

SURFACE OIL FLOW TECHNIQUE AND LIQUID CRYSTAL THERMOGRAPHY FOR FLOW VISUALIZATION IN IMPULSE WIND TUNNELS

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ABSTRACT: This paper describes flow visualization techniques employing surface oil flow and liquid crystal thermography suitable for use in impulse wind tunnels. High spatial resolution photographs of oil flow patterns and liquid crystal thermograms have been obtained within test times ranging from 7 to 500 ms and have been shown to be very useful for revealing the detailed features of 3-D separated flow. The results from oil flow patterns, liquid crystal thermograms, schlieren photographs and heat flux measurements are shown to be in good agreement.

KEY WORDS: flow visualization, oil flow technique, liquid crystal thermography, impulse wind tunnel

I. INTRODUCTION

It is well known that the measurements of surface pressure and heat transfer distribution by discrete sensors can provide accurate data to validate numerical calculations, but they may possess inadequate spatial resolution due to the limitation of the sensor size and the number of measurement points. Each measurement is taken at a single point on a model surface, which is time consuming and expensive. However, surface flow visualization, such as oil flow, can yield an overall view of the most critical region and display an entire surface mapping of the flowfield. A single flow visualization image can often provide more physical understanding than a large set of discrete point measurements. Therefore many surface visualization methods, such as oil flow, sublimation and evaporation methods, have been extensively used in conventional wind tunnels^[1,2], but they have been seldom used in impulse wind tunnels due to their short test time and very low static pressure. A few oil flow patterns obtained by using the oil film method were not too clear^[3,4]. In recent years, an oil dot method and liquid crystal thermography have been developed and successfully applied to the study of 3-D shock/turbulent boundary layer interactions induced by a sharp fin, blunt fin and square step in the isentropic light piston tunnel(ILPT)^[5,6] at Southampton University UK, the gun tunnel^[7,8] and the shock tunnel^[9] at Institute of Mechanics, Chinese Academy of Sciences. The test times are about 500, 20 and 7 ms respectively. High clarity photographs of oil flow patterns and liquid crystal thermograms as well as quantitative data of the interaction flow features have been obtained^[5,7]. This paper describes the oil dot technique and liquid crystal thermography which are suitable for the impulse wind tunnels, and

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gives detailed comparisons between the feature positions of separated flows determined from oil flow patterns, liquid crystal thermograms, schlieren and thin film gage measurements.

II. DESCRIPTION OF THE TECHNIQUES

2.1. Oil Dot Method

Oil dot visualization method is a mechanical method which is based on changes in position and shape of discrete oil drops on the model surface in the flow. In the present study, the test surface was covered with drops of a mixture of silicon oil and titanium dioxide powder instead of with oil film. Oil drops form visible streaks more easily than oil film. Silicon oil with relatively low values of viscosity has been found to be suitable for impulse wind tunnel environments, it does not vaporize under low pressure conditions, and can produce a distinct displacement within the duration of 7 – 500 ms. It also wets test surface easily. Titanium dioxide powder is a white pigment, and the test surface has been painted black in order to increase photographic contrast. Powdered pigments of different colors can also be used. The choice of oil and pigment and their proportion is mainly based on experience and preliminary experiments for each case. It is impossible to recommend a universal mixture for all cases. Drops are applied with a brush or tube onto the test surface before a test. The droplets have a diameter of about 1 – 2 mm, the space between them is about 2 – 3 mm. The height of drops should not exceed that of the local boundary layer. When the model is subjected to airflow, the surface shear stress acts on the droplets and leads to considerable deformation, resulting in oil streaks which show direction and shape of the surface streamlines. The oil flow pattern may be recorded on a camera film, or on a video tape to reveal the development with time of the oil flow pattern for a test. It can also be transplanted onto a transparent tape to get a full size image which is suitable for obtaining quantitative data of flow interaction features.

2.2 Liquid Crystal (LC) Thermography

Liquid crystals have been used for about twenty years in aerodynamic testing, by employing the temperature or shear-sensitivity of their structure. When the LCs is deposited onto a surface in the form of a thin film (about 10 – 20 μm in thickness), temperature or shear stress changes can be observed through changes in the spectral composition of reflected light. In recent years LC surface thermography has been applied to the measurements of surface heat flux in short duration facilities^[6]. In the present studies, LC thermograms are only used to observe the surface thermal field in a separated flow for comparison with the oil flow pattern. The use of microencapsulated liquid crystals, which respond only to changes in temperature, enables us to obtain a complete picture of the thermal field of a surface. The thermal response time of the LC film is measured^[10,11], which is about a few milliseconds, the slow response being attributed to the conduction lag and LC structure lag. The LCs used in the present tests were the chiral nematic thermochromic types of TCF552 and TCS656 manufactured by BDH Ltd, UK. The former has a red start temperature of 24°C with a bandwidth of 7°C, the latter has a red start temperature of 60°C with a bandwidth of 15°C. They change colour from colourless to red, to green, to blue and again to colourless as their temperature increases. This colourplay sequence is reversible, which allows a model coated with LCs to be used repeatedly. The LCs were sprayed onto a black paint coating on the metallic model or black plastic substrate which absorbs the transmitted light. Normally,

two or three layers of LCs were sprayed to a total thickness of 10 to 20 μm by an air-brush. This method resulted in a thin and even coating of uniform thickness. During a test the coloured images displayed by the LC film were recorded on video tape by a video system or on colour film by a camera. The models were illuminated using a strobe flash which was synchronized to the camera operation. The choice of LC type was based on the magnitude of surface temperature rise. The initial temperature of the model should be lower than the red start temperature of LC.

III. RESULTS OF FLOW VISUALIZATION

Wind-tunnel tests were made to verify the feasibility and reliability of surface oil dot method and LC thermography used for surface flow visualization in short duration facilities. The tests were made with sharp fins, a cylinder and a 3-D inclined step mounted on a flat plate, respectively. Figure 1 shows an oil flow pattern, a LC thermogram and heating distribution measurements by thin film gages for a sharp fin at a deflection of 30° in the gun tunnel with a test time of 20 ms. The LC type used is TCF552. The oil flow pattern and LC colourplay show the conical nature of the fin interaction in hypersonic flow, which

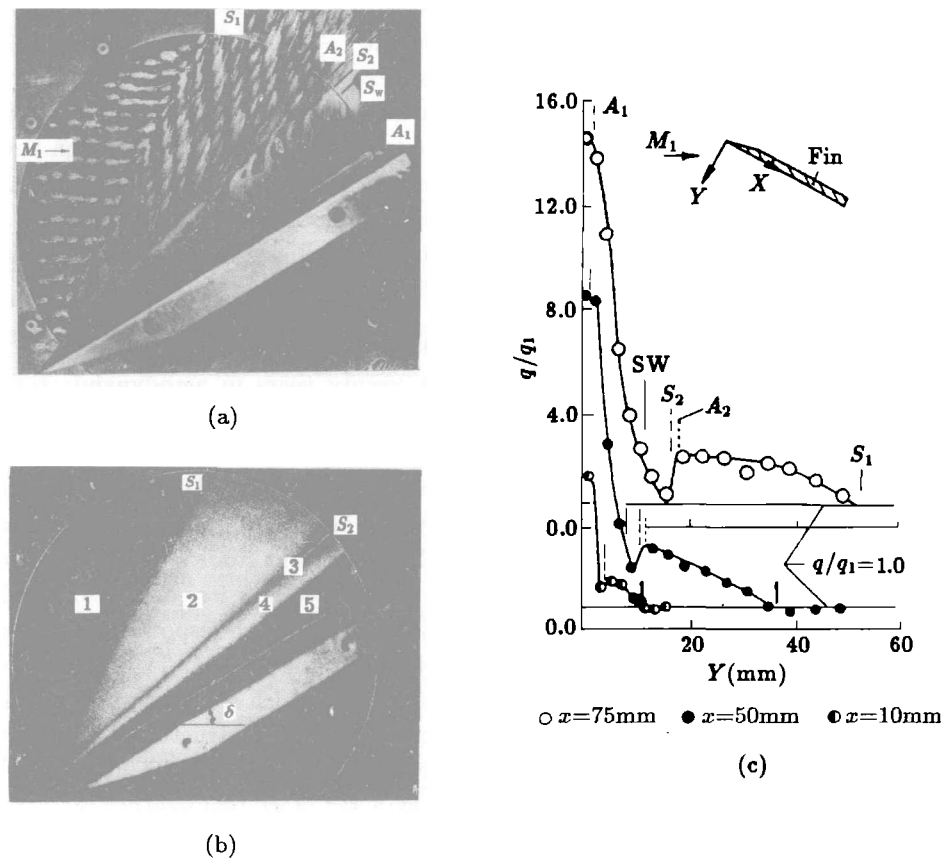


Fig.1 Oil flow pattern (a), liquid crystal thermogram (b) and heat flux distributions (c) induced by a sharp fin on a flat plate in a gun tunnel with a test time of 20 ms. $M_1 = 7.8$, $Re = 3.5 \times 10^7/\text{m}$, $\delta = 30^\circ$.

is similar to the result in supersonic flows^[1]. In the fin interaction zone the LCs revealed several regions (2, 4, 5) of relatively high surface temperature radiating downstream along straight lines originating from a point upstream of the fin apex. There are two hot regions (2, 4) separated by a region (3) of lower temperature downstream of the undisturbed region (1). From the oil flow pattern, it can be seen that two separation lines, S_1 and S_2 , where streamlines converge, and two attachment lines, A_1 and A_2 , where streamlines diverge, occur upstream of the fin. S_1 and A_1 are called the primary separation and attachment lines; S_2 and A_2 are called the secondary separation and attachment lines, respectively. S_2 is close to the inviscid shock wave, SW. The secondary attachment line A_2 has been rarely observed in the previous experiments and numerical simulations. The result shows that there exists a primary vortex, S_1A_1 , beneath which exists a small secondary vortex, S_2A_2 . These feature positions are labeled in Fig.1(b) and 1(c), respectively, to compare with each other. The separation lines (S_1 , S_2) in the oil flow pattern correspond to the lower temperature lines in the LC thermogram, and the lower heat flux points in heating distributions; the attachment lines, (A_1 , A_2), correspond to the peak temperature lines, and peak heating points. This shows that the characteristic positions obtained from oil flow pattern, LC colourplay and thin film gages measurements are in good agreement. The innermost region (5) experienced the higher shear stress and greater heat flux (darker colourplay) than the outer regions (2, 4) due to the attachment of primary vortex, S_1A_1 . The region (2) between S_1 and A_2 corresponds to the plateau heat flux region where the streamlines are nearly parallel to each other (Fig.1(a), 2(a)).

In order to examine the development with time of surface oil flow pattern during a test and the effect of tunnel shutdown, a series of oil flow patterns were recorded using a video system in the ILPT with a running time of 500 ms^[5]. The time response of oil drops to boundary layer flow is dependent on the viscosity of the oil mixture and the test flow condition, specially surface shear stress. The video pictures show that oil flow pattern can be formed several milliseconds after a steady flow is established. Although the oil dot displacements increase and oil streaks get finer with time at an early stage of the test, the local streamline directions and the feature positions, such as S_1, A_1 , do not change with time. The pictures taken just before and after shutdown, respectively, are the same, which shows that tunnel shutdown does not affect the oil flow pattern in a piston type wind tunnel, like the ILPT and gun tunnel. Shown in Fig.2 are the oil flow pattern and LC thermogram induced by a sharp fin at a deflection of 20° in the ILPT. The oil flow pattern in Fig.2(a) was printed onto a transparent tape after the test in which a combination of oil dots and oil film was used. The LC type used was TCS656. Two light coloured lines in the LC thermogram show lower surface temperature lines. The separation line S_1 and S_2 in the oil flow pattern are also in very good agreement with the lower surface temperature lines (Fig.2(c)).

For shock tunnels the utility of oil flow visualization is limited due to the very short test time and effect of driving gas flow after the steady test flow on the oil streaks. In some cases the driving gas effect can be avoided by simultaneous photographing during a test. In some cases, for example, for internal flows, it is difficult to take a picture during a test. The present oil flow tests in the shock tunnel show that driving gas flow only affects the oil flow pattern with a thicker layer of oil mixture, such as the separation line and the pattern near it. The clear oil flow patterns can be obtained by using a mixture of an adequate ratio of oil to pigment, and by applying an appropriate amount of the oil mixture to the test surface.

shock tunnel with a test time of 8 ms at Mach number of 2.3. Sketches of surface streamlines from the oil flow picture are shown in Fig.4(b). The complicated vortex flow around the step can be observed from the clear oil streaks. The extent of separation region is also in agreement with the result of heat transfer measurements.

IV. CONCLUSION

Surface oil flow technique and liquid crystal thermography are feasible and reliable for flow visualization in impulse wind tunnels. High clarity oil flow patterns and liquid crystal thermograms have been obtained for test time ranging from 7 ms to 500 ms and are shown to be very useful for revealing the detailed features of 3-D turbulent separated flows. The results indicate that the feature positions of 3-D protuberance interaction flows obtained from oil flow patterns, liquid crystal thermograms, thin film gage measurements and schlieren pictures are in good agreement.

Further improvement of the oil dot technique is necessary for use under low Reynolds number conditions.

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REFERENCES

- [1] Settles GF and Lu FK. Conical similarity of the interaction of shock/boundary layer interaction generated by swept and unswept fins. *AIAA J*, 1985, 23(7): 1021-1027
- [2] Sedney R, Kitchens CW. Separation ahead of a protuberance in supersonic turbulent boundary layer. *AIAA J*, 1977, 15(4)
- [3] Yu HR and Li ZF. An experimental investigation of heat transfer in the shock/turbulent boundary layer interaction region induced by a cylindrical protuberance. *Acta Mechanica Sinica*, 1980, (1): 68-75 (in Chinese)
- [4] Li SF, et al. Oil flow technique and application in hypersonic shock tunnel. *Acta Aerodynamica Sinica*, 1983, 3: 55 (in Chinese)
- [5] Tang GM. Application of surface flow visualization to the study of hypersonic shock wave/turbulent boundary layer interaction in a short duration tunnel. *AASU No. 92/03*, Southampton University, UK, 1992, (03)
- [6] East RA. Application of liquid crystal thermography in hypersonic flow. In: *Proceedings of 18th International Symposium on Shock Waves*, Sendai, Japan, 1991
- [7] Tang GM. Application of a surface oil dot visualization technique to the study of 3-D shock/boundary layer interaction in short duration facilities. *Aerodynamic Experiment and Measurement & Control*, 1993, 7(3): 128-134 (in Chinese)
- [8] Liu P, Tang GM, Li Q. Application of liquid crystal thermography in a gun tunnel. *Aerodynamic Experiment and Measurement & Control*, 1993, 7(3):121-127 (in Chinese)
- [9] Tang GM and Yu HR. Aerodynamic heating in the region of shock and turbulent boundary layer interaction induced by a cylinder. *Acta Mechanica Sinica*, 1992, 8(3): 224-230
- [10] Ireland PT, Jones TV. The response time of a surface thermometer employing encapsulated thermochromic liquid crystals. *J Phys E: Sci Instrum*, 1987, 20: 1195
- [11] Zhang ZC, et al. An experimental evaluation of thermochromic liquid crystals for surface temperature and heat transfer measurements in shock tube flows. In: Kim YW, ed. *Current Topics in Shock Waves*, AIP Conference Proceedings, 1990, 208: 618-623