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# Detection of Separation in S-duct Diffusers using Shear Sensitive Liquid Crystals

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***Abstract*** : In the present experimental investigation, shear sensitive liquid crystals have been successfully used to study the flow characteristics and detect separation in two-dimensional S-duct diffusers of different curvatures. Tapered-fin vortex generators in two different orientations were used to control flow separation that was observed on one of the curved walls of the diffuser. The results were verified by conventional oil flow visualization technique and excellent agreement was observed. In addition to visualization, detailed measurements that included wall static pressure, skin friction, diffuser exit total pressure and velocity distributions were taken in a uniform inlet flow with Reynolds number of 3.49 x $10^5$. These results are presented here in terms of skin friction distribution, distortion and total pressure loss coefficients. The extent of the separation zone (in terms of intensity of red distribution) in the diffuser with and without vortex generators (in both configurations) compared well with the Preston tube measurements. The present study demonstrates that shear sensitive liquid crystals can be efficiently used to study the flow physics in complex internal flows. In addition, the results also indicate that shear sensitive liquid crystals can be effectively used not only as flow visualization tool but also to gain quantitative information about the flow field in internal flows.

***Keywords*** : Liquid crystal, Visualization, S-duct diffusers, Flow separation.

## 1. Introduction

Flow visualization is a very basic but immensely useful tool in fluid mechanics research especially in understanding the physics of complex flows. In flow situations where the nature of the boundary layer, location of separation and reattachment are to be determined and studied, surface flow visualization is the commonly employed means. The conventional method of surface flow visualization using oil flow method has a disadvantage that it can only give qualitative results. Shear sensitive liquid crystals on the other hand can give quantitative results in addition to flow visualization. Liquid crystals are available in wide bandwidths of operation ranging from low subsonic to hypersonic speeds.

Shear sensitive liquid crystals have been used for surface flow visualization in aerodynamic testing in the early 1990s. Smith (1992) reviewed the use of shear sensitive liquid crystals in flows involving laminar-boundary layer transition, laminar separation bubbles, shocks and flow separation. Reda and Aeschliman (1992) conducted experiments to test the capabilities of shear sensitive liquid crystals in hypersonic flow. Abrupt changes in surface shear stress were observed in terms of sudden changes in liquid crystal coating color. The experiments were performed for various angles of attack of the cone and the response of the coating was recorded using high-speed cameras. In was concluded that the liquid crystal technique was a feasible visualization and analysis tool for use in compressible and even transient flows.

Reda and Muratore (1994, 1997) observed that the liquid crystal color response to shear depends on both magnitude of shear stress as well as the direction of the applied shear relative to observer's line of sight and later developed an improvised methodology for the measurement of surface shear stress vector distributions. The liquid crystal color distribution was quantified in terms of shear stress using a wall jet arrangement.

Reda et al. (1997) described the use of liquid crystals in simultaneous visualization of transition and flow separation on the wings of a commercial transport aircraft model. Two opposing-view color video cameras were used; one with a downstream view of the surface and the other with an upstream facing view. Wilder and Reda (1998) carried out uncertainty analysis of shear stress vector measurement using liquid crystal method. The effects of number and spacing of images and the flow-induced noise on the image analysis procedure were examined. It was observed that liquid crystal color change response is insensitive to local surface inclinations less than 15 degrees and hence the shear vector measurement method could be applied to moderately curved surfaces, too.

Buttsworth et al. (1998) used nematic liquid crystals unlike Reda and group (1992 - 1998) who used cholesteric crystals, for full surface skin friction measurement. A mathematical model describing the molecular dynamics of the nematic liquid crystal layer was proposed and the estimated skin friction from this model was observed to be in excellent agreement with the experimental results. Ireland and Jones (2000) reviewed the use of liquid crystals for measurement of heat transfer and shear stress. The mechanism of two types of liquid crystals namely, nematic and cholesteric, were discussed.

Reda and Wilder (2001) studied the effect of upstream and downstream viewing of the liquid crystal coating through transparent test surfaces. It was observed that the color pattern reverses with change in viewing orientation from upstream to downstream and vice-versa.

Liquid crystal coating was used to visualize the flow separation and reattachment downstream of a backward facing step and on a delta wing by O'Brien and Zhong (2001). It was observed that the location of separation and reattachment could be identified from the spatial color variation. Comparison was made with the surface flow visualization using oil flow method and good agreement was achieved. In a later study, Zhong (2002) used the same technique to study the flow characteristics over a two-dimensional airfoil.

Sullerey et al. (2002) studied the effectiveness of tapered-fin vortex generators and boundary layer fences in improving performance of S-duct diffusers by secondary flow control. In subsequent studies Sullerey and Pradeep (2002, 2003) effectively used tapered fin vortex generators to control flow separation in S-duct diffusers with and without inflow distortion.

Almost all the studies so far conducted using shear sensitive liquid crystals were focused on external flow situations. The aim of the present experimental investigations however, was to study the effectiveness of shear sensitive liquid crystals in the detection of flow separation in complex internal flows of S-duct diffusers of varied curvatures. Tapered-fin vortex generators in two different orientations were employed to control flow separation and liquid crystals were used to determine their effectiveness. The results were verified using the conventional surface oil flow visualization. The diffusers had radius ratios of 2, 4 and 6 with area ratio 1.39 and were scaled models of the diffusers used in previous experiments (Sullerey et al. (2002, 2003)). In addition to visualization, detailed measurements that included wall static pressure, skin friction, diffuser exit total pressure and velocity distributions were taken in a uniform inlet flow with Reynolds number, Re, $3.49 \times 10^5$. The results of radial skin friction distribution determined using Preston tubes were applied to validate the visualization results.

## 2. Nomenclature

AR = area ratio of the diffuser
$C_f$ = skin fiction coefficient
$D_c$ = distortion coefficient = $(p_{oav} - p_{omin}) / q_{av2}$
R = duct centerline radius of curvature
V = fluid velocity

| | |
|---|---|
| w | = diffuser width |
| y | = distance along duct centerline radius from inner wall of the diffuser |
| z | = distance along diffuser height from the bottom of the diffuser |
| h | = diffuser height (constant) |
| $p_o$ | = total pressure |
| q | = dynamic head |
| r | = inlet half width |
| $\rho$ | = fluid density |
| $\varpi$ | = average total pressure loss coefficient = $(p_{o1} - p_{o2av}) / (1/2\rho V_\infty^2)$ |

Subscripts

| | |
|---|---|
| av | = average value |
| min | = minimum value |
| 1,2 | = notations for inlet and exit planes |
| $\infty$ | = free stream value |
| o | = total pressure |

# 3. Experimental set up

The measurements were carried out in an open-circuit wind tunnel. A blower discharged air through a diffuser into a large settling chamber with a honeycomb and three sets of wire mesh screens. A contraction section of an area ratio of 12 accelerated the flow into the test section entrance of cross-section area of 89 mm (width) x 71 mm (height). A large contraction ratio ensured a uniform flow at the inlet. The measured free stream turbulence level of the inlet flow was less than 0.1 percent. Between the contraction and the S-duct diffuser, a straight duct of 120 mm length was provided to obtain fully developed, zero pressure gradient turbulent boundary layer at the diffuser inlet. Figure 1 gives a sketch of the tunnel contraction and the test section along with the camera and lighting orientations (to be discussed in subsequent sections). Detailed velocity measurements were carried out across the diffuser inlet (free-stream) and in the inlet boundary layers. The diffuser inlet flow was kept uniform with an average wall boundary layer momentum thickness equal to 0.28 percent of the inlet width. The tests were carried out at a Reynolds number of 3.49 x$10^5$ based on the diffuser inlet width. A constant area duct extension of 80 mm length was also placed at the diffuser exit to provide smooth, continuous flow exiting the duct.

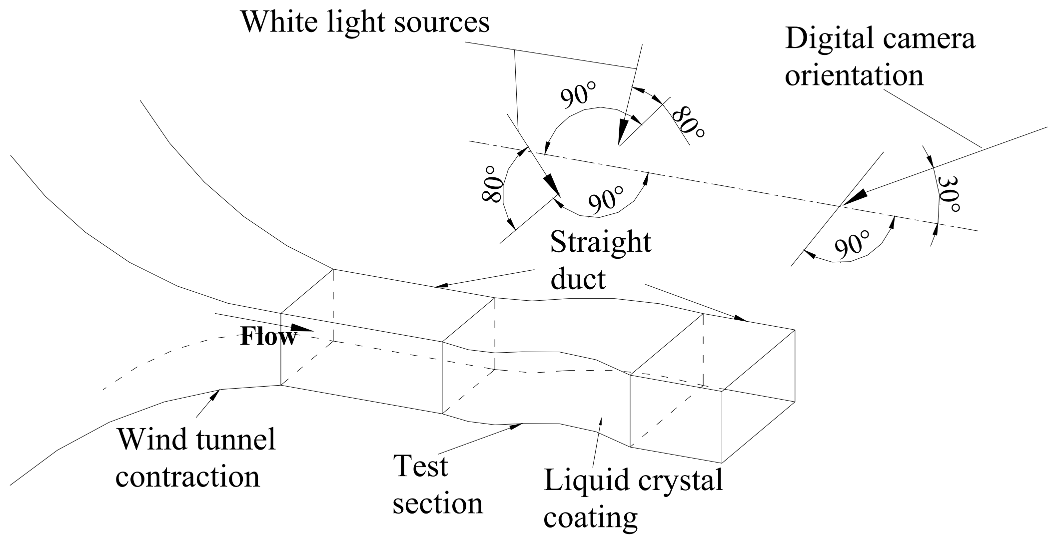



Fig. 1. Schematic of the experimental set-up.

### *3.1 S-duct diffusers*

The diffusers on which the experiments were carried out had a rectangular cross-section with an aspect ratio of 0.8 at inlet and exit-to-inlet area ratio of 1.39 (Fig. 2). To increase the area, the diffuser width was varied along the duct centerline while keeping the height constant. The width was equally distributed normal to the centerline. The radius ratis (ratio of diffuser centerline radius to half inlet width) of the diffusers were kept at 2, 4 and 6. Two planar circular arcs with identical radii defined the duct centerline. Figure 2 gives the diffuser geometries with the respective dimensions. The diffusers were fabricated using high quality Perspex. The lower wall was made of opaque black Perspex while the other walls consisted of transparent Perspex. The black Perspex wall was for coating the liquid crystals so as to maximize the intensity of the liquid crystal color distribution.

### *3.2 Vortex generators*

Tapered fin vortex generators (VG) were used with the intention of controlling flow separation. The vortex generator designs are shown in Fig. 2 alongside the diffuser geometry. The geometry chosen for control of flow separation was similar to the one given by Sullerey and Pradeep (2002). The vortex generators were used to produce a pair of co-rotating vortices and were made from 3mm aluminum sheet. These were fixed firmly to the diffuser outer wall (refer Fig. 2 for definition of outer wall) at the plane of separation. The exact orientation and placement of VG was based on Sullerey and Pradeep (2002). Two configurations of the VG were used namely +VG and –VG configurations (based on the terminology used by Reichert and Wendt (1996)) as shown in Fig. 2. Both the VG configurations produce a pair of co-rotating vortices. In the +VG configuration, boundary layer fluid is directed inward and toward the VG array center while in the –VG configuration, the boundary layer fluid is directed away from the array center.

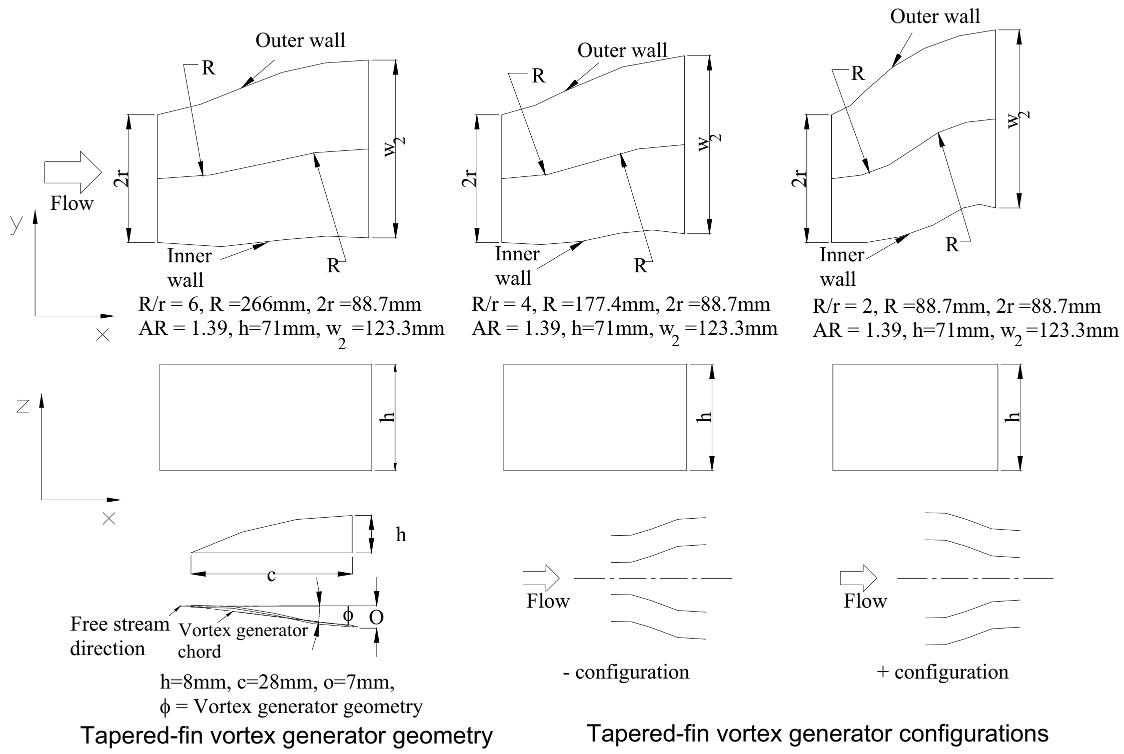



Fig. 2. S-duct diffusers and tapered-fin vortex generator geometries.

# 4. Instrumentation and measurement techniques

### *4.1 Liquid crystal coating*

The shear sensitive liquid crystals (BCN-192) used in the present experiments were supplied by M/s Hallcrest Inc. and had a bandwidth of 30 $ms^{-1}$ to 70 $ms^{-1}$ with a clearing point temperature of about 48℃. In order to coat the liquid crystals, the crystals were first dissolved in acetone and then carefully sprayed on to the surface using an artist's airbrush. The surface to be coated was thoroughly cleaned with acetone and dried to remove any traces of dirt, grease or other chemical contaminants. The thickness of the layer was estimated to be around 10μm based on the weight of the crystals used, area of coverage and approximate spraying losses. The crystal coating after spraying and drying showed a uniform rusty red color.

The coatings were illuminated using two 500W white light sources set at nearly normal direction and on either side of the test surface as shown in Fig. 1. Two light sources on either side were required as a single light source placed above the test section resulted in glare from the Perspex top wall. The illumination angles were 80 degrees in the vertical plane. The coating was viewed at a shallow angle of around 30 degrees (in the vertical plane) downstream. The angles of illumination and viewing were 90 degrees in the horizontal plane. These angles of illumination and viewing were arrived at after trying out several combinations. The optimum angle depends upon the experimental set-up and type of flow situation being studied. Hence there cannot be a universal optimum angle that can be used for all the cases. Fujisawa et al. (2003) in their extensive study on effect of viewing and illumination angles have given some guidelines on the optimum angles. However, the angles given by Fujisawa et al. (2003) could not be used here as the present study was on internal flows where the illumination and viewing angles are restricted because of glare from the test section upper surface and proper optical access to the test surface. To eliminate stray ambient light from interfering with the coating pattern, the whole set up was isolated by means of a dark room arrangement. A high-resolution color still digital camera (2,048 x 1,536 pixel resolution) was used for recording the images.

Though it is customary to express liquid crystal pattern quantitatively in terms of hue, it was observed that the dominant color that varied in the present experiments was red and hence the quantitative results are presented in terms of intensity of red because the primary objective of quantitative analysis in the present study is to detect separation and study the effectiveness of VG. The image analysis was carried out using the image processing toolbox of MATLAB. The RGB values of each pixel were determined and the intensity of red at the exit plane of the diffuser (in a direction perpendicular to the free stream) was plotted for analysis. This method avoids the conversion of the RGB images to HSI system. A low pass filter was used to reduce local standard deviation of intensity of hue as suggested by Reda et al. (1997).

### *4.2 Instrumentation*

The measurements included diffuser wall static pressures, mean velocities, boundary layer and skin friction. A Furness (FCO510 model) digital multi-channel micro-manometer (range, up to 200.0 mm of water) was used for all pressure measurements. The static pressure measurements were taken with wall pressure tapings at nine stations on each diffuser.

The skin friction measurements were made using wall mounted Preston tubes of 0.6 mm diameter. These were fitted axially along the centerline of inner and outer walls and radially (along the width of the diffuser) at different locations on the top wall at nine stations. The Preston tubes were calibrated using linear voltage displacement transformer (LVDT) displacement sensor based floating element shear stress sensor (described in detail by Sullerey and Pradeep (2003)). The skin friction measurements are expected to be within 2 percent accuracy. The Preston tubes were fitted radially after the liquid crystal experiments so as to avoid interference with the liquid crystal images.

The boundary layer measurements were made on all four walls at inlet and the exit planes of the S-duct diffuser. A 0.8 mm diameter pitot probe was used for this purpose. The total pressure and velocity measurements were made using a pitot static probe of diameter 2.0 mm. For probe traverse, an accurate three-dimensional traverse system (least count 0.5 mm) was used. The total pressure and velocity measurements are expected to be within one percent accuracy (based on multiple measurements at the same location).

## 5. Results and discussions

Flow over a backward facing step has been extensively studied and therefore initial experiments were carried out on a backward facing step to validate the liquid crystal methodology presently used. The backward facing step had an aspect ratio of 0.25 and an area expansion ratio of 1.5. The Reynolds number based on the width was $4.9 \times 10^5$. Both liquid crystals as well as oil flow visualization were carried out. The visualization revealed the four distinct regions in the flow as observed by O'Brien and Zhong (2001). The oil flow pattern too gave results similar to those obtained using liquid crystals.

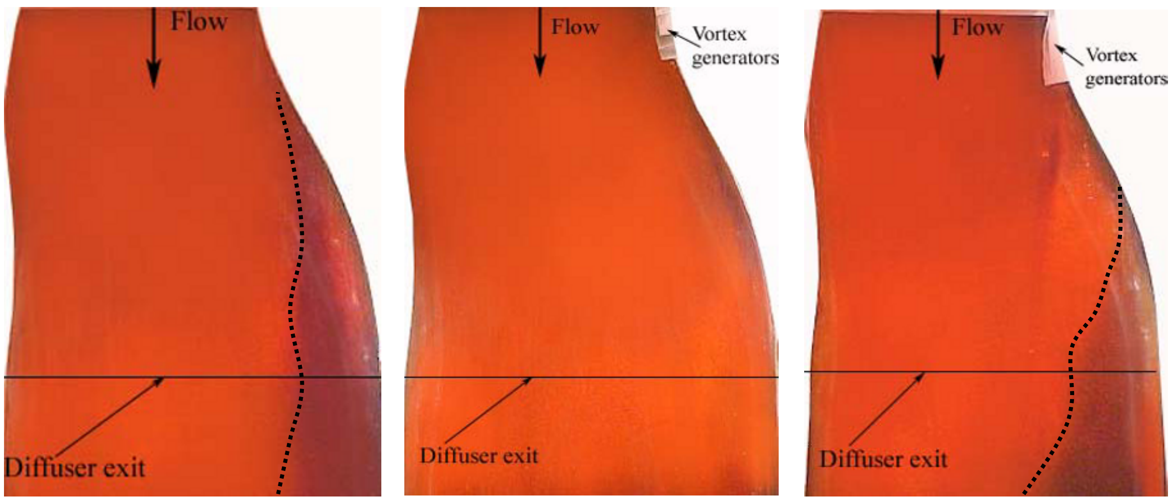
The reattachment length was approximately 7 step heights from liquid crystal measurements and about the same with Preston tube measurements and oil flow visualization. The present results compare well with those of O'Brien and Zhong (2001) who obtained a reattachment length between 5.5 and 7 step heights.

Subsequently, experiments were carried out with the S-duct diffusers for radius ratios 2, 4 and 6, both without and with tapered fin vortex generators (VG). Liquid crystal visualization results for backward facing step and diffuser with radius ratio 4 are not being presented for reasons of brevity. Oil flow visualization results are being presented only for diffuser with radius ratio 2.

### *5.1 Diffuser 1 (radius ratio 6)*

The non-uniformity in flow is higher on the outer wall (as observed from the total pressure distribution at the diffuser exit) due to increased curvature. The boundary layer hence has greater tendency to separate on the outer wall.

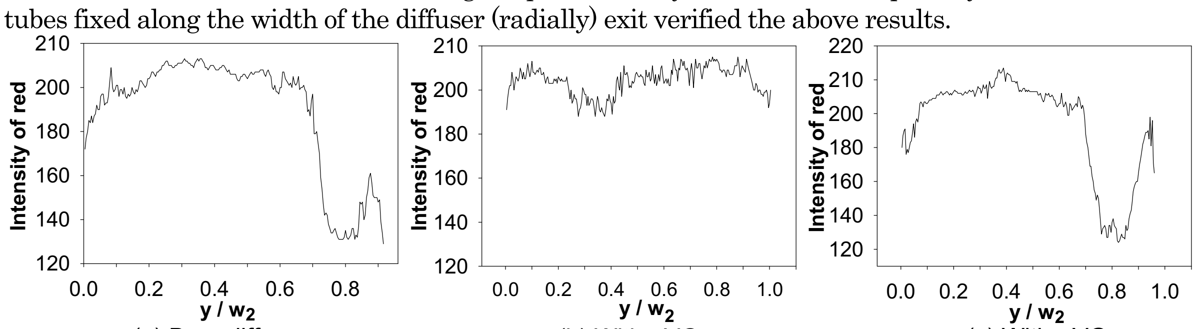
The liquid crystal visualization results given in Fig. 3(a) confirm the above observation. In Fig. 3(a), a broad region of separation on the outer wall can be observed. The +VG configuration resulted in elimination of the separated region as shown in Fig. 3(b). Figure 3(a) shows that +VG was effective in controlling and completely eliminating separation.




(a) Bare diffuser (b) With + VG (c) With - VG

Fig. 3. Liquid crystal pattern with and without VG.

The same was verified using the intensity of red distribution shown in Figs. 4(a), 4(b) and 4(c) along the width of the diffuser at the exit plane. The low red intensity region (about 30 percent of the diffuser width in Fig. 4(a)) has been eliminated with +VG as can be seen in Fig. 4(b). On the other hand, with -VG, the extent has in fact increased. The extent of separation with –VG is around 40 percent of the width of the diffuser. Oil flow visualization too gave patterns very similar to the liquid crystals and the Preston tubes fixed along the width of the diffuser (radially) exit verified the above results.




(a) Bare diffuser (b) With +VG (c) With - VG

Fig. 4. Intensity of red distribution with and without VG.

The radial Preston tubes were intended to detect the extent of separation. Figure 5 gives the radial skin friction distribution in the bare diffuser, with +VG and –VG. The extent of separation in the bare diffuser was between the seventh and ninth Preston tubes and the separation has been completely overcome with +VG as is clear from Fig. 5. Thus the figure validates the observations from the liquid crystal visualization.

From Fig. 5 it can be seen that the skin friction goes to zero at about 70 percent of the diffuser exit width. With +VG, separation has been overcome. However, with –VG, separation exists even at 50 percent of the diffuser width that confirms that –VG configuration further deteriorates the separation region.

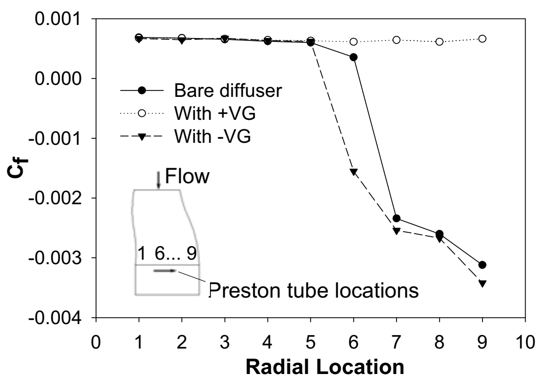


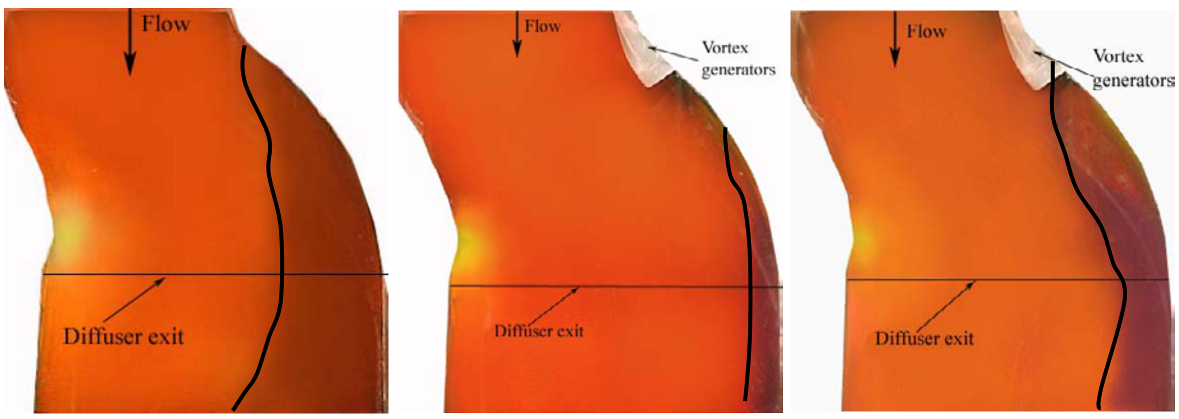
Fig. 5. Radial skin friction distribution.

The liquid crystal distribution can be used to obtain the separation point. The radial intensity of red distribution is taken at several axial locations. The intensity of red distribution at the diffuser exit plane is given as Fig. 4. The point at which there is a sudden drop in intensity of red is an indication of the beginning of the separated region. Therefore beginning from the diffuser exit, intensity of red distribution at several axial locations upstream were taken. The locus of all these points where intensity of red drops drastically is drawn as shown by the dotted line in the liquid crystal distribution. At the separation point, the dotted line touches the wall as is clear in Fig. 3. The region between the dotted line and the wall is the separated region.

## *5.2 Diffuser 2 (radius ratio 2)*

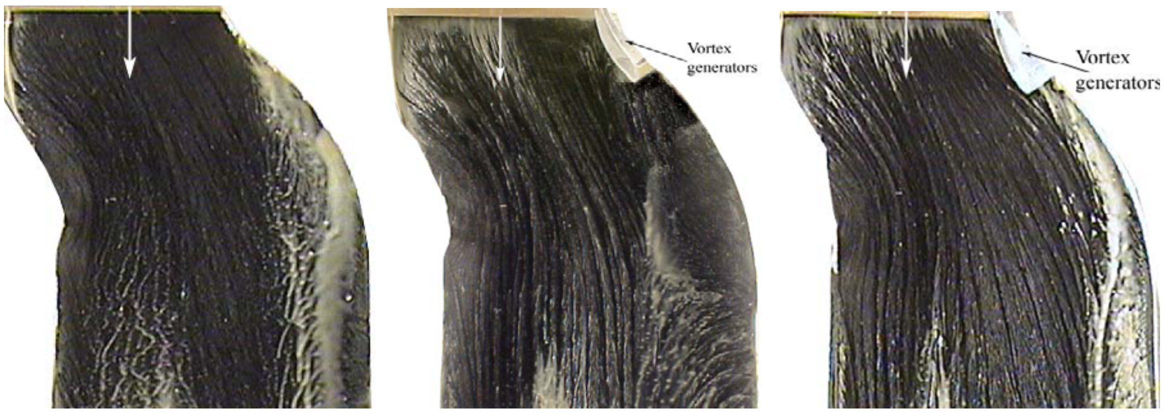
This diffuser to be tested was one with a very high centerline curvature of radius ratio 2. The flow non-uniformity as observed in the liquid crystal pattern is much more pronounced in this diffuser (as shown in Fig. 6(a)) compared to the previous diffuser. The VG that was used in diffuser 1 was not effective in controlling separation. This is due to the severe adverse pressure gradient on the outer wall. Therefore, another set of VG (both – and + configurations) with a height 1.2 times the previous VG height was used. As is evident from Fig. 6(b), + VG configuration improves the flow uniformity to a much greater extend than –VG arrangement (Fig. 6(c)). The oil flow visualization given in Figs. 7(a), 7(b) and 7(c) confirms this observation. The extensive separated region in the bare diffuser has been reduced considerably with +VG arrangement, though not fully eliminated. The –VG configuration too reduced the separation region but to a much lesser degree than +VG.

The visualization results for diffuser 3 (radius ratio 4) were similar to diffuser 1 and diffuser 2. +VG configuration was again found to be very effective in separation control compared to –VG. The dotted line shown in Fig. 6 is the locus of the points where the intensity of red drops significantly. The region within the dotted line and the wall is the separated region and the point where the dotted line touches the wall is the separation point.



(a) Bare diffuser (b) With +VG (c) With -VG

Fig. 6. Liquid crystal pattern with and without VG.




(a) Bare diffuser (b) With +VG (c) With -VG

Fig. 7. Oil flow pattern with and without VG.

Table 1 summarizes the results of separation control in all the three diffusers in terms of distortion coefficient and mass averaged total pressure loss coefficients. The effectiveness of +VG configuration is very much evident from the table. The results of the present study compare well with the previous investigations (Sullerey and Pradeep, 2002, 2003) that were carried out at a Reynolds number of 7.8 x $10^5$.

Table 1. Comparison of flow non-uniformity with and without VG.

| | Bare diffuser | | With +VG | | With -VG | |
|---|---|---|---|---|---|---|
| Performance parameter | $\varpi$ | Dc | $\varpi$ | Dc | $\varpi$ | Dc |
| Diffuser 1 (R/r=6) | 0.172 | 0.691 | 0.100 | 0.565 | 0.178 | 0.711 |
| Diffuser 2 (R/r=2) | 0.443 | 0.874 | 0.422 | 0.816 | 0.436 | 0.863 |
| Diffuser 3 (R/r=4) | 0.391 | 0.842 | 0.344 | 0.762 | 0.398 | 0.853 |

Quantification of oil flow visualization results is prone to serious errors due to issues like non-uniformity of the oil mixture and its coating. Whereas liquid crystals are spray coated after mixing with a solvent and hence is free from such errors. Calibration of liquid crystals for wall shear stress is much more easier compared to oil flow as the liquid crystal color changes with shear stress, where as it is the thickness of the oil film in the case of oil flow that is an indication of wall shear stress.

# 6. Conclusions

Shear sensitive liquid crystals were used to detect flow separation in S-duct diffusers with different centerline curvatures. The flow pattern obtained from the liquid crystal coatings were quantified in terms of intensity of red distribution and the results were verified using Preston tube measurements and the conventional surface oil flow visualization method. The extent of separation at the exit of the diffuser with radius ratio 6 was about 20 percent of the diffuser width and with +VG, the separation was completely eliminated. In diffuser with radius ratio 2, the extent of separation was around 35 percent of the diffuser width while with +VG, the extent reduced to 8 percent.

Tapered fin vortex generators were successfully employed to control flow separation and it was observed that the orientation of the vortex generators plays an important role in separation control as improper placement may have adverse effect on the flow quality. The diffuser total pressure loss and distortion coefficient results (in addition to the liquid crystal and oil flow visualizations) indicate that separation can cause the outflow to be highly non-uniform. Efficient control of separation and hence improvement in outflow quality is possible by judicious deployment of vortex generators.

The use of liquid crystals in internal flows in more complicated than external flows as the viewing angles possible in internal flows are very restricted and coating the liquid crystals on the test surface is much more complicated. The present study demonstrates that shear sensitive liquid crystals can be efficiently used to study flow physics in complex internal flows like ducts and diffusers, cascades and other turbo machinery applications in spite of the difficulties.

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