Study on Internal Supersonic Flows with Pseudo-shock Wave Using Liquid Crystal Flow Visualization Method

WANG Dong-ping[1], ZHAO Wen-zhong[1], SUGIYAMA Hiromu[2], TOJO Akira[2]
(1. College of Mechanical Engineering, Dalian Jiaotong University, Dalian 116028, China)
(2. Department of Mechanical Systems Engineering, Muroran Institute of Technology, Muroran, Hokkaido 050-8585, Japan)

Abstract: The flow visualization technique using shear-sensitive liquid crystal is applied to the investigation of a Mach 2 internal supersonic flow with pseudo-shock wave (PSW) in a pressure-vacuum supersonic wind tunnel. It provides qualitative information mainly concerning the overall flow structure, such as the turbulent boundary layer separation, reattachment locations and the dimensionalities of the flow. Besides, it can also give understanding of the surface streamlines, vortices in separation region and the corner effect of duct flow. Two kinds of crystals with different viscosities are used in experiments to analyze the viscosity effect. Results are compared with schlieren picture, confirming the effectiveness of liquid crystal in flow-visualization.

Key words: surface flow visualization; turbulent boundary layer separation; pseudo-shock wave; shock wave/turbulent boundary layer interaction; shear-sensitive liquid crystal; corner effect

液晶流动可视化方法研究拟似冲击波的内部超声速流动. 王东屏, 兆文忠, 杉山弘, 东条启. 中国航空学报(英文版), 2005, 18(2): 102-107.

摘 要: 在一个压力-真空超声速风洞中, 剪切应力敏感液晶流动可视化技术被应用来研究方管内马赫数 2 拟似冲击波(pseudo-shock wave) 的超声速流动。它主要提供关于整个流动的定性信息, 诸如湍流边界层分离、再附着位置以及流动的维数等。而且液晶也反映了表面流线, 分离区内的涡流和管道流动的角效应。使用两种不同黏度的液晶分别进行实验, 分析黏度对结果的影响。液晶实验的结果与纹影照片所得结果比较吻合, 说明了液晶是一个非常有效的流动可视化工具。

关键词: 表面流动可视化; 湍流边界层分离; 拟似冲击波; 冲击波/湍流边界层相互作用; 剪切敏感液晶; 角效应

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The use of the liquid crystal flow visualization technique has increased greatly over the past few years. Selective reflection of a particular wavelength is one of the most significant characteristics of liquid crystals. When a beam of white light is incident on the liquid crystal material, changes in the color of the reflected light are seen as the result of heating or shear stress advanced.

The shear-sensitive liquid crystal coating (SSLCC) method can provide area visualizations of instantaneous shear stress distributions on surfaces in dynamic flow fields[1]. It is useful for visualizing subtle flow features of boundary-layer separation, which are otherwise difficult to detect.

In the early 1980's, scientists at NASA Langley investigated the use of liquid crystals for qualitative illustration of surface flow features. Since then, many researches have been done, but obtaining satisfactory results at high dynamic pressure remains one of the significant challenges to be resolved for the liquid-crystal technique[2]. Moreover, most of the researches done mainly is on the outer flow field, and not on the internal flow field[3]. So far, the research paper about surface flow visualizations of the pseudo-shock wave (PSW) by liquid crystal has seldom appeared.

When a supersonic flow is decelerated to subsonic in a confined channel, PSW appears due to

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the interaction between a boundary layer and a shock wave. The PSW significantly affects the performance and efficiency of various flow devices, such as scramjet engine, supersonic wind tunnel diffuser and supersonic ejector. Its most important feature is the interaction of shock waves with boundary layer. The present understanding of the complex boundary layer flows of PSW is rather limited and many physical aspects are not well understood. Therefore, a careful study of this phenomenon is of practical and fundamental value.

The purpose of the present investigation is to obtain qualitative information concerning the boundary layer flow in Mach 2 with PSW supersonic wind tunnel experiment by using shear-sensitive liquid crystal. It provides information concerning the turbulent boundary layer separation, reattachment locations and the dimensionalities of the flow. Besides, it can also give an understanding of the surface streamlines, vortices and the corner effect of the duct flow.

1 Experimental Apparatus

The experiments are carried out in a pressure-vacuum supersonic wind tunnel of Muroran Institute of Technology of Japan.

By adjusting the size of the second throat (shock generator), the PSW is positioned at the desired locations. The structure of the PSW is visualized *via* a high speed color schlieren system, and the light source is a nanospark flash (30 ns).

Experimental condition: free-stream Mach number $Ma_\infty \doteq 2.0$; Reynolds number based on unit length $Re_\infty/m = 2.5\times 10^7$; the ratio of the undisturbed boundary layer thickness to the duct half height $\delta_\infty/h = 0.25$.

When the liquid crystal experiments are done, one sidewall window of the tunnel is removed and replaced with a solid metal insert as the experimental surface. It has the size of 300 mm long and 80 mm high, and is positioned directly on one side of the off-centerline window ports and can thus be uniformly illuminated from the light outside the tunnel.

The liquid crystal coating is illuminated with a white light source mounted outside of the tunnel. Digital video and high-resolution camera are used to record the liquid crystal color change while the tunnel runs. When determining the shear stress change from the color changes of liquid crystals, the lighting and viewing angles are important. These angles are chosen on the basis of that they give the greatest color change in this experiment as shown in Fig. 1. By comparison, a shallow lighting angle and nearly perpendicular viewing angle produce intense color change, which is agreed with the result of Ref. [2].

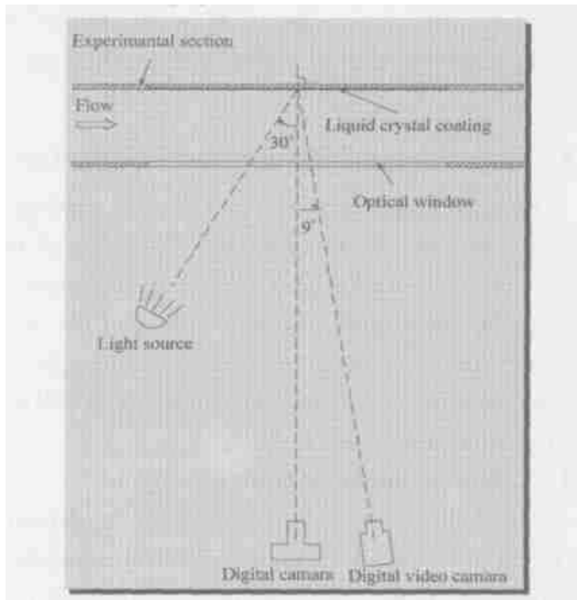

Fig. 1 Diagrammatic sketch of the lighting and viewing angles

The run time of the tunnel is approximately 10.5 s. The experiment is done presence and absence of PSW.

2 Flow Visualization Method

Liquid crystals have properties of both liquid-phase and solid-phase materials. Although appearing fluid-like, liquid crystals exhibit optical properties of solid crystals. The chemical structure of the liquid crystals is not affected, so the liquid crystal coating can respond rapidly and reversibly and be repeatable to these external effects. Many different experimental conditions can be studied with one application, which is an advantage over other techniques such as oil film method, which must be re-applied after each experimental condition.

The viscosity of the liquid crystal is very important. Two different shear sensitive liquid crystals, CN/R7 and BCN/192 are used. BCN/192 has a viscosity of 1000 cps and the CN/R7 has a much higher viscosity of 11500 cps.

The 15%-20% SSLCC solution (acetone solvent) is coated on the experimental section uniformly. The solvent evaporates, leaving a uniform thin film of liquid crystal whose thickness, based on mass conservation and estimated spray losses, is approximately 10-20 μm. If the thickness is not adequately, the clear color change cannot be observed, which is assured many times in the experiment.

3 Experimental Results and Discussions

Rapid response of the liquid crystal coating is observed during the experiment. The color of the liquid crystal typically goes from red or yellow at the smaller shear stress through to blue at the larger shear stress. Several important features of the surface shear field are made visible by these SSLCC color-change responses.

3.1 Effect of liquid crystal viscosity

Fig. 2 shows the comparison of the experimental result of two kinds of liquid crystals in the Mach 2 supersonic flow, and the flow is from left to right. Fig. 2(a) is the experimental result of CN/R7. Fig. 2(b) is the result of BCN/192.

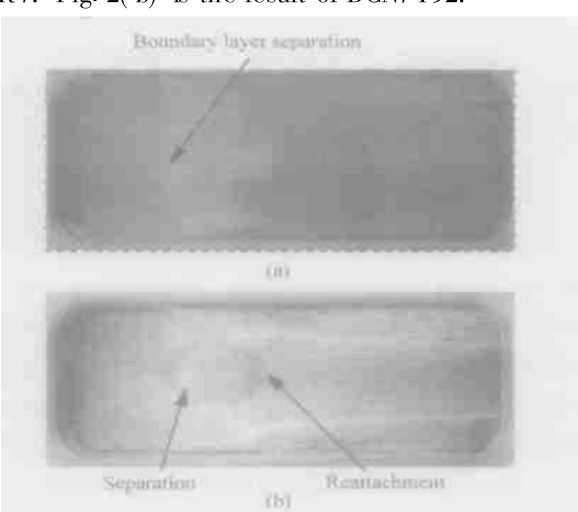

Fig. 2 Comparison of the different liquid crystals

The viscosity of BCN/192 is lower so that the liquid crystal flows while the tunnel is running. The separation region in the boundary layer can be observed. In the separation region, the liquid crystal flows towards the upstream and culminates in an accumulation of crystals at the zero stress location. The accumulation line indicates separation and the attenuation line indicates reattachment. The surface flow of liquid crystal gives a good indication of the flow directions. The viscosity of CN/R7 is higher so that the liquid crystal does not flow during the experiment. The separation line is observed with the color change from blue to red. The reattachment line is not observed.

Comparing the two photos, the conclusion from the Fig. 2(b) is better. Although the different stress magnitudes can be expressed, the stress direction cannot be indicated by CN/R7. BCN/192 can express not only the stress magnitude but also the stress direction. Moreover, boundary layer flow features such as two vortices in the reverse region and the corner effect can be observed in BCD/192. Therefore, BCN/192 is better than CN/R7 in Mach 2 flow.

Based on the above-mentioned, the following conclusions can be made: flowing liquid crystal can show flowing direction and many tiny flow characteristics. It is better to make the liquid crystal flow slowly. However, if the viscosity of the liquid crystal is too low, as the rate of gas flow increases, the liquid crystals flow too quickly and result in a reduction of its surface thickness to spurious color indication.

In the present experiments with the liquid crystals, the run time of the tunnel is 10.5 s. This relatively short run time allows the crystals not only to undergo changes in color but also to move in the direction of the shear without causing a dramatic loss in the quantity of crystal at any location.

In real-time observation, the liquid crystal flows quickly during the experiment. Therefore, the viscosity of the liquid crystal BCN/192 is lower for Mach 2 flow. It is better to use higher viscosity liquid crystal. However, the viscosity of CN/R7 is higher for Mach 2. For a particular experiment, a certain extent of experimentation will be required to get appropriate viscosity liquid crystal.

3.2 Liquid crystal time response

The liquid crystals have sufficient frequency response to reflect tunnel flow unsteadiness. The time response of the liquid crystal coating is in the order of 1 millisecond, namely 1000 Hz, and the PSW fluctuates about at 250 Hz[3]. Therefore, the liquid crystal can respond to the fluctuation of PSW. From the high-speed color video, the fluctuations in the instantaneous surface shear stress magnitude are found to be present in the core region of this flow. At the photo of the 0.25 s / one piece of camera, the instantaneous change of the liquid crystal color cannot be observed. The liquid crystal changes at different time can be observed as showed in Fig. 3.

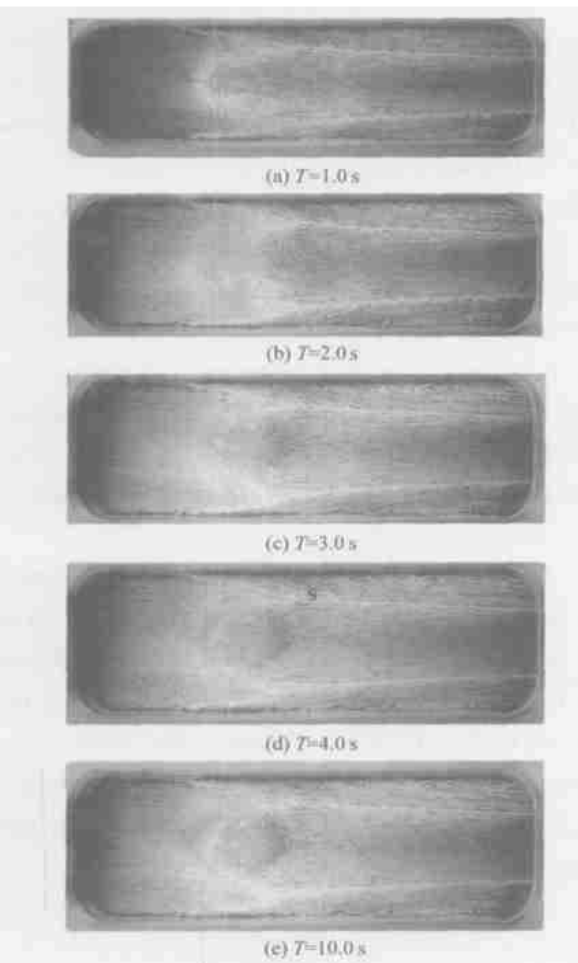

Fig. 3 Liquid crystal time changes

Fig. 3 shows the liquid crystal color responses at different time during the tunnel running. After the ventilation begins 2.5 s, the flow becomes in steady condition and the liquid crystal pattern becomes steady. As the time goes, the shape of the separation region can be observed to have a little change. It seems more circular at the time of 4.0 s, but it becomes ellipse as the time goes, which may be caused by the shock wave fluctuating. Moreover, the color before the separation becomes redder than before as the time goes. The reason may be that the viscosity of BCN/192 is lower for the Mach 2 flow, so that the liquid crystal quantity decreases as the time goes. If the higher viscosity is used, it may be better.

3.3 Comparison of liquid crystal experimental results with corresponding schlieren experimental results

It is very important to use other method to confirm the accuracy of liquid crystal experiment. The schlieren photograph shows the flow situation in the center plane of the duct from the side view. The structure of PSW and the corresponding boundary layer flow can be observed. Liquid crystal visualization from side view shows the boundary flow on the sidewall of the duct, while the one from top view shows the flow on the bottom wall of the duct.

Fig. 4 is the comparison of Mach 2 liquid crystal experimental results with the corresponding schlieren experimental result, and the flow is from left to right.

Fig. 4(a) and Fig. 4(c) are the photos of typical flow patterns with the shock wave present for BCN/192 and observed from side view and top view respectively. Fig. 4(b) is the corresponding schlieren photo of Mach 2 pseudo-shock from side view.

A symmetric λ-type oblique shock wave can be observed from schlieren photo. The boundary layer separations are observed to exist on the bottom wall beneath the shock wave/boundary-layer interaction region and the corresponding top wall respectively. The boundary layer separation region begins from the wall at the foot of the front leg of the first shock wave.

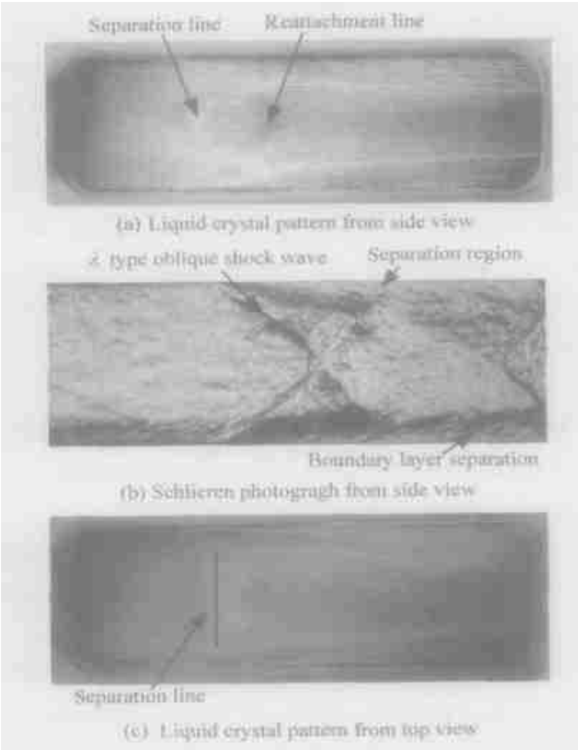

Fig. 4 Comparison of liquid crystal and schlieren experiments

Two distinct vortices exist in the separation region on the sidewall. The separation region is in the middle of the duct and appears as the strong three-dimensional reverse flow. The shape of the separation region is circular. The color in front of the separation region is purple, which should be due to the large stress in the main flow. The color is light green in the separation region, which means that the stress is smaller and the flow is reverse one. After the flow reattaches, the color of the liquid crystal becomes dark blue from light blue, while the stress becomes larger and larger. Around the reattachment line, the color is green, which means that the liquid crystal is in attenuation as shown in Fig. 5. The color is light blue around the separation line, where the liquid crystal is in accumulation.

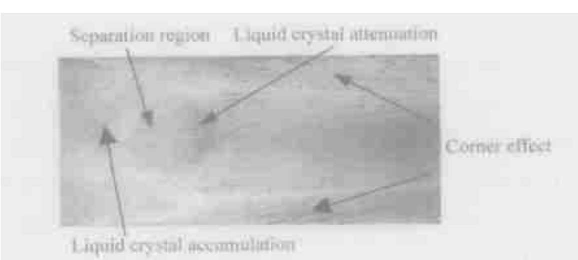

Fig. 5 Detailed photo of side wall separation region

On the bottom wall, a fairly straight separation line occurs at the same position as the circular separation line on the sidewall. The separation can be observed with the color of the liquid crystal changing from blue to green. Ahead of the separation, the color is blue, which means that it is in the main flow area and has larger stress. Separation flow is reverse flow and the liquid crystal color is green with yellow color in some area where the stress is smaller. The liquid crystal accumulation can be seen around the separation line, which appears light blue. The reattachment line cannot be clearly observed. Again, the effects of the corner flow formed by sidewall and bottom walls can be observed on the side and bottom walls, as shown in Fig. 5. The separation happens in the middle of the duct on the side and bottom walls, where the flow near the corner heads away from the sidewall so that the the liquid crystal is accumulated on the edge of boundary layer with only the middle section of the flow being two-dimensional. The flows near the corners are three-dimensional. A corner effect develops behind the sidewall separation region and continues to grow with downstream distance, which grows in size at a faster rate on the bottom wall than on the sidewall. The similar tendency was observed by oil film method in Ref. [5]. The phenomena of the corner effect were explained in Ref. [6].

The liquid crystal results show that the boundary layer flows are symmetric and the separation in the boundary layer can be observed clearly below the first oblique shock on both the sidewall and the bottom wall, which is the same as the result of the schlieren photo. However, it is difficult to compare the separation region with the schlieren photo, and more research is required in the future.

4 Conclusions

(1) The use of liquid crystals to visualize boundary-layer flow has been well established, and may be considered as an available technique. It

provides information concerning as the turbulent boundary layer separation, reattachment locations and dimensionalities of the flow. It also provides the information concerning the surface flow direction, vortices in the separation region and corner effect.

(2) Because the running time of the high Mach number wind tunnel is so short that it is better to make the liquid crystal flow slowly during the experiment without causing a dramatic loss in the quantity of crystal, so as to express the information concerning the stress magnitude and stress direction. For a particular experiment, a certain extent of experimentation will be required to get an appropriate viscosity liquid crystal.

(3) The liquid crystal BCN/192 is better than CN/R7 in the present experiment. However, the viscosity of the BCN/192 is lower. It is better to choose the higher viscosity than that of BCN/192 for Mach 2 flow.

(4) The liquid crystal flow visualization method is compared with schlieren experiment. The liquid crystal results show that the boundary layer flows are symmetric and the separations in the boundary layers can be observed clearly below the first oblique shock on both the sidewall and bottom wall, which are the same as the results of the schlieren photo.

(5) The thickness of the liquid crystal is very important. If the thickness is not adequate, the clear color change cannot be observed, which is assured many times in the experiment.

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Biographies:

WANG Dong-ping Born in 1962, she received B.S. and M.S. from Xian Jiaotong University in 1984 and 1991 respectively, and then became a teacher in Dalian Jiaotong University. She did teaching and research work in fluid dynamics. Now she is a doctoral student. From 2003 to 2004, she had been to Muroran Institute of Technology of Japan, and did the computational and experimental research about the pseudo-shock wave. E-mail: wdp1962@163.com. Tel: 0411-84106966.

ZHAO Wen-zhong Born in 1944, male, in Liaoning Province, Professor and Ph. D supervisor. Graduated from Northeastern University in 1967. Got M.S. Degree of Dalian Jiaotong University in 1982. And working as a teacher there from 1982 until now. During this period, as a visiting professor visiting U.S.A. for two years. Right now, Directory of Research Center of Modern CAD/CAE Technology, and the research area is on the key problems in mechanical CAE. 62 papers published and obtained twice the second prizes from Railway Ministry. Tel: 0411-84106207. E-mail: wzzhao@djtu.edu.cn