# Effects of Vortex-Generator Spacing on The Performance of Diffusers in Three Flow Regimes

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**Abstract**

The effects of vortex-generator spacing on the performance of diffusers in three flow regimes were investigated. The vortex generators were of half-delta wing type with a sweepback angle of 70°, an angle of attack of 15°, and a relative height measured in terms of the normalized parameter $h/\delta$ of 1.3 ($h/\delta_2$ = 9.6), where $h$ is the height of the wing tip, $\delta$ is 95 per cent boundary layer thickness, and $\delta_2$ is the momentum thickness. The generators were arranged in a co-rotating fashion. The three test diffusers were of straight-wall rectangular type with an area ratio of 3.9 and an inlet aspect ratio of 3.3 and could be classified according to flow regimes as transitory stall diffuser ($2\theta$=28°), fully-developed stall diffuser ($2\theta$=50°), and jet flow diffuser ($2\theta$=70°). The experiments were conducted at six relative 'spacings': $\delta/S$ = 0 (no vortex generators), 0.15, 0.19, 0.25, 0.37, and 0.75, where $S$ is the spacing between neighboring vortex generators, and at flow Reynolds number based on the diffuser inlet width of $1.6\times10^5$. The results indicated that the performance characteristics of diffusers with vortex generators were quite similar for the transitory stall and fully-developed stall diffusers and were different from that of the jet flow diffuser. Specifically, it was found that as $\delta/S$ increased from 0 to 0.25, the static pressure recovery ($C_p$) for transitory stall and fully-developed stall diffusers increased. Beyond this range, i.e., $\delta/S$ > 0.25, $C_p$ was approximately constant. The optimum spacing for both diffusers was found to be at $\delta/S$ = 0.25 with $C_p$ for transitory stall diffuser increased by 50 per cent and that for fully-developed stall diffuser by 25 per cent. Furthermore, loss coefficient ($k$) changed very little over the whole range of spacing. On the contrary, for the jet flow diffuser, the vortex generators almost had no effect on $C_p$ and caused $k$ to increase slightly. Generally, the use of vortex generators in the range of $\delta/S$ from 0 to 0.25 caused the exit flow to become increasingly more uniform when measured with the total pressure distortion index $D$ although the standard deviation of the total pressure coefficient $\sigma_{Cpt}$ indicated slightly different scenarios. The use of the two indices as a means for indicating flow-uniformity was discussed.

## 1. Introduction

This study is our continued effort in finding appropriate and simple means to improve the performance of diffusers. Depending upon the use of a diffuser and the flow quality desired, different flow manipulation/control scheme may be required. For example, for conventional diffusers such as those in supply air duct, high static pressure recovery, low loss, and low noise are desirable, and flow manipulation by vortex generators (VG), vanes, and contoured walls may be employed. On the other hand, for diffusers in a blower tunnel, steadiness and uniformity of the exit flow are most desirable - static pressure recovery and loss being of secondary concern -

in this respect screens are generally employed. In this study we focus on conventional diffusers, therefore the improvement in static pressure recovery, loss, and, to some extent, uniformity of an exit flow are of primary concern.

We have reviewed some of the studies on general aspects of flow in diffusers and flow manipulation schemes in Pimpin and Bunyajitradulya (1998), thus we shall avoid repeating them here. The reader is simply referred to the cited reference for some of the general aspects. For the reason of simplicity in engineering applications, the use of vortex generators continues to be the subject of the present study. In the past study, we focused on a diffuser which can be classified as transitory stall diffuser. In this study, however, we expand our attention to the effect of vortex generators on the performance of all three problematic classes of diffusers, namely, transitory stall diffuser (TSD), fully-developed stall diffuser (FSD), and jet-flow diffuser (JD).

The use of vortex generators to improve the performance of a diffuser has been studied for some time in the past. Brown et al. (1968) employed wall contouring in combination with airfoil-type vortex generators in the integrated design of a Mach 0.5 asymmetric subsonic-diffuser inlet. The relevant test diffusers had rectangular cross-section with an area ratio ($AR$) of approximately 2 and the equivalent wall angle ($\theta$) of 9.5$^{\circ}$. The vortex generators were flat-bottomed cambered airfoil (6 per cent thickness) with rectangular planform and chord-to-height (span) ratio of 2, mounted at 16$^{\circ}$ angle of attack, and arranged in counter-rotating pairs. The relative vortex generator height measured in terms of $h/\delta$ was 1.2, where $h$ is the height of the generators above ground and $\delta$ is the boundary layer thickness. The spacing between two vortex generators in a pairs was one-tenth of the spacing between pairs. No data were however available regarding the relative spacing between pairs. Forty per cent reductions in total pressure recovery loss and distortion were reported when compared with the well-designed conventional trumpet-shaped diffuser. Nonetheless, the penalties in recovery were more severe when design mismatches occurred for the integrally designed diffuser than for the conventional one.

Senoo and Nishi (1974) studied the use of vortex generators in conical diffusers with area ratios of 4 (without tailpipe) and 3.76 (with tailpipe), and diverging angles ($2\theta$) of 8, 12, 16, 20, and 30 degrees. These diffusers are well within transitory stall flow regime according to the diffuser chart of Reneau et al. (1967), see also McDonald and Fox (1966). The vortex generators were flat-bottomed circular-back airfoil (10 per cent thickness) with rectangular planform and chord-to-height ratios of 0.67 and 1.0, mounted at 10-, 14-, and 20-degree angles of attack, and arranged in co-rotating and counter-rotating pairs fashion. The relative height of the vortex generators measured in terms of $h/\delta_2$ was varied from approximately 8 to 40. Various numbers of vortex generators or, equivalently, the relative spacings were experimented. It was found that flow separation could be prevented upto the diffuser diverging angle of 16 degree with twelve vortex generators of chord-to-height ratio of 0.67, angle of attack of 14 degree, and co-rotating arrangement. In addition, generally the static pressure recovery was found to increase with the decrease in relative spacing until it reached a maximum, and then slightly decreased. The optimum value of the relative spacing measured in terms of $S/\delta_2$, where $S$ is the spacing, can be deduced from their data to be approximately 35. Furthermore, it was found that the co-rotating arrangement was generally performed better than the counter-rotating one because of an additional effect. Namely, the generated vortices in co-rotating arrangement did not only help exchanging momentum between the freestream and the boundary layer, but also helped inducing swirling flow near the wall region of the diffuser that contributed to prevention of flow separation.

Anabtawi et al. (1998) employed vortex generators with a semi-circular cross section diffuser. The diffuser had an area ratio of 1.7 and diverging angle ($\theta$) of 3.4°. Such a diffuser is intended for the NASA-Boeing Blended-Wing-Body (BWB) aft engine inlet. The vortex generators were flat-plate rectangular wing and half-delta wing types with the chord-to-height varied from 1 to 10 (sweepback angle from 45° to 84° for half-delta wings), mounted at 15 degree angle of attack, and arranged in a co-rotating fashion on each side of the line of symmetry with the opposite side forming a mirror image. The relative height $h/\delta$ was varied from 1/4 to 1 and the relative spacing $S/\delta$ from 0.75 to 1.5. It was found that the gains in total pressure recovery as well as the total pressure distortion depended primarily on generator heights, as opposed to their chords, relative to the boundary layer thickness, and that the wetted generator areas had strong adverse effect on the total-pressure recovery. In addition, the half-delta wings were found to perform better than the rectangular wings because the vortices generated from half-delta wings appeared to have much better surface attachment characteristics than those generated from rectangular wings. In addition, because half-delta wings had smaller wetted area for equal height, they produced less drag, therefore had less adverse effect on the performance. Their results showed the best improvements in total pressure loss measured in terms of $k/k_o$ of 0.91 and in total pressure distortion measured in terms of $D_{min}/D_{mino}$ of 0.38 for the case of half-delta wings with the relative height $h/\delta$ of one, chord-to-height ratio of three (sweepback angle of 71.6°), and relative spacing of 1.5. Note that they used slightly different definition for the total pressure distortion from the one we shall employ here. The reader is referred to the cited work for more details. Similar study on this kind of diffuser was given by Foster et al. (1996).

On the other hand, there were many related studies that focused on the vortex/boundary-layer and vortex/vortex interactions (e.g., Shabaka et al., 1985; Bradshaw and Cutler, 1987; Westphal et al., 1987; Mehta and Bradshaw, 1988; Pauley and Eaton, 1988; Wendt et al., 1992; Cutler and Bradshaw, 1993a and b; and Jacob, 1998) and the physics of vortex generators (e.g., Klausmeyer et al., 1996; Wendt and Hingst, 1994; and Wendt, 1998). The reader is referred to the cited references for more details.

Of particular interest, however, are the studies related to delta wing vortex generators. As mentioned earlier, because of their simplicity and because of their superiority in performance over rectangular wings as indicated by the results of Anabtawi et al., we chose delta wing vortex generator in the present study. In this regard, there were many studies related to the vortex dynamics of delta wings. Examples are those of Lambourne and Bryer (1961), Earnshaw and Lawford (1964), Campbell (1976), Ericsson and Reding (1977), Erickson (1982), McKernan and Nelson (1983), Gad-el-Hak and Blackwelder (1987), Payne et al. (1988), and Johari and Moreira (1998). We shall come back to this in the next section.

From these past studies, it can be seen that much attention was paid to the use of vortex generators in diffusers in transitory stall flow regime, and very little to the use in the other two problematic flow regimes, and even less to the comparison of the relative effectiveness among all three problematic flow regimes. The reasons are that much focus was laid on inlet diffusers rather than conventional diffusers and that conventional vortex generators were not expected to perform well in the fully-developed stall and, particularly, the jet flow regimes. Nonetheless, the answer to the question of to what extent the conventional vortex generators are effective in these latter two flow regimes in comparison with the transitory stall flow regime is undoubtedly important for engineering applications. The present study therefore attempts to address this question in general. And, in specific, it attempts to address the question of the relative effect of vortex generator spacing on the performance of all three problematic classes of diffusers.

## 2. Facility and Experimental Setup

The experiments were conducted in the Fluid Mechanics Research Laboratory, Department of Mechanical Engineering, Faculty of Engineering, Chulalongkorn University. The flow facility is described in Pimpin and Bunyajitradulya (1999), Sathapornnanon et al. (1999), and Sakulyanontvittaya et al. (1999). To facilitate for this experiment, the leading pipe, the test diffuser, and the tail pipe were attached to the contraction. The leading pipe with rectangular cross section of 60x18 $cm^2$ and length of 240 cm was made from 10-mm thick acrylic plates. Three straight-walled two-dimensional diffusers with rectangular cross section were tested. The test diffusers were made from 4-mm thick steel plates. They had an inlet area of 60x18 $cm^2$ (an inlet aspect ratio of 3.3) and an exit area of 60x70 $cm^2$, resulting in an area ratio of 3.9. The transitory stall diffuser had a diverging angle $2\theta$ of 28° ($N/W_1 = 5.8$, where $N$ is the length of the diffuser measured along its axis and $W_1$ is the inlet width), the fully-developed stall diffuser of 50° ($N/W_1 = 3.1$), and the jet flow diffuser of 70° ($N/W_1 = 2.1$). The tail pipe was also made from 4-mm thick steel plates with a rectangular cross section of 60x70 $cm^2$ and length of 160 cm.

The vortex generators used in this study were of half-delta wing type, in contrast to our past work in which a full-delta wing type was used. The reason for the use of a half-delta wing instead of a full-delta wing is the desire to have freedom in controlling the sense of rotation of each vortex generated. A full-delta wing generates two counter-rotating leading edge vortices, while a half-delta wing generates only one leading edge vortex whose sense of rotation can be controlled by its relative orientation to the freestream. The study of Johari and Moreira (1998) and Anabtawi et al. (1998) suggested that a half-delta wing of sweepback angle in the order of 70° and angle of attack in the order of 15° be used. At these angles, the phenomenon of vortex breakdown occurs well beyond the trailing edge of the wing and the normalized circulation ($\Gamma/U_0c$) at the location $x/c = 0.8$ is in the order of 0.3, see Johari and Moreira for more details. Note that for the sweepback angle of 70°, vortex breakdown occurs at the trailing edge when the angle of attack is approximately at 25° (Erickson, 1982; McKernan and Nelson, 1983; also, Johari and Moreira). In addition, the study of Anabtawi et al. suggested that the relative height $h/\delta$ of the half-delta wing be in the order of the boundary layer thickness and that the wings be arranged in a co-rotating fashion, see also Gad-el-Hak (1998) and Pauley and Eaton (1988). Therefore, in the present study, half-delta wing vortex generators with a sweepback angle of 70° $\pm$ 1° and a height of 4 cm, which resulted in $h/\delta$ of 1.3 (see the boundary layer data below), were used. The generators were installed at an angle of attack of 15° $\pm$ 1° in a co-rotating arrangement as shown in Fig. 1. The trailing edges of the generators were aligned at 1 cm upstream of the diffuser inlet. The generators were made from 1 mm thick steel plate cut into the required shape and welded onto a 1 mm thick steel base to form a row of co-rotating generators.

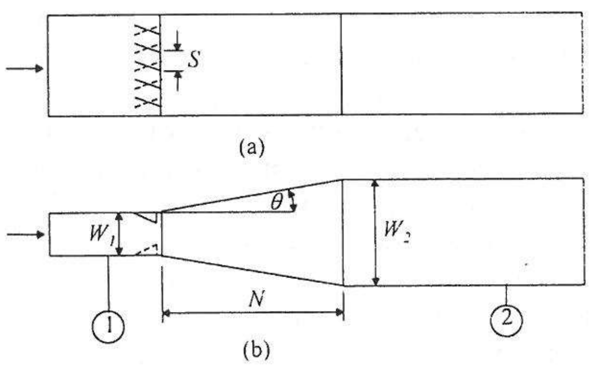



Fig. 1. Nomenclature and the arrangement of vortex generators; (a) top view, (b) side view.

For each test diffuser, a base case, i.e., the case without vortex generators, and five spacings were tested: $S$ = 4, 8, 12, 16, and 20 cm. Anticipating the case without vortex generators to be relatively similar in performance to the case of largest spacing than that of the smallest one, we selected the parameter $\delta/S$, where $\delta$ is a 95 per cent boundary layer thickness, to represent the relative 'spacing' over $S/\delta$. Hence, the corresponding six spacings are $\delta/S = 0$ (without vortex generator, $S = \infty$), 0.15 ($S = 20$ cm), 0.19, 0.25, 0.37, and 0.75 ($S = 4$ cm). For convenience, we shall refer to a test case by the diffuser type (T for transitory stall, F for fully-developed stall, and J for jet flow) and the two digits of the relative spacings, e.g., T0 refers to the case of transitory stall diffuser without vortex generators, and J37 to the case of jet flow diffuser with relative spacing $\delta/S$ of 0.37. Table 1 summarizes the parameters for the arrangements.

| $S$ (cm) | $S/\delta$ | $\delta/S$ | $\delta_2/S$ | Number of VG's (2 sides) |
|---|---|---|---|---|
| $\infty$ | $\infty$ | 0 | 0 | 0 (w/o VG's) |
| 20 | 6.7 | 0.15 | 0.021 | 6 |
| 16 | 5.3 | 0.19 | 0.026 | 8 |
| 12 | 4.0 | 0.25 | 0.035 | 10 |
| 8 | 2.7 | 0.37 | 0.052 | 14 |
| 4 | 1.3 | 0.75 | 0.104 | 26 |

Table 1. Parameters for vortex generator spacings.

Measurements were made at the inlet station, station 1, located at approximately one diffuser inlet width (19 cm) upstream of the diffuser inlet and the exit station, station 2, located at 1.5 times the hydraulic diameter of the tail pipe (97 cm) downstream of the diffuser exit. For measurements of static pressure at station 1, a total of four static pressure taps (1 mm in diameter) were located along four walls, one at the center of each wall. At station 2, a total of 22 static pressure taps were distributed evenly (spacing of 10 cm) along four walls, 5 taps each on the top and bottom walls and 6 taps each on the two side walls. For measurements of total pressure, pitot probes were used; a small probe (0.8 mm ID, 1.2 mm OD) made from a hypodermic needle for measurements at station 1 and a large probe (2.5 mm ID, 5 mm OD) made from stainless steel tube for measurements at station 2. The measurements of total pressure at station 1 were made at the center of the cross section, while the measurements at station 2 spanned the center area of 68 x 56 cm$^2$ of the total area of the cross section (70 x 60 cm$^2$) and were made in a grid of 18 x 15 with the spatial resolution of 4 x 4 cm$^2$. All pressure measurements were made differentially with respect to a reference static pressure tap ($p_{ref}$) located at the center of the top wall at station 1 and with an AutoTran differential pressure transducer model 750D-212, range $\pm$ 0.5 in. Water, and $\pm$ 0.25 per cent accuracy quoted by the manufacturer.

| | | $\delta$ | $\delta_1$ | $\delta_2$ | $H$ | $n$ |
|---|---|---|---|---|---|---|
| TSD | Min | 28.0 | 5.3 | 3.9 | 1.3 | 5.6 |
| | Max | 32.0 | 6.2 | 4.5 | 1.4 | 6.3 |
| | Ave | 30.2 | 5.7 | 4.2 | 1.3 | 6.0 |
| | Std | 1.3 | 0.2 | 0.2 | 0.1 | 0.2 |
| FSD | Min | 28.0 | 5.0 | 3.9 | 1.3 | 5.6 |
| | Max | 32.0 | 6.0 | 4.5 | 1.4 | 6.3 |
| | Ave | 30.2 | 5.6 | 4.2 | 1.3 | 6.0 |
| | Std | 1.6 | 0.4 | 0.2 | 0.1 | 0.2 |
| JD | Min | 28.0 | 5.0 | 3.9 | 1.2 | 5.6 |
| | Max | 30.0 | 5.9 | 4.2 | 1.4 | 6.7 |
| | Ave | 28.8 | 5.4 | 4.1 | 1.3 | 6.0 |
| | Std | 0.7 | 0.3 | 0.1 | 0.1 | 0.3 |

Table 2. Parameters of the inlet boundary layers. $n$ is the exponent of the best-fit velocity profile using power law. The thicknesses are in mm.

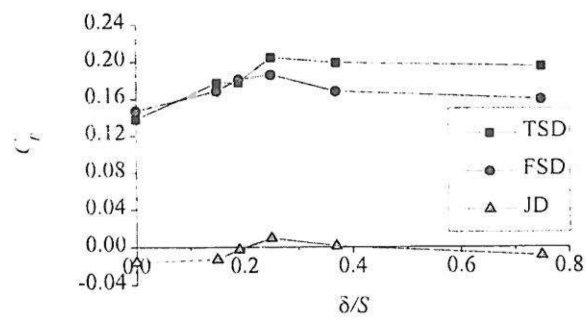
The experiments were conducted at the inlet velocity of 13.3 m/s, corresponding to the Reynolds number based on the inlet width of 1.6x10$^5$. The measurements of the inlet boundary layer profile were made with the small pitot probe, at station 1, and at the center locations on the top and the bottom walls. The results for all cases indicated that the 95 per cent thickness $\delta$ ranged between 28 to 32 mm with the average at 29.7 mm and the standard deviation at 1.4 mm. The details are summarized in Table 2. Note that the displacement thickness $\delta_1$, the momentum thickness $\delta_2$, and the shape factor $H$ were calculated from best-fit velocity profiles using power law.

## 3. Results and Discussion

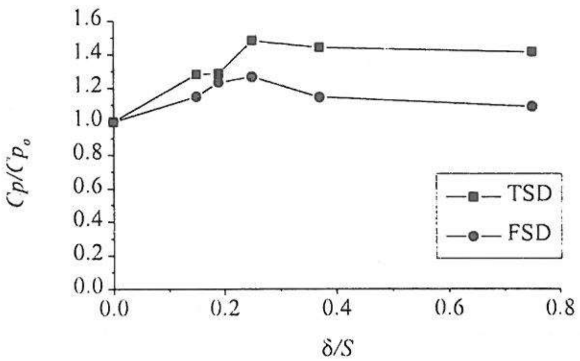
In evaluating the performance of the diffusers we use static-pressure recovery ($C_p$), total-pressure loss coefficient ($k$), total-pressure coefficient ($C_{pt}$), total-pressure distortion index ($D$), and the standard deviation of the total-pressure coefficient ($\sigma_{Cpt}$). The results are summarized in Table 3 (see back).

### Static pressure recovery ($C_p$)

The static pressure recovery $C_p$ is defined as $(p_2-p_1)/q_1$, where $p_1$ and $p_2$ are the arithmetic averages of the static pressure readings from all the taps located at station 1 and 2, respectively, and $q_1$ is the dynamic pressure at station 1. The uncertainty in $C_p$ is estimated to be within $\pm$ 0.01. Figures 2a and 2b show the variations in $C_p$ and $C_p/C_{po}$, respectively, with the relative spacing $\delta/S$. From now on, we shall use the subscript 'o' to refer to the corresponding base case of diffuser without vortex generators. Hence, $C_{po}$ refers to the static pressure recovery of the corresponding case T0, F0, or J0. Also, note that owing to large uncertainty in $C_p/C_{po}$ for the case of jet flow diffuser the result is not shown in Fig. 2b. Further details on this are discussed below.




(a)




(b)

Fig. 2. (a) Variation in $C_p$ with $\delta/S$; (b) variation in $Cp/Cp_o$ with $\delta/S$.

For the transitory stall diffuser, as $\delta/S$ increases from 0 to 0.25, $C_p$ increases until it reaches maximum at $\delta/S$ = 0.25. At this point, the improvement in $C_p$ is approximately 50 per cent over the case without vortex generators. As $\delta/S$ increases further, however, $C_p$ stays approximately constant or slightly decreases. This result has implications in two folds. Firstly, the increase in $C_p$ in the range from $\delta/S$ = 0 to 0.25 implies that the use of vortex generators - even a few number or even at relatively large spacing - can help improving the static pressure recovery in comparison with the case when no vortex generators are used at all. Secondly, the constant in $C_p$ in the range from $\delta/S$ = 0.25 to 0.75 implies that beyond the optimum number of vortex generators, which in this case corresponds to $\delta/S$ = 0.25, an increase in the number of vortex generators installed will not have any favorable effect on $C_p$. In addition, this may have an adverse effect on $C_p$ and $k$ since blockage increases. Similar trend is observed for the case of fully-developed stall diffuser with the optimum value of $\delta/S$ at 0.25, the same value as that for the transitory stall diffuser. The improvement in $C_p$ for this case - albeit less than that of TSD but nonetheless significant - is approximately at 25 per cent. The fact that the maximum improvement in $C_p$ for the fully-developed stall diffuser is less than that for the transitory stall diffuser is expected since separation in the former is more severe. Similar trend of the variation in $C_p$ with $\delta/S$ was also observed in conical diffusers of Senoo and Nishi (1974) although in that study $C_p$ was correlated with the number of generators installed. However, the study of Senoo and Nishi covered conical diffusers with diverging angle upto $30^o$ only and the similarity ends at the diverging angle upto $20^o$. At $30^o$, their result showed continually increase in $C_p$ with the increase in number of generators installed.

On the contrary, for the case of the jet flow diffuser, $C_p$ for all cases are practically zero, and no significant improvement is observed when the vortex generators are applied. Thus, there are large errors associated with $C_p/C_{po}$; the plot is therefore not shown in Fig. 2b. It can then be concluded that vortex generators with more suitably designed strength are required. To this end, Goenka et al. (1989 and 1990) had attempted using pyramid inserts. However, the inserts in the study seem to produce excessively high loss.

Finally, it is interesting to note that the optimum values of $\delta/S$ for TSD and FSD are approximately the same while the corresponding optimum $C_p$'s are a factor of two different. This implies that the interaction between vortices generated has minor or little effect on $C_p$ in comparison to the strength of the vortices generated.

**Total-pressure loss coefficient ($k$)**

The total-pressure loss coefficient $k$ is defined as $(p_{t1} - \hat{p}_{t2})/q_1$, where $p_{t1}$ is the total pressure at station 1, $\hat{p}_{t2}$ is the area average of the total-pressure at station 2, and $q_1$ is the dynamic pressure at station 1. The use of area average in evaluating $p_{t2}$, in contrast to past work where mass average was used, stems from the fact that the mass average value cannot be determined with reasonable accuracy when severe separation associated with high total angle is present such as in this experiment. The uncertainty in $k$ is estimated to be within $\pm$ 0.02. Figure 3 shows the variation in $k/k_o$ with the relative spacing $\delta/S$ for all three diffusers tested.

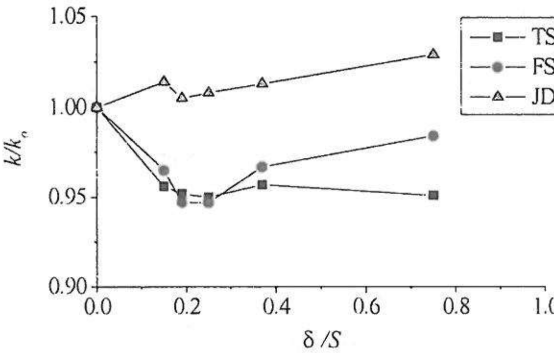



Fig. 3. Variation in $k$ with $\delta/S$.

From the figure, slight changes, approximately within $\pm$ 5 per cent, in the loss coefficients are observed for all cases. As $\delta/S$ increases from 0 to 0.25, $k$ for cases TSD and FSD decreases. Beyond this, $k$ for TSD stays approximately constant while that for FSD slightly increases. On the contrary, $k$ for cases JD continually increases except at the point between $\delta/S$ = 0.15 and 0.19. Nonetheless, all these changes are relatively slight.

The variations in $k/k_o$ with blockage $B$, defined as the fraction of the diffuser inlet area blocked by the presence of the displacement thickness and the vortex generators, is shown in Fig. 4 together with the data from past work (Pimpin and Bunyajitradulya, 1998). It is interesting to note that, for the present study, even if the blockage changes by a factor of two, $k$ only changes slightly. This suggests that the vortex generators contribute, either favorably or adversely, insignificant fraction of total energy loss and that the primary source of energy loss is within the recirculation zone. This is unlike our past work in which large change in $k$ is observed with similar change in blockage. This, on the contrary, suggests that the vortex generators contribute relatively large fraction of total energy loss and that the primary sources of energy loss are both in the recirculation zone and from the generators.

Insight can be gained when the differences between the parameters of the two experiments are considered. Firstly, unlike the present study, in the past study full-delta wings were employed instead of half-delta wings and the relative height and angle of attack were varied instead of the spacing. Secondly, the diffuser in the past study was of transitory stall type with smaller area ratio and diverging angle ($AR$ = 2.25, $2\theta = 24^{o}$ in comparison to TSD: AR = 3.9, $2\theta = 28^{o}$). Therefore, less severe separation was present which resulted in less loss ($k$ = 0.18 in comparison to T0: $k$ = 0.71, albeit slightly different method of evaluation). Thus, it is expected that the additional energy loss associated with the vortex generators can be relatively large. With these in mind, the results shown in Fig. 4 suggest the followings. Firstly, energy loss is strongly dependent upon the form or the drag of the vortex generators but relatively weakly upon the number of generators. Secondly, the penalty in loss for the vortex generator design mismatches is relatively larger for transitory stall diffusers than fully-developed stall and jet flow diffusers.

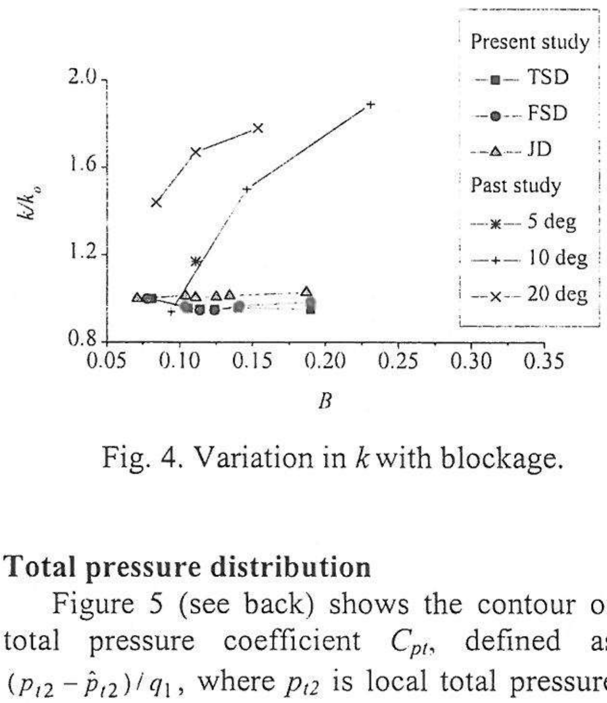



Fig. 4. Variation in $k$ with blockage.

### Total pressure distribution

Figure 5 (see back) shows the contour of total pressure coefficient $C_{pt}$, defined as $(p_{t2} - \hat{p}_{t2})/q_1$, where $p_{t2}$ is local total pressure at station 2. The uncertainty in $C_{pt}$ is estimated to be within $\pm$ 0.03. The first row shows the results for TSD, the second for FSD, and the third for JD, while the first column shows the results for $\delta/S$ = 0 (without vortex genrators), the second for $\delta/S$ = 0.15, the third for $\delta/S$ = 0.19, and so on. The darkest band shows the level of total pressure in the vicinity of the mean total pressure.

The relative severity and the extent of separation among cases without vortex generators can be seen in the first column. As the figure shows, separation occurs at the bottom half for all cases. The transitory stall diffuser shows the weakest separation which is indicated by the smallest low pressure region behind the recirculation zone at the bottom and the smallest high pressure region, or jet-like region, at the top. On the other hand, the jet flow diffuser shows the strongest separation which is indicated by the largest corresponding regions. In addition, in the case of jet flow diffuser, separation is relatively so strong that the highest pressure region is one contour level above those of the other two.

As is clearly seen, when vortex generators are applied in cases TSD, the low pressure region at the bottom becomes smaller. In fact, even the case of largest spacing, T15, can reduce the extent of the low pressure region considerably, and the case of smallest spacing, T75, practically makes it disappears. The vortex generators generally have similar effect, albeit not as dramatic, on the high pressure region at the top. It is also interesting to note that the high pressure region at the top moves closer towards the upper wall as the spacing decreases from case T0 to T75. Similar observation can be said for the low pressure region, i.e., the high pressure region moves closer towards the lower wall as the spacing decreases. In other words, the vortex generators have the effect of transfer high momentum fluid towards the walls.

Generally, the application of vortex generators in the case of fully developed stall diffuser shows similar effects, though less drastic. That is, they make the low pressure region smaller and drive high momentum fluid towards the walls. However, two interesting observations can be made. As the spacing decreases, there appears higher pressure region at the top and the high pressure region moves down the wall on the left. The latter is similarly observed in the case of TSD.

In the case of a jet flow diffuser, general observations made in the cases of TSD and FSD are also applied. That is, the extent of the low and high pressure regions decreases, and the high momentum fluid is driven towards the wall, as the spacing decreases. Unlike the FSD, however, this time the high pressure region seems to move up and then down again along the right wall.

**Uniformity of total pressure distribution**

To quantify the uniformity of total pressure distribution at diffuser exit, we explore two indices. The first is the total pressure distortion index *D*, defined as $(\hat{p}_{tw} - \hat{p}_{t2})/(\hat{p}_{t2} - p_{ref})$, where $\hat{p}_{tw}$ denotes the area-averaged total pressure over any specified window w at station 2. The second is the standard deviation of the total pressure coefficient $\sigma_{Cpt}$.

For the calculation of the total pressure distortion index, the window size w is chosen and the distortion index *D* is calculated for every possible position of the window on the exit plane. Thus, $D_{max}$ represents the maximum value of distortion on the exit plane which corresponds to the region of highest average total pressure, $D_{min}$ the minimum value corresponding to the region of lowest average total pressure, and $\Delta D$ = $(D_{max}$ - $D_{min})$ the maximum deviation in distortion on any exit plane. Table 3 gives the values of these parameters for a window size of grid 8x8 which corresponds to 24 per cent of an exit area.

Figure 6 shows the variation of the normalized deviation in distortion, $\Delta D/\Delta D_o$, with the spacing for a window size of 8x8. The transitory stall and the fully-developed stall diffusers display similar characteristics which is also observed in $C_p/C_{po}$ in Fig. 2b. That is, as $\delta/S$ increases from 0 to 0.25, the deviation continually improves. Beyond this range, the deviation stays relatively constant. This suggests that the optimum value for $\delta/S$ is equal to 0.25. On the contrary, in the case of the jet flow diffuser certain minimum proximity between neighboring vortex generators is required before any significant improvement shows, and, in this case the deviation starts to improve when $\delta/S$ is larger than approximately 0.15. On the other hand, the result also suggests the optimum value for $\delta/S$ of 0.25, similar to the other two diffusers.

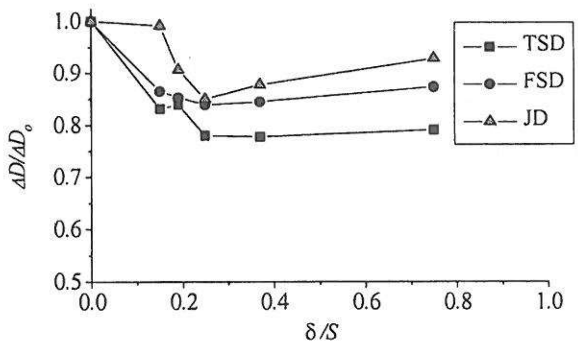



Fig. 6. Variation in distortion index with $\delta/S$.

A glance back at the total pressure contours in Fig. 5, however, seems to indicate some contradiction for the fully-developed stall diffuser. Specifically, one would generally describe the distribution in case, e.g., F75 as less uniform than case F0, in contradiction to what $\Delta D$ may indicate. However, it is to be noted that, by definition, *D* does not represent local variation of total pressure but rather the global or average variation within a region larger than the window size w. To investigate further on this, we consider the followings.

Firstly, the effect of window size on $\Delta D$ is considered. Figure 7 shows the normalized deviation for case FSD as a function of spacing for a range of window size from 6 to 55 per cent of the exit area. Note that in this plot the normalizing factor $\Delta D_o$ is evaluated at the corresponding window size. As the figure shows, all graphs exhibit the same trend. That is, there is a local minimum and it is near $\delta/S$ =0.25. Although there are some variations in the value of $\Delta D/\Delta D_o$ with window size, which is to be expected, but it should be noted that the variations stay within 15 per cent for the change in window size over 50 per cent.

Secondly, the standard deviation of the total pressure coefficient $\sigma_{Cpt}$ over an exit plane is calculated. Figure 8 shows the normalized standard deviation of $C_{pt}$ as a function of spacing. From the figure, it can be seen that $\sigma_{Cpt}$ seems to depict the uniformity of total pressure in a more conventional sense and in accordance with the contour of $C_{pt}$ in a conventional manner. Generally, decrease in $\sigma_{Cpt}$ in cases TSD and JD and increase in case FSD are observed as $\delta/S$ increases.

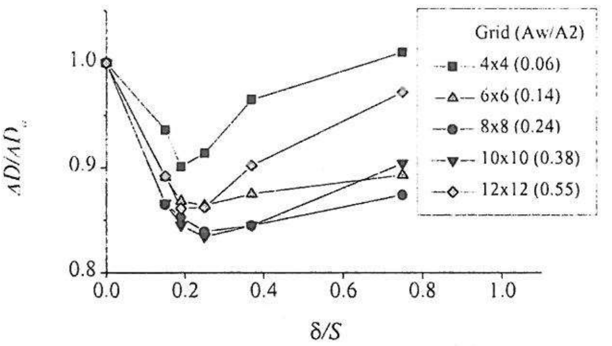



Fig. 7. Effect of window size on $\Delta D/\Delta D_o$ for case FSD.

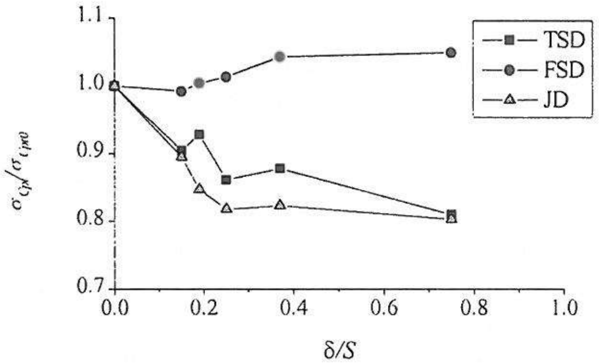



Fig. 8. Normalized standard deviation of $C_{pt}$.

From these results, the discussion in terms of the use of $D$ as a measure of uniformity is in order. As an example, consider a cyclic loading in the axial direction on a blade of axial-flow turbomachines. In such case, the appropriate window size for an evaluation of $D$ is the frontal area of the blade. Now, consider two scenarios of total pressure distribution; both are uniform in the radial direction and sinusoidal in the circumferential direction. One, however, has a period equal to the angular width of the blade, and the other has twice as large. The evaluation of $\sigma_{Cpt}$ for both cases would indicate that they are equal. On the other hand, that of $\Delta D$ would indicate the difference; the one-width period being zero, and the two-width period a finite value. Therefore, in this case $\Delta D$ would be able to differentiate the difference in cyclic loading while $\sigma_{Cpt}$ would not. Generally, thus the choice of the suitable parameter for measurement of uniformity depends upon the application.

## 4. Conclusions

The effect of vortex-generator spacing on the performance characteristics of diffusers in three flow regimes were investigated. The vortex generators were of half-delta wing type and the diffusers were of transitory stall, fully-developed stall, and jet flow types. The results indicated that the performance characteristics of diffusers with vortex generators were quite similar for the cases of transitory stall and fully-developed stall diffusers and were different from that of the jet flow diffuser. The optimum spacing for the former two was found to be at $\delta/S = 0.25$ at which the static pressure recovery for the transitory stall diffuser was found to increase by 50 per cent and that of fully-developed stall diffuser by 25 per cent. On the other hand, the current generators could not improve the recovery in the case of the jet flow diffuser. In addition, the loss coefficients changed only slightly for all three diffusers.

Generally, the use of vortex generators in the range of $\delta/S$ from 0 to 0.25 caused the exit flow to become increasingly more uniform when measured with the total pressure distortion index $D$ although the standard deviation of the total pressure coefficient $\sigma_{Cpt}$ indicated slightly different pictures. The use of the two indices as a means for indicating flow-uniformity was discussed.

Finally, the results suggested that, for a given design of the generators similar performance characteristics can be expected when the generators are applied to either transitory stall or fully-developed stall diffuser but different characteristics can be expected when applied to a jet flow diffuser. This is likely due to the fact that the former types of diffuser have relatively similar overall flow structure while the latter's is relatively different. (Separation occurs on any one wall in the formers and on both walls in the latter.) In addition, the facts that the optimum spacings for the transitory stall and fully-developed stall diffusers were practically equal and that none of the spacings tested helped improving the performance of the jet flow diffuser also suggest that vortex interaction has secondary or minor role in improving performance when compared with the vortex strength generated by the generators. Thus, a new design with stronger vortex strength than the one employed here is needed for the jet flow diffuser. In light of this, the more appropriate boundary layer thickness that should be used to correlate the data should be the momentum thickness and the more appropriate parameters of vortex generators should be, for the relative height, $h/\delta_2$ and, for the spacing, $\delta_2/S$. The data for $\delta_2/S$ in this experiment are given in Table 1.

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| Case | $B$ | $C_p$ | $k$ | $D_{min}$ | $D_{max}$ | $\Delta D$ | $\sigma_{Cpt}$ |
|---|---|---|---|---|---|---|---|
| T0 | 0.081 | 0.14 | 0.71 | -0.64 | 0.79 | 1.43 | 0.23 |
| T15 | 0.106 | 0.18 | 0.68 | -0.53 | 0.66 | 1.19 | 0.20 |
| T19 | 0.114 | 0.18 | 0.67 | -0.54 | 0.66 | 1.20 | 0.21 |
| T25 | 0.124 | 0.21 | 0.67 | -0.51 | 0.61 | 1.12 | 0.19 |
| T37 | 0.140 | 0.20 | 0.68 | -0.50 | 0.61 | 1.11 | 0.20 |
| T75 | 0.190 | 0.20 | 0.67 | -0.50 | 0.63 | 1.13 | 0.18 |
| F0 | 0.078 | 0.15 | 0.69 | -0.62 | 0.82 | 1.44 | 0.24 |
| F15 | 0.104 | 0.17 | 0.66 | -0.55 | 0.70 | 1.25 | 0.23 |
| F19 | 0.114 | 0.18 | 0.65 | -0.53 | 0.70 | 1.23 | 0.24 |
| F25 | 0.124 | 0.19 | 0.65 | -0.53 | 0.68 | 1.21 | 0.24 |
| F37 | 0.141 | 0.17 | 0.67 | -0.55 | 0.67 | 1.22 | 0.25 |
| F75 | 0.190 | 0.16 | 0.68 | -0.59 | 0.67 | 1.26 | 0.25 |
| J0 | 0.071 | -0.02 | 0.83 | -1.34 | 1.79 | 3.13 | 0.28 |
| J15 | 0.104 | -0.01 | 0.84 | -1.38 | 1.72 | 3.10 | 0.25 |
| J19 | 0.111 | -0.00 | 0.84 | -1.28 | 1.55 | 2.84 | 0.24 |
| J25 | 0.125 | 0.01 | 0.84 | -1.22 | 1.44 | 2.66 | 0.23 |
| J37 | 0.134 | 0.00 | 0.84 | -1.27 | 1.48 | 2.75 | 0.23 |
| J75 | 0.187 | -0.01 | 0.85 | -1.35 | 1.56 | 2.91 | 0.23 |

Table 3. Summary of the performance data.

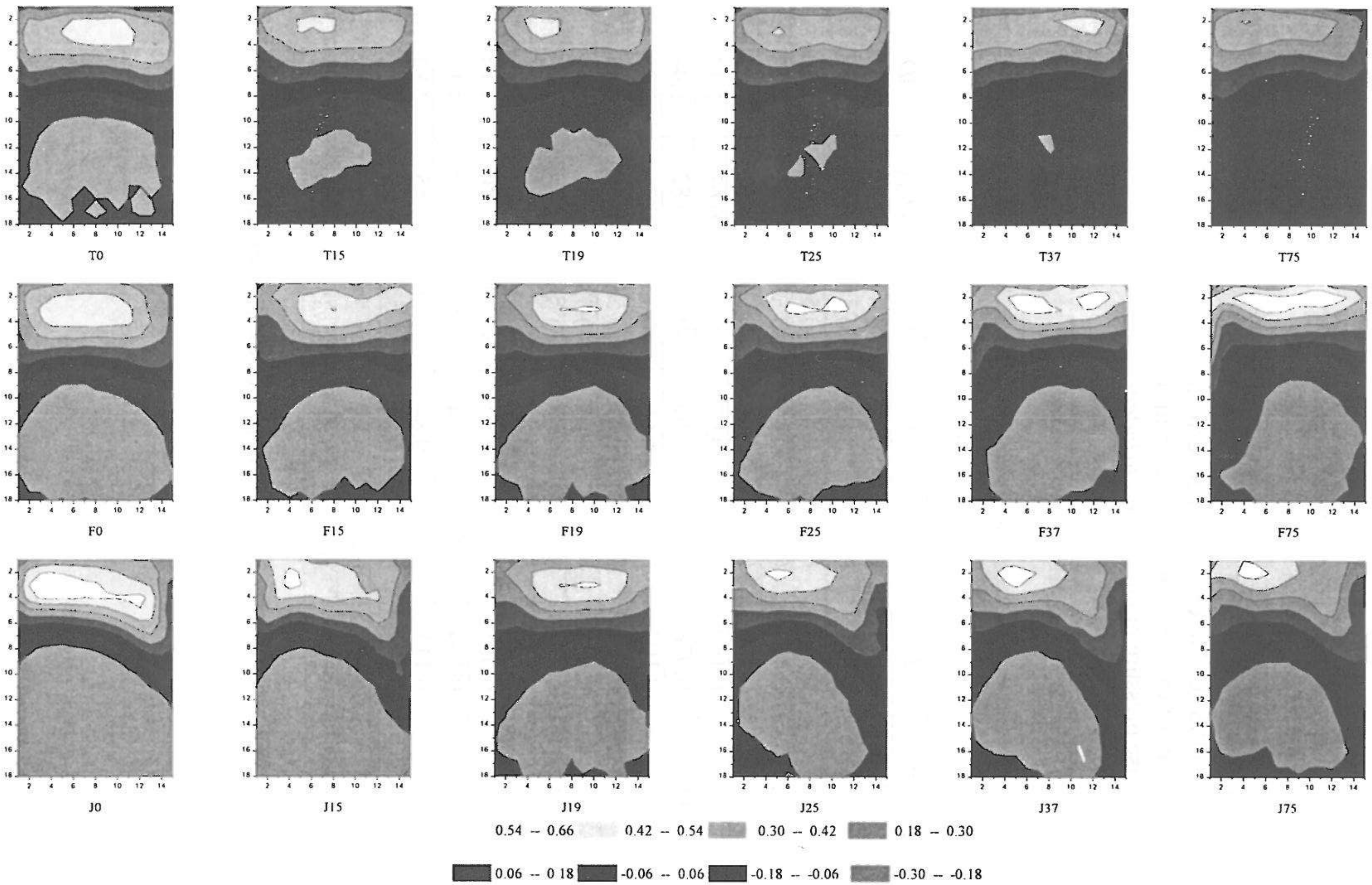


Fig. 5. Total pressure distributions.