VISUALIZATION OF TURBULENT WEDGES UNDER FAVOURABLE PRESSURE GRADIENTS USING SHEAR SENSITIVE AND TEMPERATURE-SENSITIVE LIQUID CRYSTALS

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Emmons[1] discovered in 1951 that boundary layer transition occured when some arrow shaped disturbances, or *turbulent spots*, formed randomly and grew as they propagated downstream until they merged and covered the entire flow field. Using Emmons' spot hypothesis, and with a knowledge of the spot's propagation rate and spreading angle, one could model the boundary layer intermittency distribution more accurately, hence the transition process.

INTRODUCTION

Boundary layert ransition that is initiated via the turbulent wedge was studied by Schubauer and Klebanoff[2] , who used hot wire anemometry to measure the shape of the wedge. The turbulent wedge was induced by placing a 3D-roughness element of sufficient size in a laminar boundary layer. Based on their findings, the turbulent wedge caused by the 3D-roughness can be interpreted as a continual generation of turbulent spots. Thus, a turbulent wedge provides a simplified case to study the growth of a turbulent region in laminar background and the transition mechanism. Clark *et.al*[3]. and Petrie *et.al.*[4] contributed to the visualisation of turbulent wedges/turbulent spots. The latest report on this topic is by Zhong *et.al*[5]. who used thermo-chromic liquid crystals to visualise the development of turbulent spot under the influence of adverse pressure gradient flows.

It is known that momentum and thermal transitional boundary layers undergo different transport mechanisms. This difference questions the conventional Reynolds Analogy, which relates skin friction to heat transfer, especially when a streamwise pressure gradient is present. In turbomachines, the leading edge of the suction surface and trailing edge of the pressure surface of gas turbine blades are often covered by accelerating transitional flows. Thus, it is important to accurately predict the heat transfer characteristics in the transition zone of the turbine blades in order to design more reliable, internally cooled turbine blades. In this paper, both shear sensitive and temperature sensitive liquid crystals are used to visualise the development of a turbulent wedge under favourable pressure gradients. The purpose of this work is to investigate the effect of pressure gradients on growth of a turbulent wedge and thus obtain further insight into the link between the momentum and thermal structures of the flow.

EXPERIMENTAL METHODS

Liquid crystals

Shear sensitive (chiral-nematic) liquid crystal is capable of responding to different levels of shear stress by way of color changes. As shear stress increases, the color of the liquid crystals coating will shift from dusty red through the visible spectrum to violet. Since under the same Reynolds number, the shear stress underneath a turbulent boundary layer is considerably higher than that in its laminar counterpart, the colour variations displayed by the crystal can provide the information about the growth of a turbulent wedge.

Temperature sensitive (encapsulated cholesteric) liquid crystal shows variation of color from red through the visible spectrum to blue as temperature increases. Since a turbulent boundary layer exhibits high heat transfer rates, the surface temperature will be lower than underneath its laminar counterpart. Hence, this type of liquid crystal can be used to visualise the thermal footprint of a turbulent wedge.

Experiment apparatus

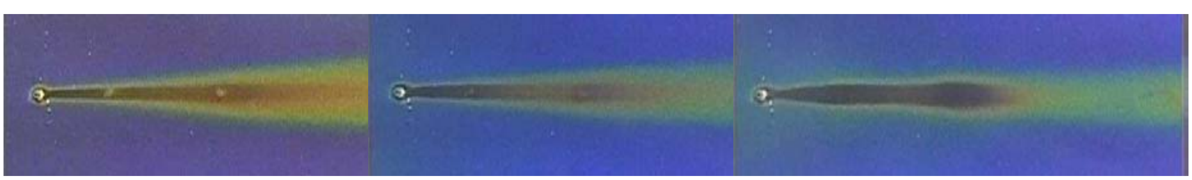
The experiments were conducted in the Farnborough low-speed wind tunnel at the Goldstein Laboratory at Manchester School of Engineering. The tunnel has a test section measuring 460mm by 200mm and a maximum speed of 28m/s. Two perspex flat plates, 750mm in length were used, one for each type of liquid crystal. They were mounted horizontally across the whole width of the tunnel test section. A cylindrical rod 1.5mm in height was used as the surface roughness element and was placed 100mm from the leading edge of the plate. The roughness Reynolds number of 2800 was sufficiently high to produce a wedge immediately downstream. The favourable pressure gradients were generated by attaching a flat perspex sheet at varying angles to the ceiling of the working section. An aluminium foil was used to provide a uniform heat flux across the plate for the tests with the temperature-sensitive liquid crystal. This crystal has an active color bandwidth of 5^0C, showing red at 17^0C and blue at 22^0C.

RESULTS

The tests were carried out at a freestream velocity of 28m/s at a zero, mild and a strong favourable pressure gradient respectively.

a). Zero pressure gradient b). Mild pressure gradient c). Strong pressure gradient

Fig. 1. SSLC results for the turbulent wedge under zero, mild and strong pressure gradients respectively.



a). Zero pressure gradient b). Mild pressure gradient c). Strong pressure gradient

Fig. 2. TSLC results for the turbulent wedge under zero, mild and strong pressure gradients respectively.

Both Fig.1 and Fig.2 show that the spreading angle of the turbulent wedges decreases in size as the favourable pressure gradient increases. Interestingly the spreading angles indicated by the temperature sensitive liquid crystals are smaller than those indicated by the shear sensitive liquid crystals. These results seem to be consistent with the findings of Blair[6], i.e. in favourable pressure gradient transitional flow, the temperature profile is established over a longer length than the velocity profile.

Examining the HUE values of the graphs can help to determine the boundary of the turbulent wedge more accurately. The boundary can be defined as existing where there is a sharp change of HUE value , which indicates distinct color change of the liquid crystals. A Summary of the wedge spreading half angles of SSLC and TSLC for zero, mild and strong pressure gradients is presented below:

	Zero pressure gradient	Mild pressure gradient	Strong pressure gradient
SSLC	10.3^0	9.4^0	7.8^0
TSLC	5.5^0	4.1^0	2.5^0

Table 1. Summary of the wedge spreading half angles for zero, mild and strong favourable pressure gradients for SSLC and TSLC

CONCLUSIONS

This experiment clearly demonstrates the capability of both shear sensitive and temperature sensitive liquid crystals to display information on turbulent wedges in an otherwise laminar boundary layer on a flat plate. The results show the dependency of wedge spreading angle on the level of flow acceleration, while at the same time exhibiting the different flow structures present in momentum and thermal boundary layer flows.

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