

The Distribution of Surface Shear Stress surrounding a small Protuberance in Supersonic Flow

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Abstract:

The local surface shear stress around small triangular protuberances in supersonic flow has been measured, quantitatively and qualitatively, using calibrated Liquid Crystals. Measurements were taken within a turbulent boundary layer on the floor of a Mach 3.8 wind tunnel using high speed image capture of 1000 fps. Results are presented of the distribution of the shear stress values upstream and downstream of the protuberance as well as the streamwise distribution at the side of the protuberance. It is shown that shear stress patterns for protuberances at an inclined angle to the boundary layer, the bow shock is asymmetrical producing stress levels some 80% higher than that of the freestream boundary layer flow.

Key Word: Supersonic Flow, Surface Shear Stress, Protuberance, Liquid Crystals

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I. Introduction

It is well understood that small protuberances on the surface of high speed aerodynamic platforms produce complex flow structure interactions. Such complex flows are the result of either shock–boundary layer interactions or shock-shock interactions in supersonic or hypersonic flows. The protuberance produces changes in the local surface pressure distribution and can modify the surface heating loads, [1]. The detail of the complex flow interactions has been the subject of many experimental and computational studies for a number of different high speed cases ranging from Mach 1 to Mach 12, [2 – 5].

Early work on this subject established the criteria concerning the interaction of the boundary layer, laminar or turbulent, with the bow shock generated by a small surface protuberance in such flow regimes. Indeed, the interaction of the oncoming turbulent boundary layer to a protuberance is known to develop a lambda shock wave pattern culminating in two shock waves; boundary layer shock wave interference, and a bow shock ahead of the protuberance, [6].

A number of studies have dealt with different geometrical features of a protuberance, namely geometric pattern of the protuberance in relation to the boundary layer height. One such numerical study has revealed that in order to reduce the increase in side force created by the presence of a hemisphere-cylinder protuberance on a slender body at Mach 1.5, the height to width ratio should be reduced with the condition that the volumetric value of the protuberance remains constant, [3]. However, various protuberance configurations have been analysed, including cylindrical planforms as well as square planforms, along with some small spherical and triangular shapes for tripping the boundary layer, [7 – 9].

The complex flow arising from the presence of a protuberance has been studied with a myriad of experimental techniques as well as being analysed using CFD simulations. These techniques have ranged from pressure probe measurements using miniature pressure taps on the model and protuberance, pressure sensitive paints, to flow visualization techniques such as Schlieren, shadowgraphy and surface oil flow methodologies, [10], to more advanced optical approaches such as nanoparticle-based planar laser scattering [7], as well as measuring the thermal influence of small protuberances using thermo gauges and temperature sensitive paints, [2]. Indeed, many of the complex flow regimes associated with a protrusion located within the turbulent boundary layer of supersonic and hypersonic flows have been highlighted and the aerodynamic forces on the obstruction analysed. Nevertheless, very few studies have been undertaken to determine the global surface shear stress associated with a protuberance mainly because of the difficulties in measuring this parameter. Point measurements, using fast response shear stress transducers, are not very practical since they do not provide a clear indication of the extent of the surface flow conditions. However, there is one technique available that is able to provide a global evaluation of the surface shear stress around a protuberance that has not been used extensively, and that is the use of shear stress sensitive Liquid Crystals (S³LC).

II. Experimental Investigations

The method of determining surface shear stress using shear sensitive liquid crystals is widely known and has been the subject of many studies over the past 50 years or more [11]. In principle, these crystals possess a structure of both a solid (crystalline) and a liquid (isotropic) thereby providing optical properties and aeromechanical properties, respectively. These properties are very beneficial in the measurement of heat transfer and aerodynamic forces (stresses) because they allow investigations of the full-field distribution rather than at a single point.

Shear stress sensitive liquid crystals (S3LC) are un-encapsulated liquid crystals that are sensitive to an external force (in this case shear stress) and do not react to temperature (for a particular range) by the addition of different compounds [12]. When acted upon by a shear stress the S3LC will display a range of colours dependent upon the direction of the shear stress and the illumination of the area, [13 – 14]. Digitized images of the field of view may be determined and stored in terms of Red (R), Green (G) and Blue (B) components which is often transformed into Hue (H), Saturation (S) and Intensity (I), or Value (V) in order to overcome the problem with any light intensity of the original image. This transformation is of particular significance since the colour data is within the quantity H and is given in degrees demonstrating that Hue is an angular quantity with the primary colours R, G, and B having the Hue value of 0° , 120° , and 240° , as given in a colour-space transformation model, [15 – 16], with the shear stress ranging from Red (low SS) through Green to Blue (high SS).

For example, an algorithm used in the OpenCV library for Python Software users provides an HSV transformation of the form

$$H = \begin{cases} 60(G' - B') / (V - \min(R', G', B')), & \text{if } V = R' \\ 120 + 60(B' - R') / (V - \min(R', G', B')), & \text{if } V = G' \\ 240 + 60(R' - G') / (V - \min(R', G', B')), & \text{if } V = B' \end{cases} \quad (1)$$

$$S = \begin{cases} \frac{V - \min(R', G', B')}{V}, & \text{if } V \neq 0 \\ 0, & \text{otherwise} \end{cases} \quad (2)$$

$$V = \max(R', G', B') \quad (3)$$

$$\text{Where } R' = \frac{R}{255}, G' = \frac{G}{255}, B' = \frac{B}{255} \quad (4)$$

Previous experimental studies have included different methods of calibrating Hue against surface shear stress including aerodynamic as well as mechanical procedures. Aerodynamic calibrations have often used laminar or turbulent boundary layers in a wind tunnel or a circular jet across a flat plate, [17 – 18]. Mechanical calibrations have used purpose built rigs either of the planar form or of a circular geometry, [19 – 22].

The present work used a mechanical calibration rig, [22], with LC produced by Engineering & Scientific Innovations (ESI) using components supplied by Hallcrest and formulated by ESI under an agreement granted to ESI by Spotsee. A typical Hue versus Shear Stress calibration curve provides repeatable data sets for a particular production batch with a good 5th order polynomial fit and an R^2 value of better than 0.94, Fig 1. However, it should be noted that it is important for a calibration of the S³LC to be performed before any aerodynamic tests are conducted, and certainly performed if the LC batch is changed.

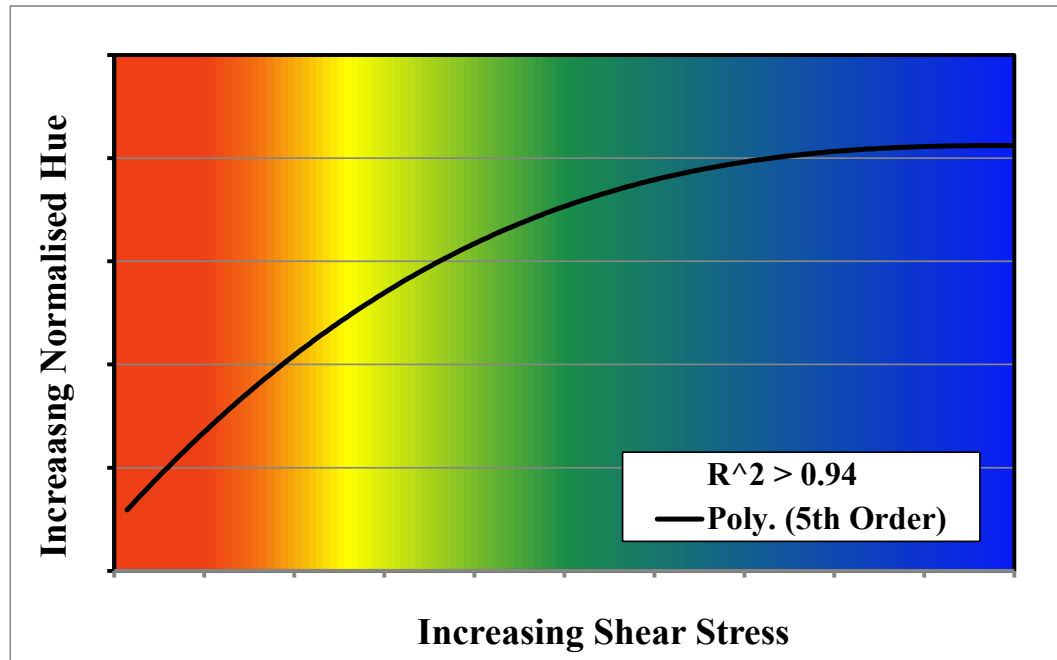


Fig 1: Typical Liquid Crystal – Shear Stress Calibration

III. Mach 3.8 Flow Facility

A purpose designed wind tunnel was constructed for this study that supplied a flow of Mach 3.8 into a test section 15.24 cm x 15.24 cm in cross-section and 0.9 m in length, Fig 2. This tunnel is of the blow down type with compressed air being released into a plenum chamber and expanded through a supersonic nozzle throat with a supersonic diverging length of 457 mm. The air then passes through the working section and exits through a supersonic diffuser. The run time of the facility is of the order of 10 seconds.

Shear stress analysis using the S³LC was carried out immediately below the centre of the viewing window, approximately 685 mm from the supersonic nozzle exit, with illumination of the target area being viewed with a clear line of sight. The Reynolds number based on working section length at this location was 2.32×10^7 . With this arrangement an area of approximately 40 mm wide and 60 mm in length was able to be observed and the protuberance was mounted at the prescribed location.

A synthesis of shear stress sensitive liquid crystal, using similar components of BCN165 and reformulated by ESI, was sprayed onto the area after it was thoroughly cleaned with Petroleum Ether and allowed to dry. A high-speed colour video camera, Chronos 2.1, operating at 1000 frames per second, was installed perpendicular to the test article and the area illuminated with a Halogen lamp at an angle of 45° to the vertical, upstream of the target area, Fig 2.

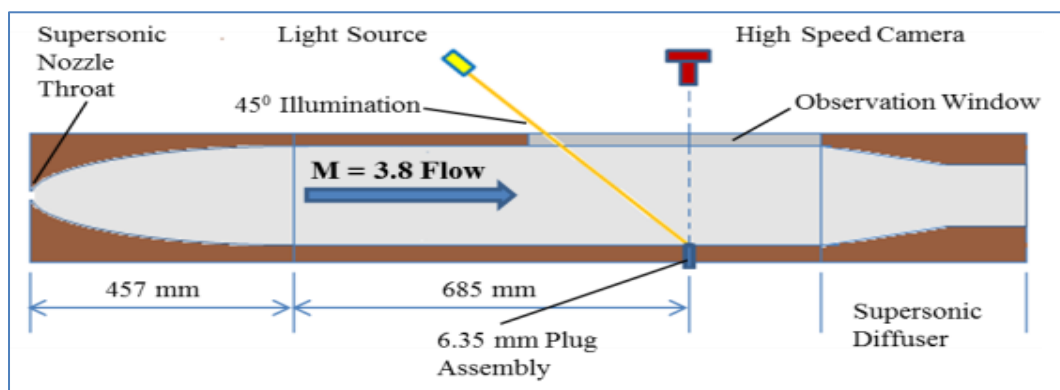


Fig 2: Test section of Mach 3.8 Wind Tunnel

A Pitot probe analysis of the boundary layer at this location provided a boundary layer thickness of approximately 20 mm based on the local velocity being about 99% of the freestream flow. However, it should

be noted that pressure within the plenum chamber did fluctuate between runs and every point in the boundary layer was a single run, thereby giving some small variations to the local boundary layer height. However, the form of the boundary layer profile was determined to be of a $1/5$ power law, which has been known to be acceptable for short duration supersonic wind tunnels.

Although a $1/7$ power law is often used to describe a turbulent boundary layer in supersonic flow for analytic purposes, it may not cover all particular properties of a given flow regime. It is conceivable the exponent of the power law can vary according to the local surface boundary layer flow conditions at such high speeds, such as the local temperature, pressure and density. Indeed, it has been suggested that the velocity profile for a $1/7$ power law may be described only when the thickness of the thermal boundary layer and the turbulent boundary layer are comparable, [23]. Even though their research concentrated on the flow through a conical nozzle, the difference in a power law of $1/7$, $1/5$ and $1/4$ was considered realistic for some flow conditions.

The Pitot probe traverse through the boundary layer on the floor of the tunnel at the measurement location suggested that the boundary layer was approximately $\delta = 20$ mm in depth, and has been plotted against a $1/5$ and a $1/7$ Power law, Fig 3.

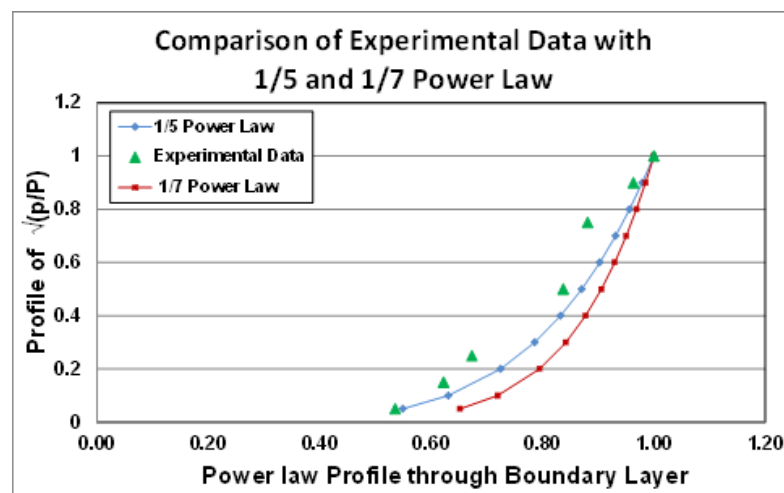


Fig 3: Comparison of experimental boundary layer data with Power Laws

Given that the experimental data is similar to that for the $1/5$ Power law, the Displacement thickness would be approximately $\delta^* = 3.3$ mm and the Momentum thickness $\theta = 2.4$ mm. This would infer that the Shape Factor of $H = 1.4$ is typical of turbulent flows, providing a boundary layer in the turbulent region, [24].

IV. Model Geometries

Three separate geometric triangular protuberances were produced on the surface of a 6.35 mm plug that could be mounted on the centreline of the floor of the wind tunnel. The surface of the plug was flush with the tunnel floor. Each of the models had a 20° half angle and were constructed such that they were at three different angle of incidence to the flow direction, being 0° , 30° & 60° , Fig 4. The base dimension was 4.08 mm and its overall length was 5.61 mm, with a plan area of 11.44 mm^2 .

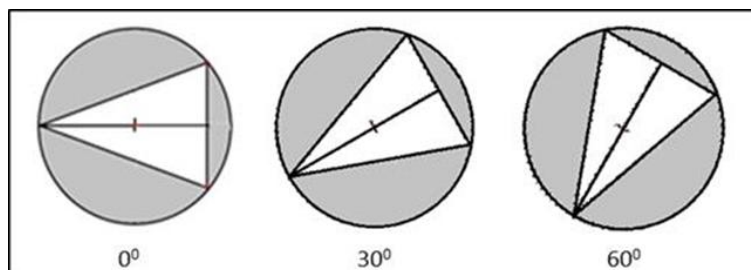


Fig 4: Three separate models at different Angle of Incidence to the Flow

Furthermore, two different model heights were analysed, one of 1.5 mm in height, and the other of 3.0 mm. The area blockage from these models ranged from 2.6×10^{-4} , for the 1.5 mm high model set at 0° incidence, to 7.6×10^{-4} , for the 3.0 mm high model set at 60° incidence, and it was considered that these

blockage ratios were very small and would not cause any tunnel flow instabilities. Furthermore, the choice of heights of the two model variations provided a model height of less than the momentum thickness for the 1.5 mm model, and a height larger than the momentum thickness for the 3.0 mm model.

Spanwise Shear Stress measurements were acquired at 5 upstream locations of -4, -5, -6, -8 and -10 mm determined from the center of the circular base, and 5 downstream locations of the same values, with streamwise measurements taken on the Starboard and Port sides of the protuberance at ± 4 mm from the center, Fig 5. For clarity, negative location values depict the upstream positions, and positive locations the downstream positions, with negative values for the Starboard side and positive values for the Port side. The shear stress values along each of the lines of interest was acquired by determination of the average value of Hue, Saturation and Value from a 11 x 11 pixel square (0.393 mm x 0.393 mm) and determined from a calibration curve, Fig 1.

Given that the static pressure within the plenum chamber fluctuated from one run to another which will affect the flow within the test section giving rise to small changes in the development of the turbulent boundary layer. It has been estimated that these small differences would result in changes in the local surface shear stress of the order of 6%.

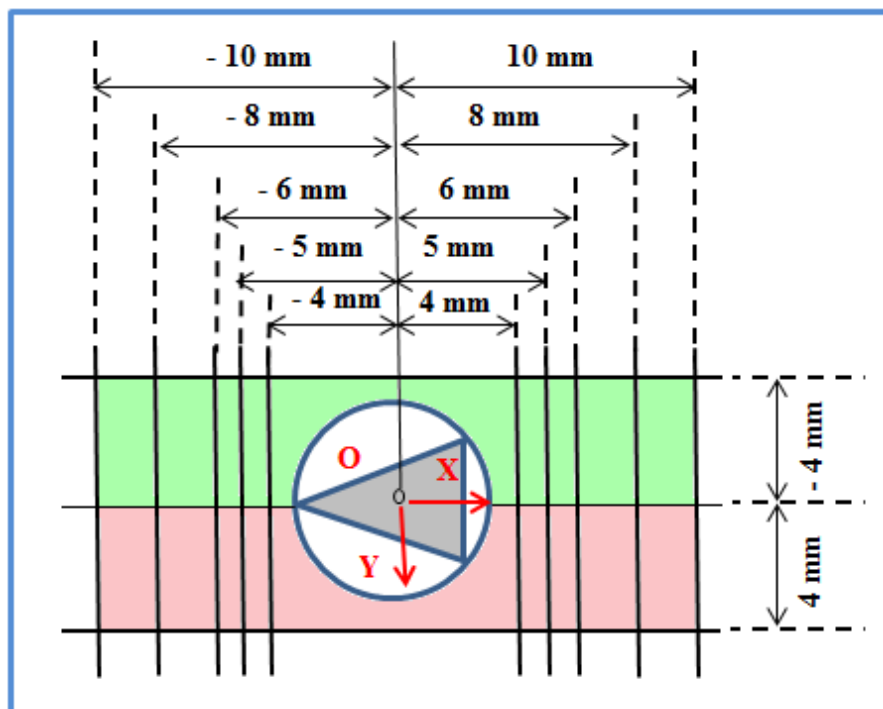


Fig 5: Shear Stress distribution around small triangular protuberances at different Angles of Incidence.

V. Results & Discussion

An analysis of the shear stress measurements around each of the protuberances set at each of the three angles of incidence to the oncoming boundary layer was carried out a minimum of 5 times and the results averaged to provide a clear sense of the shear stress distribution.

The following images are indicative of the shear stress distribution on the floor of the tunnel created by the presence of the small protuberances at each of the angles of incidence, Fig 6. However, these images are not necessarily those that were used in the shear stress analysis program, which was performed by specifically written, in-house, suite of programs.

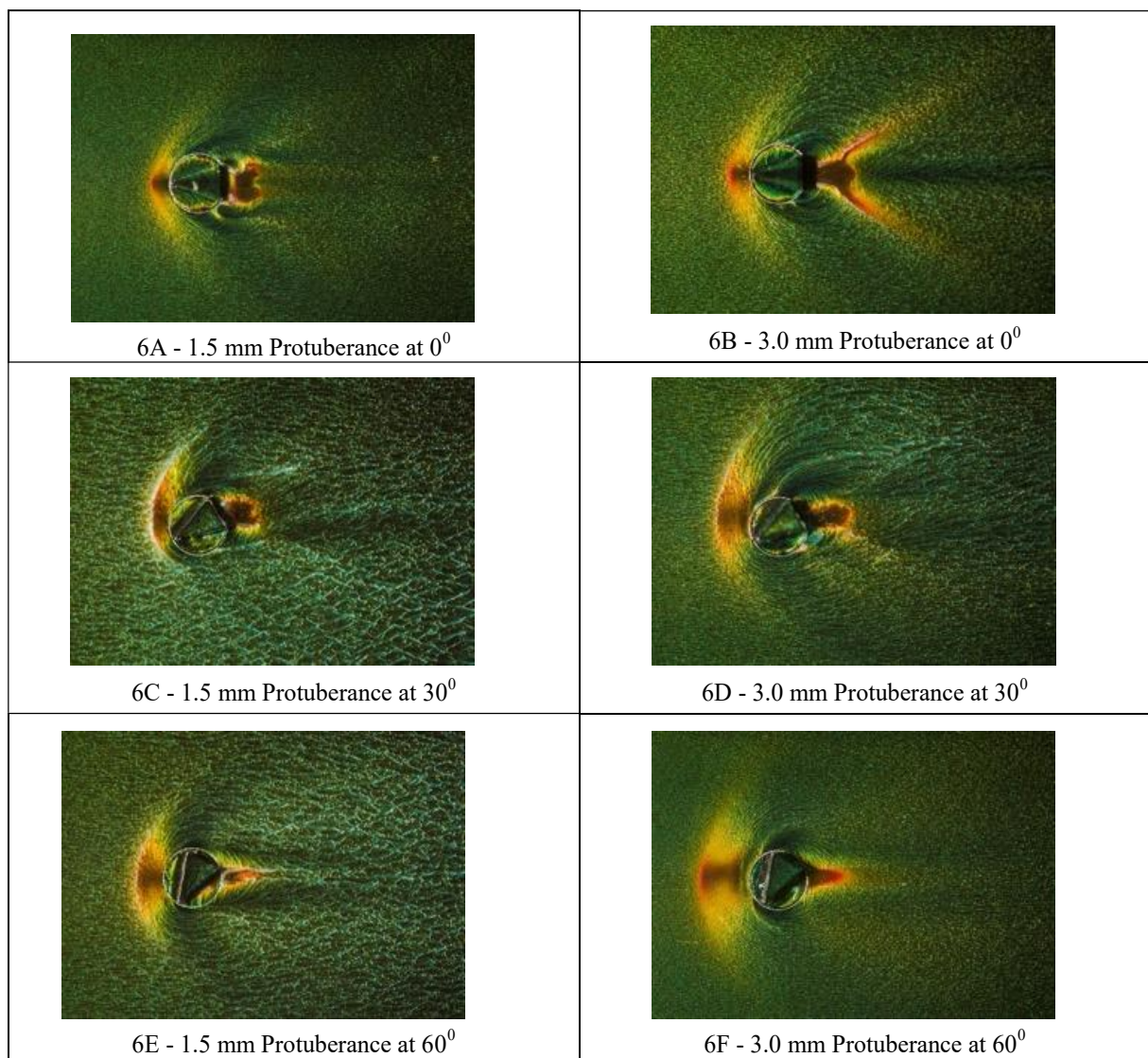


Fig 6: Shear Stress distribution around small triangular protuberances at different Angles of Incidence.

Visual inspection of the surface shear stress flow pattern provides an insight into some of the flow behaviour, for example:

- 1) For both the 1.5 and 3.0 mm protuberances the turbulent recirculation region (TRR) ahead of the bow shock increases in area as the incidence angle increases from 0° to 30° and to 60° .
- 2) At 0° the TRR for both the 1.5 and 3.0 mm protuberances are symmetrical, figure 6A & 6B, thereby suggesting that shear stress would increase the drag along the sides of the protuberance equally.
- 3) The increase in height of the protuberances from 1.5 mm to 3.0 mm increases the TRR for all angles of incidence.
- 4) For the protuberances set at 30° the TRR is clearly modified by the forward facing side (Starboard) of the protuberances and would lead to a distinct change in side force on the protrusion, figure 6C & 6D.
- 5) With the Starboard side of the protuberance nearly normal to the boundary layer flow at 60° , the TRR is again close to symmetry; however, this also indicates that the Port side of the protuberance will become part of the wake, signifying, yet again, a change in the side force, figure 6E & 6F.
- 6) The immediate wake reduces in area for both the 1.5 and 3.0 mm protuberances as the angle of incidence increases.

There is a clear difference in the wake formation between the 1.5 mm and the 3.0 mm protuberance at 0° incidence with the larger protrusion producing a bifurcating wake formation. This bifurcation has an angle of approximately $\pm 28.30^\circ$ from the centreline of the wake and is a probably a product of the low aspect ratio, wall mounted, body of the protuberance creating a complex, three-dimensional flow structure that is characterized by a double vortex pair.

Upstream Shear Stress Distribution

An analysis of the distribution of the surface shear stress upstream of each of the protuberances in the spanwise direction is presented in Fig 7, where the SS is shown to reduce in value through the TRR from a 'near constant' freestream value at the two extremities of approximately -15 mm and + 15 mm. A number of observations is readily discernible, namely:

- 1) The shear stress (SS) distribution for the 1.5 mm and 3.0 mm protuberance at 0° incidence are very similar, Figs 7A and 7B, thereby indicating that the height of the models for this angle has not played a significant part in the TRR development. Furthermore, the spanwise distribution at -4 and -5 mm for both protuberance heights are similar with the distribution at -6 mm providing a reduction of the extent of the SS region, and distributions at -8 and -10 mm only showing a modest change in the SS values upstream of the main TRR area. However, the magnitude of the SS outside of the bow shock development, between -10 and -15 mm (starboard side) and +10 and +15 mm (port side) are different in values, with the average SS of approximately 123 Pa for the 1.5 mm protuberance and approximately 140 Pa for the 3.0 mm protuberance.
- 2) At 30° incidence, the TRR for the 1.5 mm protuberance at locations -4, -5, and -6 mm are displaced from the centreline of the circular planform by about -2 mm (towards the starboard side), Fig 7 C. This may also be observed in the 30° , 1.5 mm, image in Fig 6, with the center of this displacement coinciding with the center of the side face of the protuberance.
- 3) A similar TRR pattern is replicated for the 3.0 mm high protuberance with an area that is approximately twice that of the shorter 1.5 mm protuberance, Fig 7D. This is in evidence by the larger distribution for the -4, -5, and -6 mm locations, figure 7, which displays similar SS values from -15 mm (starboard) to +15 mm (port). Although the SS value at -10 mm is similar to that for the 1.5 mm protuberance (albeit at a slightly higher value of 138 Pa) the distribution for the -8 mm location is being affected by the incidence angle of the protuberance and offset from the centerline.
- 4) The SS distribution at 60° inclination for the 3.0 mm protuberance, Fig 7F, shows values depicting a greater width of the TRR compared to the 1.5 mm protuberance, Fig 7E. Furthermore, this distribution also has a number of differences from its smaller counterpart, such as,
 - The distribution for the -4, -5 and -6 mm locations for the 1.5 protuberance are all very similar in value, although the -6 mm is slightly less in extent because it is near the TRR front.
 - The distribution for the -8 and -10 mm locations for the 1.5 mm protuberance are outside of the main TRR but shows a small reduction in SS from 120 Pa to 80 Pa and 100 Pa respectively; thereby indicating that the presence of the protuberance affects the oncoming shear stress values outside of the TRR.
 - The effect of the 3.0 mm protuberance on the SS distribution is far greater showing a similar dispersal for the -5, -6 and -8 mm locations whereas that for the -10 mm location has fallen from approximately 140 Pa to 60 Pa. However, the distribution for the closer location of -4 mm shows signs of two regions of reduced SS, one on the starboard side of the centerline and one on the port side of 40 Pa and 60 Pa respectively.

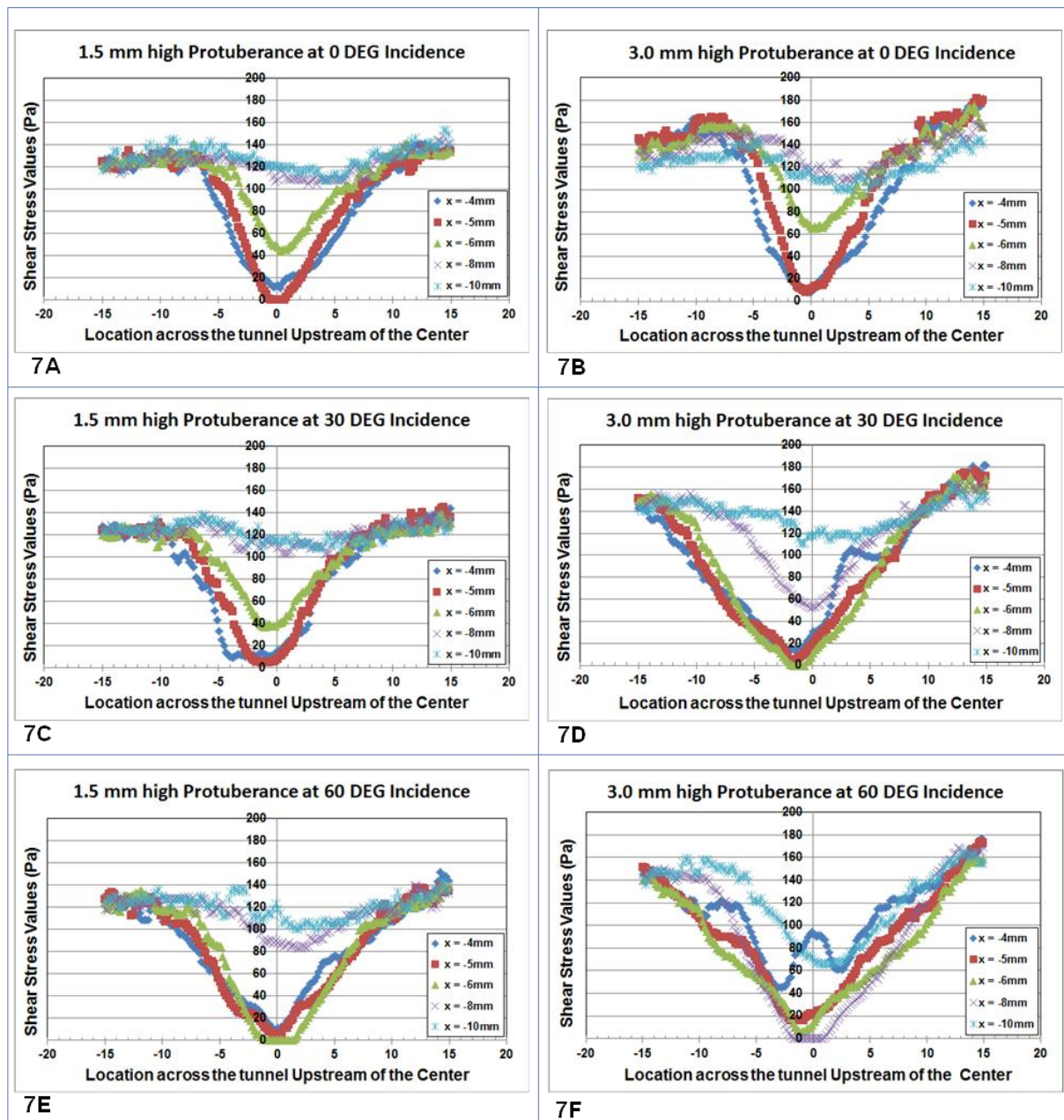


Fig 7: Spanwise Shear Stress distribution at different **upstream** locations for the two geometries at different Angles of Incidence.

Downstream Shear Stress Distribution

The shear stress distribution in the wake of the protuberances is more complex than that of the TRR. This is readily noticeable from the two distributions for the 1.5 mm and 3.0 mm protuberances set at 0° incidence angle, Figs 8A and 8B. Measurements of the SS were determined in a similar manner to that for the upstream TRR, at streamwise locations of 4, 5, 6, 8, and 10 mm, Fig 5, using the same method of analysis.

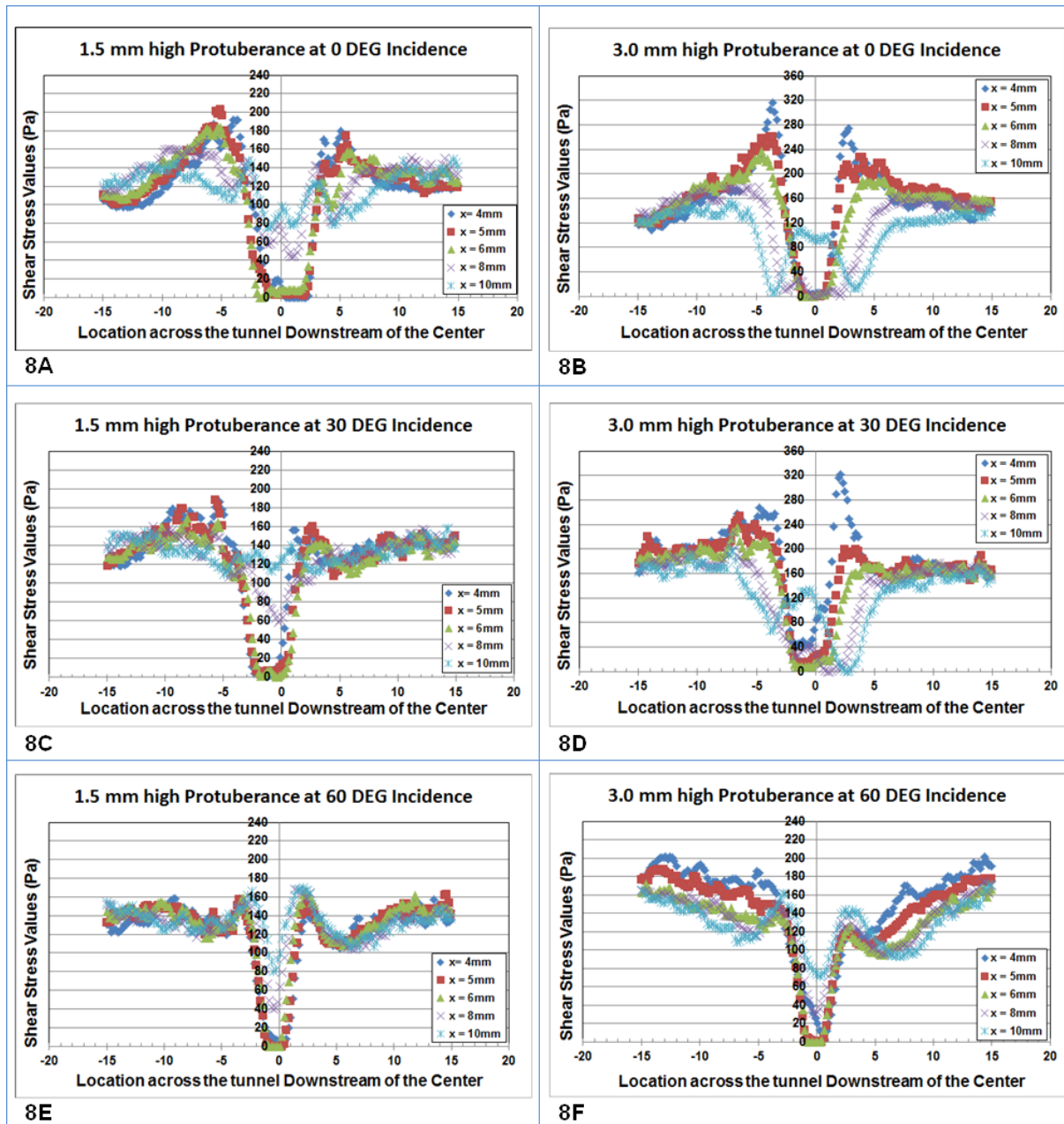


Fig 8: Spanwise Shear Stress distribution at different **downstream** locations for the two geometries at different Angles of Incidence.

For the two geometries at 0° incidence the following trends may be observed:

- 1) The SS outside of the immediate wake at ± 15 mm is approximately the same for both the 1.5 mm and the 3.0 mm protuberances of about 120Pa, Figs 8A and 8B.
- 2) The SS distribution within the immediate wake of the 1.5 mm protuberance, close to the base, has similar values at 4, 5 and 6 mm, increasing in stress from the outer regions of ± 15 mm with a peak value of 200 Pa at -6 mm on the starboard side, and 180 Pa at 4 mm on the port side; (the slight

asymmetry may be due to the flow structure such as reflected shock waves and turbulence characteristic upstream of the protuberance). Further downstream, the wake at 8 and 10 mm starts to broaden and return to the freestream value of about 120 Pa.

- 3) For the 3.0 mm protuberance, the immediate wake is clearly narrower in extent at 4, 5 and 6 mm, rising in stress value from the outer wake regions of ± 15 mm and peaking at 320 Pa at -4 mm (starboard side) and 280 Pa at approximately 4 mm on the port side, Fig 8B. Unlike the wake of the 1.5 mm protuberance, the wake at 8 and 10 mm shows evidence of a bifurcated nature with the wake broadening at 8 mm downstream of the protuberance, and fully bifurcated at 10 mm. Again, this bifurcation is a complex flow due to a low aspect ratio structure that is producing a vortex phenomenon from the interaction of the separating flows from the two sharp base angles of the protuberance and possibly the separation of the shear layer from the edge (similar to that for a backward facing step). Although the 1.5 mm protuberance is also classed as a low aspect ratio, wall mounted, body it did not display the same flow structure and this may be because the height of the smaller protuberance was within the momentum thickness of the boundary layer ($\theta = 2.4$ mm) whereas the 3.0 mm protuberance was above the momentum thickness and would have been subjected to a higher velocity (approximately 13% higher than that at 1.5 mm height).

For the protuberance set at an angle of incidence of 30° , asymmetry of the SS distribution occurs due, in part, to the deflection of the boundary layer along the starboard side of the protrusion, and the following observations may be made, Figs 8C and 8D:

- 1) The far field SS at ± 15 mm for the 1.5 mm high protuberance is similar in value at approximately 140 Pa. However, for the 3.0 mm protuberance the value on the starboard side is about 180 Pa, whereas the value on the port side is typically 160 Pa. This difference clearly shows that SS distribution is affected in the far field by the angle of 30° of the protuberance.
- 2) In the immediate wake of the 1.5 mm protuberance at locations 4, 5 and 6 mm, the SS distribution is relatively similar with the minimum SS close to the centreline of the protrusion. However, at location 8 mm, the distribution is skewed to the port side with the distribution falling from about 140 Pa at -15 mm to 60 Pa close to the centreline of the protuberance. At location 10 mm, the SS distribution remains relatively stable throughout this part of the wake.
- 3) The SS distribution for the 3.0 mm high protuberance is very dissimilar to that for the 1.5 mm protrusion with only locations 5 and 6 mm showing some similarity to each other but with higher SS values on the starboard side compared with that for the port side. The very near location of 4 mm shows two very high SS peaks, skewed about the centreline at approximately 270 Pa on the starboard side and at 320 Pa on the port, leeward, side. However, the minimum SS value for these three locations of 4, 5 and 6 mm is on the centreline of the protrusion but at approximately 1.5 mm for the 8 mm location and 3.0 mm for the 10 mm location, a significant skew in the SS profile.

At 60° angle of incidence, the SS distribution is far more orderly and may be due to the protuberance being more of a bluff body since the starboard side is close to being normal to the oncoming turbulent boundary layer at 80° . It can be observed that the distribution is symmetrical about the centreline of the protuberance, figures 8E and 8F;

- 1) The SS distributions for the 1.5 mm protuberance between -15 mm and 5 mm, as well as +5 mm to +15 mm are similar at each of the five locations at about 140 Pa. However, there is a small peak at -3 mm (starboard side) and +3 mm (port side) of about 160 Pa and 170 Pa respectively for all locations as the SS changes from outside of the wake region to within. Furthermore, it is readily noticeable that within this small wake region, the SS distribution for the 4, 5 and 6 mm locations are all very similar and decrease to zero SS on the centreline. The SS distribution for the 8 mm and 10 mm locations both decrease but not to the same extent since the measurements are taken further downstream at the edge of the region.
- 2) The SS distribution for the 3.0 mm protuberance is very similar to that of the 1.5 mm protrusion except for the larger spread of the SS in the outer part of the wake. The values of the SS within the near wakes are nearly identical.

Streamwise Shear Stress Distribution

The SS distribution at ± 4 mm on the Starboard and Port side of the protrusions from about -17 mm (upstream) to +27 mm (downstream) are very similar in pattern for the 1.5 mm and the 3.0 mm protrusions at 0° angle of incidence, Figs 9A and 9B. The main difference being scale rather than form, with a minimum value at approximately -5 mm, created by the TRR area, and increasing in value downstream of this area to

approximately 250 Pa for the 3.0 mm protrusion compared to about 180 Pa for the shorter protrusion at + 5 mm, a 50% increase in SS compared to that within the oncoming turbulent boundary layer. Furthermore, the value of the SS further downstream of the 3.0 mm protrusion, Fig 9B, exhibits a second larger decrease in SS, close to zero Pa, at about 10 mm compared to the shorter protrusion that only shows a reduction of about 80 Pa. This second large decrease is due to the measurements taken through the bifurcation, shown in Fig 6B.

Although the SS distribution for the 1.5 mm and 3.0 mm protuberances at 30° angle is similar in form to that of the 0° angle case, there is a clear difference between the results for the Starboard and Port side, Figs 9C & 9D.

- Here, the Starboard (-4 mm) distribution shows that both protuberances exhibit a larger decrease in SS within the TRR to a value of about 15 Pa, with the 3.0 mm protrusion providing a wider spread between -10 mm and -2 mm, compared with that for the 1.5 mm protrusion of between -7 mm and -1 mm. The SS then increases through the TRR and reaches a peak at approximately +2 mm for both sizes of protrusions, some 60% higher than the freestream SS value for the 1.5 mm high protrusion and about 80% higher for the larger 3.0 mm protrusion. The distribution for both protuberances then falls to a minimum 8 mm downstream, after which the SS starts to return to the freestream SS value although the SS for the 3.0 mm protrusion is, as expected, a higher value than that for the 1.5 mm protrusion due to its increased size and flow disturbance.
- On the Port side (+4 mm) of the protuberances the SS is less active since the turbulent boundary layer is affected by the 50° angular face of the protrusions (see Figs 6C & 6D). The TRR is diminished on this Port side but still provides a reduction in SS to 80 Pa for the 1.5 mm protrusion and 50 Pa for the larger protuberance. The peak SS values downstream of the TRR is only about 30% higher than the freestream value for the 1.5 mm protrusion, and about 40 % higher for the larger protuberance.

The difference in these two distributions will undoubtedly produce a different force on either side of the protuberance.

The SS for the protuberances set at 60° to the freestream turbulence flow the distributions are very similar to that for the 0° case, being very symmetrical with the magnitude of the SS larger for the 3.0 mm protrusion compared with that of the 1.5 mm, Figs 9E & 9F. Furthermore, the position of the start of the TRR and its minimum SS location is further forward compared to that for the 1.5 mm case by about 4 mm and 2 mm respectively. Additionally, the size of the TRR for the 3.0 mm case is approximately twice that for the 1.5 mm protrusion, and the location of the maximum SS, (downstream of the TRR) has also progressed forward by approximately 4 mm.

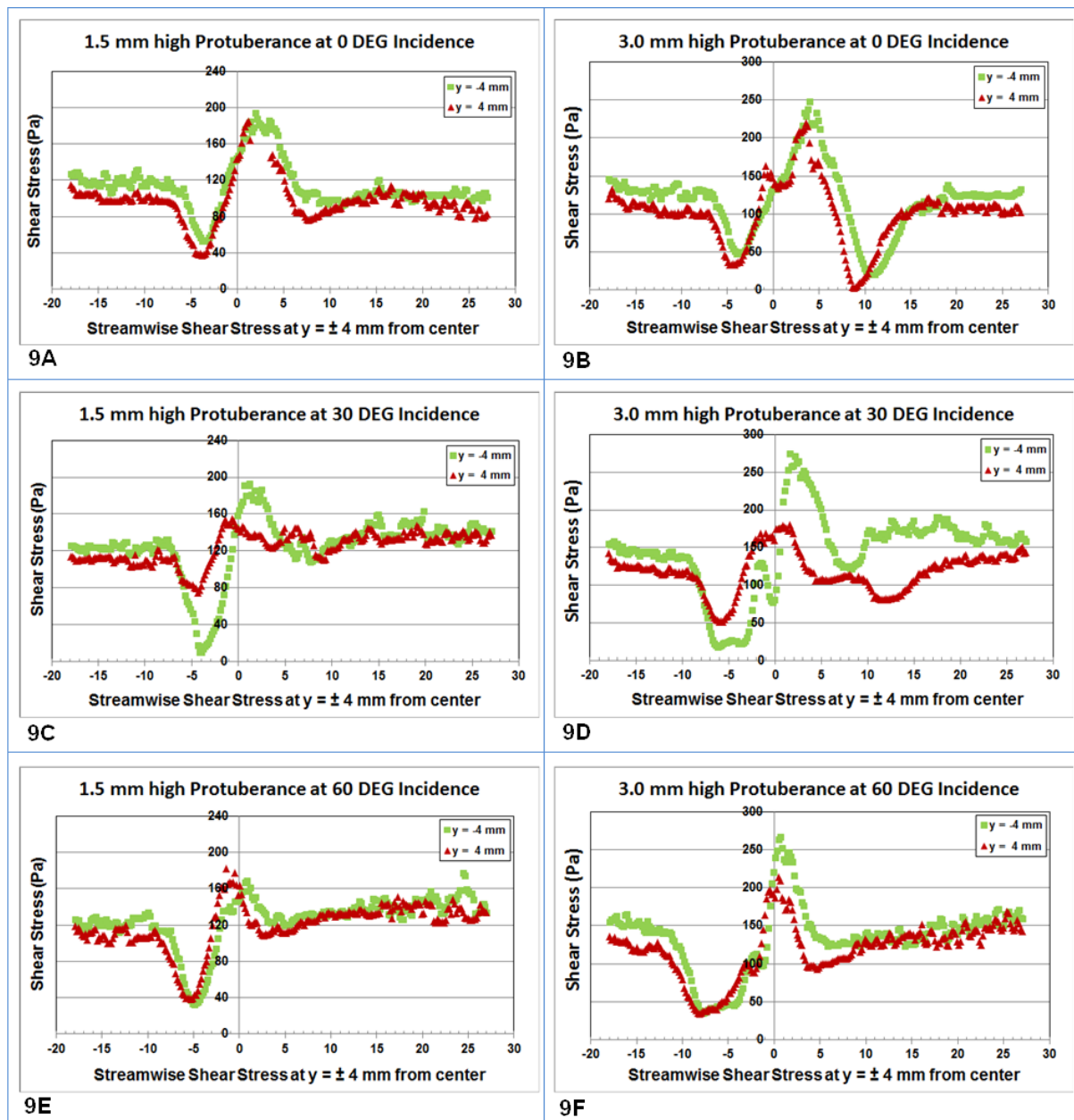


Fig 9: Streamwise Shear Stress at **Spanwise** locations of ± 4 mm from Protuberance Center

VI. Conclusions

The presence of small protuberances in the turbulent boundary layer of a 3.8 Mach number tunnel produces significant changes to the local shear stress levels. The two small triangular protuberances of 11.44 mm² planform and 1.5 mm and 3.0 mm high, used in this study has highlighted, both qualitatively and quantitatively, the extent of the shear stress distribution, especially when the protuberance is inclined at different angles to the oncoming boundary layer flow. The shear stress was determined using calibrated shear stress sensitive liquid crystals, available from ESI, using a high speed camera providing a temporal resolution of 1 msec, and analysed using purpose developed in-house software.

The size and shape of the recirculation region in front of the bow shock, as well as the wake region, shows how the inclination of the protuberance to the freestream oncoming turbulent boundary layer is affected, and highlights a number of features, such as a bifurcating wake pattern, some symmetry as well as asymmetry, including the effect of protuberance height in relation to the momentum thickness of the turbulent boundary layer. Measurements of the shear stress at specific locations, upstream, downstream and at the sides of the protuberance have provided details of the local shear stress levels indicating the positions of low shear stress and

where very high levels may be expected, values that are as much as 80% higher than the freestream boundary layer value.

This methodology of using Liquid Crystals for measuring surface shear stress in supersonic flow has been shown to be practical and an efficient technique, especially with Liquid Crystals that are calibrated prior to testing

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