The structures imparted by each modified trailing edge seem to develop almost independently even beyond x/D_{eq} of 4 in the present experiments. Thus, the mixing enhancement by each cut-out is almost additive.

A kidney-type pair of counter-rotating vortices was observed in the underexpanded case for modifications OS and RS, while a mushroom-type pair of vortices was observed for modifications OC and RC as shown in instantaneous images at x/D_{eq}=4 in Fig. 6. The kidney-type pair of vortices entrains the ambient air into the jet plume. As can be observed in Figs. 4-6, the kidney-type pair of vortices experiences destructive interaction between vortex mates. The unfavorable interaction begins at a further upstream location for a shorter center-to-center vortex distance (r_o). In addition, the mutually induced velocity V_i for the kidney-type pair of vortices is toward the jet center. This obviously retards the jet spreading. On the other hand, the mushroom-type pair of counter-rotating vortices, that eject the jet air into the ambient, do not experience any unfavorable interaction between vortex mates up to x/D_{eq}=8.

For the overexpanded case, the compression in the jet cross section causes the modifications from two sides to interact very early in the jet development. Unfortunately, the development and role of streamwise vortices are not conclusive because of complex features of the flow, including separation inside the nozzle (will be shown later).

Overall Mixing

Mixing areas, indication of mixing layer thickness, were calculated from 50 instantaneous images in the same way as described by Samimy et al. (1997b, 1998). In an instantaneous image, a pixel with an intensity greater than a threshold value was counted as a part of the mixing region. After calculating the mixing area for each instantaneous image, ensemble averages of 50 images were obtained. The reference mixing area for each nozzle was acquired at M_j = 2.0 (ideally expanded jet) using the baseline nozzle to remove the effects of room temperature and humidity on the condensation process of visualization seed particles in the mixing layer. All the mixing areas were normalized by the associated reference value.

Underexpanded case. Figure 7 shows variations of mixing area with x/D_{eq} for three flow regimes for all the nozzles. The results at x/D_{eq} =1 are less accurate than the other locations because of reflection of laser light from the nozzle. In this figure, one could get the normalized mean mixing area directly and also the normalized growth rate of the mixing layer from the slope.

The mixing area for the underexpanded jet, shown in Fig. 7(a), is substantially larger than that of the reference case at all locations. Nozzles OS-OS and RS-RS, which generate a kidney-type pair of streamwise vortices, seem to have higher mixing level in the near field. However, the mixing rates of these nozzles is deteriorated as the destructive interaction between vortex mates is started. Although near field mixing level is lower for nozzles OC-OC and RC-RC, that generate mushroom-type pairs of vortices, these nozzle have higher growth rates all the way down to x/D_{eq}=8 due to favorable pumping action of the counter-rotating vortices. Thus, it is expected these nozzles would have higher mixing level than nozzles OS-OS and RS-RS at a farther downstream location.

The nozzles OC-OS and RC-RS, have characteristics in between OS-OS and OC-OC, and RS-RS and RC-RC, respectively.

Ideally expanded case. As in the nozzles with single-side trailing edges (Samimy et al., 1997a, 1997b, 1998), the mixing enhancement by nozzles with double-sided trailing edges is negligible as shown in Fig. 7 (b). The growth rates of trailing edge modified nozzles are the same as those for the baseline nozzle for this flow regime.

Overexpanded case. When the jet is overexpanded, Fig. 7 (c), the baseline case has higher mixing level than half of the modified nozzles at $x/D_{eq} = 8$. In addition, the growth rate of the baseline nozzle is higher than that of any other nozzles beyond $x/D_{eq}=4$. There are three main reasons for this: 1) the jet for the baseline nozzle case is flapping, which provides significant mixing enhancement for the baseline case, 2) no strong streamwise vortical structures are generated due to flow separation inside the nozzle for the overexpanded flow condition, and 3) unlike the underexpanded cases, where a pair of vortices on one side of the jet did not interact with the pair of vortices on the other side until $x/D_{eq}=4$, or even until $x/D_{eq}=8$ in certain cases, the mixing layers interact immediately due to compression, owing to the smaller cross section of the jet. For these reasons, comparisons and conclusions in this flow regime are not straightforward.

Streamwise Vorticity Sources

As was observed in the cross-sectional images, the streamwise vortices played a significant role in jet development and mixing. In previous work (Samimy et al., 1997b, 1998), three potential sources of streamwise vorticity were discussed: 1) the vorticity convected downstream in the boundary layer approaching the modified region, 2) the spanwise (z) pressure gradient on the nozzle inside, and 3) the baroclinic torque due to the possible misalignment of pressure and density gradients. Kim et al. (1998) conjectured that the spanwise pressure gradient may be the major source of the streamwise vorticity. However, they were not able to provide experimental results to support the conjecture. A more detailed discussion on these sources are found in Kim et al. (1999).

Surface flow visualization results. Surface flow visualizations were conducted to observe the flow pattern on the modification and to determine the range of upstream influence zone. As shown in Fig. 8, the surface flow pattern was significantly altered by the cut-out for modification RC at $M_j=2.3$. In the figure, the flow direction is from bottom to top of the page, with alternating black and white stripes representing the streaklines on the modification. The flow pattern and zone of downstream influence for underexpanded cases are similar for different Mach number as shown schematically in Fig. 9.

In the overexpanded regime, the jet flow experienced flow separation as marked on the modification (Fig. 8). Over the separation line on the modification, a separation shock is expected to exist at the upper portion of the boundary layer. As the fully expanded jet Mach number and thus the jet exit pressure decreases, the angle of the separation line increases and eventually becomes 90° relative to the jet axis at $M_j= 1.5$ (Fig. 5 in Kim et al. (1999)). In contrast to the underexpanded case, the flow pattern was changed significantly with the fully expanded jet Mach number in the overexpanded cases, as depicted in Fig. 9.

Wall pressure measurement results. The measured wall pressure distribution on modification RC is shown in Fig. 10. The location of each tap on the modification is tabulated in Fig. 2. The measured wall pressure was normalized with the ambient pressure of 99.3 kPa. In addition, the spanwise distance z was normalized by the cut-out width W_{co}, which is equal to 1/3 of the nozzle width of 76.2 mm.

As expected, no significant spanwise or streamwise pressure gradients were measured in the ideally expanded case. The negligible streamwise vorticity source for this case resulted in almost the same jet cross section regardless of the type of modifications as shown in Figs. 3-6.

By the spanwise pressure gradient, a pair of counter-rotating streamwise vortices is formed with the same direction as a log rolling down the "pressure hill" (Lighthill, 1963; Zaman et al., 1994; Honkan and Andreopoulos, 1997) as shown in Fig. 11. The measured spanwise pressure gradients, $\partial p/\partial z$, for both modifications RS and RC are strong enough to generate streamwise vorticity on the wall (Eq. 1). The vorticity flux due to the surface pressure gradient for incompressible flows is given as:

$$\left(\frac{1}{\rho}\frac{\partial p}{\partial x}\right)_w = -\left(\nu\frac{\partial\Omega_z}{\partial y}\right)_w \tag{1}$$

where x, y, and z are for streamwise, normal, and spanwise directions, respectively, and ρ, p, and Ω_x are respectively density, pressure, and streamwise vorticity. The subscript w represents the conditions at the wall. Equation 1 is valid not only for incompressible flow but also for compressible flow without significant heat transfer to the wall as in the present case (Kim, 1998; Kim et al., 1999).

In contrast to the underexpanded cases, the pattern of pressure distribution on a modification varies with the fully expanded jet Mach number M_j in the overexpanded cases, since the separation location and accompanying separation shock location significantly depend on M_j as shown schematically in Fig. 9. The flow experiences an adverse pressure gradient, which in turn results in flow separation as shown in the surface flow images of Fig. 8. Because of the complex nature of the flow in the overexpanded case, the interpretation of the spanwise pressure gradient as a streamwise vorticity source is not straightforward.

At $M_j=1.5$ the spanwise pressure gradient was very small due to a two dimensional separation shock generated well upstream of the cut-out as can be seen in Fig. 6. More detailed surface flow visualization and wall pressure measurement results are found in Kim (1998).

Figure 11 shows the senses of vorticity by each source on modification RC. The spanwise vorticity convected downstream in the boundary layer was skewed toward to the streamwise direction in the upstream influence zone by spanwise velocity gradient of $\partial V_x/\partial z$. The realigned spanwise vorticity has negative streamwise component. The vorticity generated by spanwise pressure gradient is almost aligned with the streamwise direction with positive x-component. In addition, the sign of baroclinic torque is depicted. As shown in the figure, the sense of the streamwise component of vorticity for the skewed vortex and baroclinic torque is opposite to that of the vortex generated by the spanwise pressure gradient. As shown in Fig. 6, the sense of generated streamwise vortex matches with that due to spanwise pressure gradient. For this reason, the major source of streamwise vorticity is most likely the spanwise pressure gradient on the modification in the underexpanded flow regime.

CONCLUSIONS

In the underexpanded flow regime with double-sided trailing edge modifications, the nature of mixing enhancement over the baseline nozzle strongly depends on the type of streamwise vortices generated by the modifications. At upstream locations, the mixing enhancement is more significant for nozzles which generate a kidney-type pair of counter-rotating streamwise vortices that entrain ambient air into the jet plume, as in nozzles with modifications OS or RS (nozzles OS-OS and RS-RS). On the other hand, nozzles OC-OC and RC-RC, which generate mushroom-type pairs of vortices, performed better in mixing at a farther downstream location due to fluid pumping action of pairs of counter-rotating vortices. In this flow regime, the mixing layer by each cut-out developed independently, resulting significant mixing enhancement by double sided cut-outs. However, the mixing enhancement by double-sided cut-outs was almost in the same range with that by single-sided cut-out in the overexpanded case, not only due to severe interaction between mixing layers but also due to weaker streamwise vortices.

In the underexpanded cases, the measured spanwise pressure gradient was significant enough to generate strong streamwise vortices, which were clearly observed for modifications RS and RC, and is believed to be the major source of streamwise vorticity. However, the interpretation of the results is not straightforward in the overexpanded cases due to the complex flow features, including flow separation on the modified trailing edges.

In summary, mixing can be significantly enhanced by generating pairs of streamwise vortices via trailing edge modifications, especially in the underexpanded flow regime.

ACKNOWLEDGMENTS

The support of this research by NASA Lewis Research Center (with Dr. Khairul Zaman) and by the Air Force Office of Scientific Research (with Drs. Steven Walker and Thomas Beutner) is very much appreciated. The authors are thankful for the assistance of William R. Erskine in conducting the experiments.

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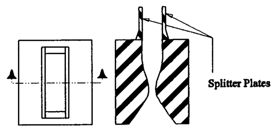
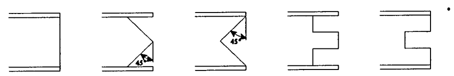
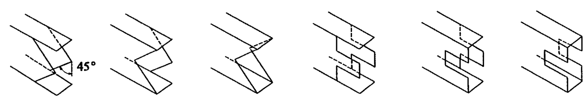


(a) Baseline nozzle head-on view and cross section



(b) Baseline trailing edge, BL, and modifications OS, OC, RS, and RC from left to right



(c) OS-OS (d) OC-OS (e) OC-OC (f) RS-RS (g) RC-RS (H) RC-RC

Fig. 1 Schematic of the nozzles and the modified trailing edges.

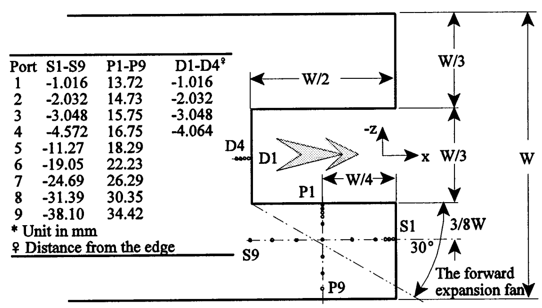


Fig. 2 The location of spanwise and streamwise pressure taps on modification RC. The width of the nozzle, W, is 7.6 cm.

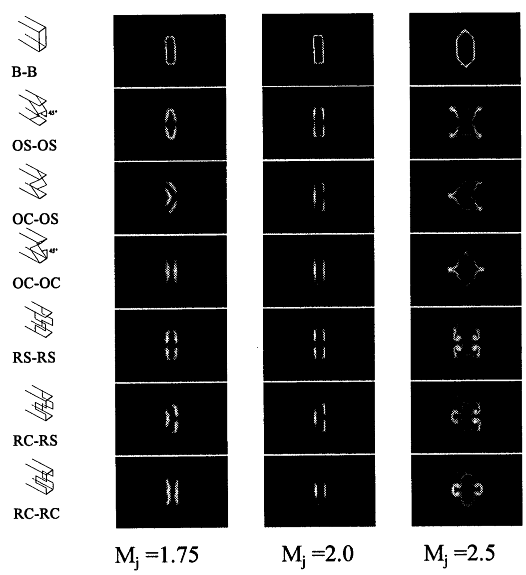


Fig. 3 Average cross sectional images at x/D_{eq}=1. The physical image size is $6.8D_{eq}$ wide and $4.1D_{eq}$ high (126.7 mm x 75.7 mm).

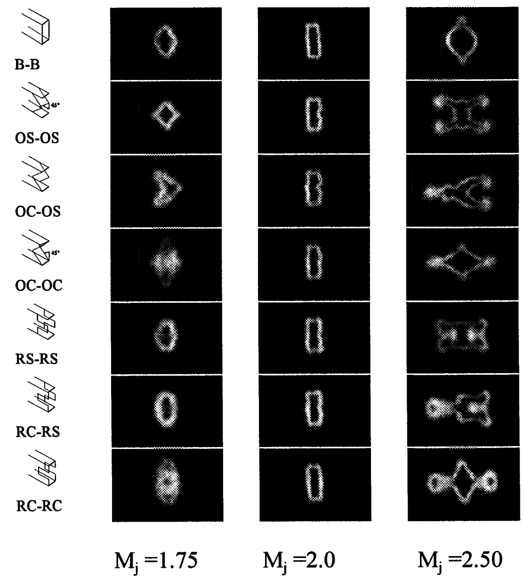


Fig. 4 Average cross-sectional images at x/D_{eq}=4. The physical image size is $6.4D_{eq}$ wide and $3.8D_{eq}$ high (120.0 mm x 70.8 mm).

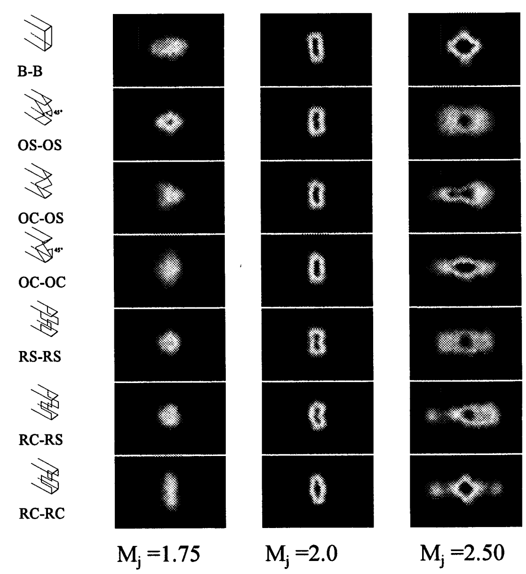
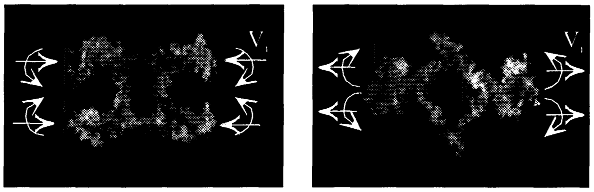


Fig. 5 Average cross-sectional images at x/D_{eq}=8. The physical image size is $9.5D_{eq}$ wide and $5.6D_{eq}$ high (176.8 mm x 103.8 mm).



(a) Nozzle OS-OS (b) Nozzle RC-RC

Fig. 6 A different pair of vortices generated by each trailing edge modification: (a) a kidney-type has a pair of vortices which entrains the ambient air and (b) a mushroom-type has a pair vortices that ejects the jet air into the ambient air in the underexpanded flow regime. The images are instantaneous cross-sectional images at $x/D_{eq}=4$.

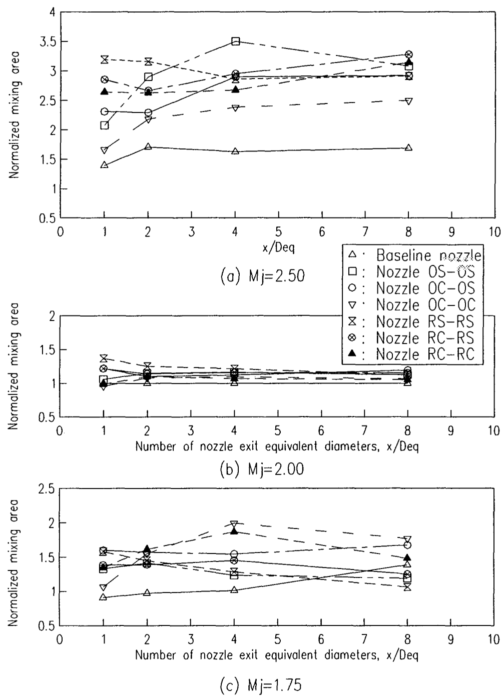
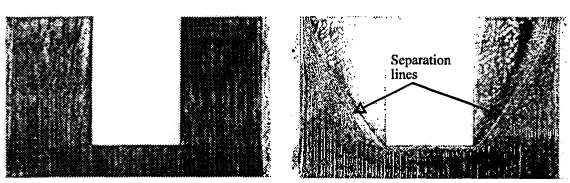


Fig. 7 Variation of normalized mixing area with downstream locations for underexpanded (a), fully expanded (b), and overexpanded (c) flow regimes.



(a) $M_j=2.3$ (b) $M_j=1.75$

Fig. 8 Surface flow streaklines on the inside surface of modification RC. The flow direction is from bottom to top of the page.

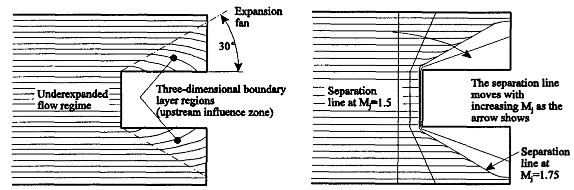


Fig. 9 Schematics of the zone of the upstream influence and resultant surface flow patterns on modification RC for underexpanded (left) and overexpanded (right) cases. The flow direction is from left to right.

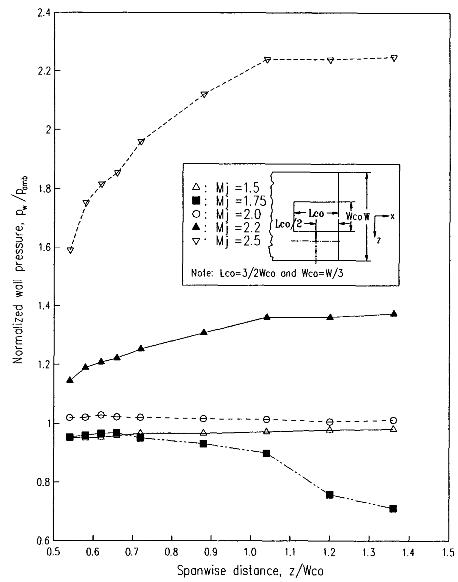


Fig. 10 Spanwise pressure distributions for modification RC at five flow conditions. The wall pressure, p_w, was normalized by p_{amb}.

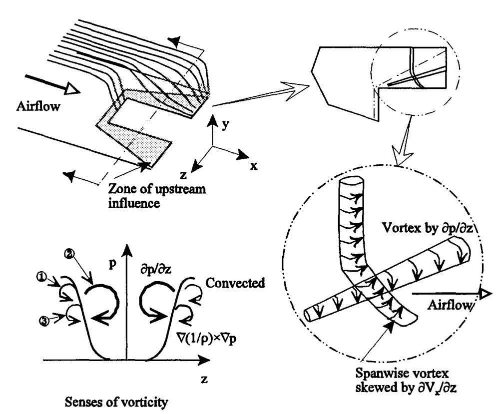


Fig. 11 Senses of vortices in the upstream influence zone: convected downstream (vortex ①) and generated by $\partial p/\partial z$ (vortex ②), and their senses. The sense of vorticity by baroclic torque is indicated by ③.