Shock stand-off distance visualization in hypersonic shock tunnel using electrical discharge technique

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ABSTRACT

Visualization of the detached shock wave that forms ahead of a blunt body flying at hypersonic Mach number using electrical discharge technique is a simple and convenient technique to measure the stand-off distance experimentally in an hypersonic shock tunnel. In this technique a thin sheet of electrical discharge generated between a point electrode attached to the wall of the test section and a line electrode embedded on the model surface reveals the position of the shock wave around the body in hypersonic flow. In this paper we present the details of this technique and sample results obtained for typical body shapes tested in HST2 shock tunnel at a freestream Mach number of 5.75. The detached shock waves in front of the test models are clearly visualized using this technique. The shock stand-off distance estimated based on the numerical results for a large angle blunt cone obtained using a commercial CFD code match well with the experimentally measured value. These results clearly demonstrate the suitability of the electrical discharge technique for visualizing the flowfields in hypersonic testing facilities having very short test times.

Keywords: Hypersonic flow, Shock tunnel, Shock wave, Stand-off distance, Flow visualization

1. INTRODUCTION

The potential use of hypersonic vehicles for civilian applications has induced global interest in hypersonics in recent times. Many high enthalpy tunnels have been established in order to meet the demands for the experimental aerodynamics data for the design of future hypersonic vehicles. In addition efforts are being made to generate the design data through CFD techniques. The experimental data generated from the ground based testing facilities is also crucial for validating the computer codes developed by the CFD community.

Visualisation of the detached shock wave that forms ahead of a blunt body in hypersonic flight is an important aspect of the hypersonic research as the stand-off distance is a convenient parameter for validating any analytical or numerical models before using them for predicting the other flowfield parameters[1]. Conventionally many optical techniques like schlieren, shadowgraphy, interferometry and holography have been used for this purpose with fair degree of success. These classical methods are based on changes in the light due to the variation of the refractive index of the fluid. Both shadowgraphy and schlieren systems are based on the light deflection in the flowfield while interferometry is dependent on the change of optical phase in the fluid. Although these techniques are useful in visualizing the two dimensional shock shapes and boundary layer details, glaring inadequacies come to fore when one attempts three dimensional or cross sectional shock shape visualization. Holography on the other hand is a technique capable of providing three-dimensional whole field details. A hologram can freeze all the information contained in the amplitude and the phase of the light wave and then it can be reconstructed to visualize the flowfield details. Also, three-dimensional shock shape visualization is possible using the electron beam and vapour screen methods. But the electron beam method is suitable for rarefied gas or extremely low-density gas but not suitable for normal density flows and the vapour screen method has the possibility of changing the characteristics of the gas by the water vapour.

The flow visualization in a pulsed facility like hypersonic shock tunnel is quite a challenging task. This is primarily because

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of very short useful test times, shorter optical path lengths which is dictated by the size of the test section and of course very low free stream density levels. For example, typical useful test time in the IISc shock tunnel HST2 is ~ 800 μs and free stream density is of the order of 10^{-2} to 10^{-3} kg/m^3. The free-piston driven shock tunnel HST3 which is capable of simulating the real gas effects and velocities up to 7 km/s has much shorter test time. Although the above mentioned techniques can be used for visualizing flowfields in these tunnels the complete system of visualization is complex and require vibration free environment for producing good results. Moreover these methods require powerful light sources along with the associated expensive instrumentation. In light of this there is a strong need for developing alternate simple and inexpensive flow visualization technique suitable for using in testing facilities like hypersonic/hypervelocity shock tunnels with test times of the order of few hundred microseconds.

Keeping in mind both the present requirement and also futuristic needs of flow visualization in pulsed hypersonic test facilities, a novel flow visualization technique based on electric discharge has been developed[2,3]. This technique is developed from the basic principles and is extensively used for visualizing the flowfield nature around different aerodynamic body shapes in IISc shock tunnels HST1 and HST2. The purpose of the present paper is to show that the electrical discharge technique can be used to visualize the detached shock waves in front of the blunt bodies travelling at hypersonic Mach numbers. Detached shock waves around a slender cone with blunt nose, large angle blunt cone and a semi-spherical body are presented. With further refinements the technique can be used to measure the shock stand-off distance.

2. DESCRIPTION OF ELECTRICAL DISCHARGE TECHNIQUE AND EXPERIMENTAL ARRANGEMENT

In general, strong spatial variations in the intensity and spectral nature of the light generated by electrical discharge occur whenever there are large gradients of basic parameters like pressure, density and temperature along the discharge path. This implies that if a discharge is generated in a flowfield where strong gradients of flow properties are present these variations can be captured by photographing the spontaneous light emitted from the electrical discharge. This feature of electric discharge can be used in qualitative visualization of the flowfield around bodies flying at hypersonic Mach numbers, as the hypersonic flowfields around bodies comprise of strong regions of varying density and temperature due to presence of shock waves and strong viscous interactions. When a discharge takes place across a shock wave, the position of the shock wave can be clearly seen as the light intensity from the shock wave will be different from that of the free stream.

Based on this basic principle we have developed a flow visualization technique suitable for hypersonic shock tunnels with very short test time. The experimental arrangement for the flow visualization in HST2 hypersonic tunnel along with the electrical circuit used for the generation of discharge across the flowfield is schematically shown in Fig.1. The HST2 shock tunnel consisting of a 7m long stainless steel shock tube of 50 mm internal diameter is capable of producing reservoir enthalpy ~5 MJ/kg at the entrance of the hypersonic nozzle in the reflected mode. In the straight through mode the 10° expansion angle conical nozzle of 30 cm exit diameter produces freestream Mach number of 5.75 in 30 cm x 30 cm size test section. The test model with the electrical connections is fixed in the test section using a bow-sting arrangement with provision for varying the angle of attack. The electrical discharge is generated inside the test section using a point-line electrode pair arrangement. The point electrode is suspended from the roof of the test section such that the disturbances generated due to the hypersonic flow over this electrode are not impinging on the test model. The line electrode is a thin (~0.2mm) copper strip mounted vertically on the model such that the edge of the electrode is flush with the surface of the model. Typical electrode arrangement for a large angle blunt cone is shown in Fig. 2. The distance between the electrodes is maintained around 60 mm to ensure uniform illumination of the flowfields at moderate voltage levels. Extreme care is taken to insulate the shock tunnel from high voltages during the discharge and the models are fabricated using Bakelite material to ensure insulation as well as to eliminate reflection of stray light from the model surface. Reflections from the side walls of the test section are eliminated by pasting black paper to the inner walls.

The high voltage power pack used in the experiments reported here is a dry type air cooled high reactance single phase transformer. The primary voltage is rated from 0 to 220 V. The secondary of the transformer has three ranges namely 0 to 2 kV, 0 to 2.5 kV and 0 to 3 kV. These variations in the output of the transformer enables operation of the discharge device with different field strengths. The full load current is 1 Amp. and the maximum short circuit current is 2 Amp. For ensuring the stable discharge and hence a controlled radiation from the discharge for a short duration, special current clamping mechanism has been incorporated in the high voltage transformer. Common ground terminal is provided for the entire shock tunnel metallic structure and the transformer body.

In a pulsed facility like shock tunnel it is very critical that both the duration and the exact timing of the discharge pulse are properly controlled. The delay in the occurrence of the discharge pulse in the tunnel test section has to be precisely set to ensure striking of the discharge during the steady hypersonic flow over the model. Since the experimental test time scales are in microseconds both the high voltage pulse and delay has to be controlled electronically. Hence a special purpose integrated switching and delay pulse control module is built for precise operation of the discharge device. The three major tasks performed by the circuit are rectification of the high voltage AC supply, precise switching of the high voltage power source for initiating the discharge process and controlling of the quenching of the discharge after the predetermined transient time scale which is usually ~ 2 to 3 μ sec. The delay control unit consists of CPU 8031, 8 bit microcontroller, EPRAM 2764 programmable 8 K memory, couple of optocouplers and thumb wheel switches. The input signal for starting of the discharge is obtained from the platinum thin film sensors placed near the end of the shock tube for shock speed measurement. Once the shock wave reaches the sensor, due to the sudden increase in the temperature an output voltage signal is given out from the thin film sensor. The voltage level of this signal is suitably conditioned using an amplifier to about 4 V before feeding into the pulse control module. The crystal clock inside the CPU starts instantly. Before the commencement of the experiment both the delay and the duration of the discharge are adjusted using thumb wheel switches. While the delay can be varied upto 10 ms, the duration can be adjusted to a maximum of 1 ms. The delay time set is fed into the timer and when the memory overflows after the set delay, an interrupt signal is sent to the optocouplers (OP1 & OP2). An optocoupler is an integrated single chip comprising of a light emitting diode (LED) and a photo transistor. On the arrival of the interrupt signal the LEDs are activated and the light from the LEDs is sensed by the photo transistors and the corresponding photo current generated will result in the biasing of the high voltage transistor, there by switching them ON. The electric circuit is closed and the high voltage is applied after rectification to the capacitor HC1, which in turn discharges, there by, triggering the discharge between the electrodes. After the time lapse set by pulse duration controller the microcontroller sends another interrupt signal to the optocouplers resulting in turning the transistors OFF, there by quenching the discharge between the electrodes. The high voltage supply to the electrodes is cut-off which results in instant termination of the discharge. Residual glow surrounding the electrodes is observed sometime even after discharge quenching in actual experiments.

3. RESULTS AND DISCUSSIONS

The appropriate delay during the experiments is adjusted using the trigger signal from the thermal sensor near the end of the shock tube. It is important to minimise the electric field-flowfield interaction for meaningful flow visualisation. This is ensured in the present technique by limiting the duration of the discharge to 2 μs. During this short time the whole flow field appears to be frozen as the flow velocity is much smaller than the velocity of electrons in the electric field. The light emitted by the electrical discharge is photographed using Olympus OM-2 model F1.8 camera mounted outside the test section. Since the light emitted is very weak and the duration of the emission is short we need to use films of high sensitivity. In the experiments reported in this paper we have used high speed ASA 1600 films and the camera is operated in B exposure mode. Efforts are being made to use a CCD camera.

The electrical discharge technique has bee extensively used to visualize the shock waves formed by a flat plate and a slender cone at different angles of attack in an hypersonic flow[3]. Also we have demonstrated the suitability of this technique for three dimensional flow visualization. However, extension of the technique for visualising the detached shock wave in front of the blunt bodies was found to be difficult due to the interference of the disturbances generated by the point electrode with the detached shock wave. Hence the slender cone with blunt nose was used as a test case to establish the suitability of this technique for visualization of shock shapes for such class of bodies at hypersonic Mach numbers. The timing and the duration of the discharge were standardized with the help of this simple model before testing the complex models. The shock waves, visualized using the electric discharge technique in HST2 tunnel, ahead of the slender cone with blunt nose, blunt cone of 120° apex angle and semi-sphere at zero degree angle of attack at a flow Mach number 5.75 are shown in Figs 3, 4 and 5, respectively. The shock wave in front of the slender cone is not sharp as no effort was made to optimise the operating parameters of the flow visualization technique for this particular model. Figs. 4 and 5 show the detached bow shock wave in front of the hypersonic bodies and also the shock waves generated by the point electrode in the test section. It is clear from these pictures that the flow disturbances generated by the point electrode are not touching the model surface and the shock wave in front of the model is purely due to the undisturbed hypersonic flow. On the other hand when we mounted the large angle blunt cone at 45° angle of attack using a special mounting arrangement we noticed the impingement of the shock wave generated from the point electrode on the model surface, as shown in Fig. 6. The interaction of the shock wave generated by the point electrode with the detached shock wave ahead of the body has resulted in lifting of the body shock. This picture clearly indicates that the flow visualization technique proposed in this paper can be used for investigating the shock-shock interaction phenomenon in hypersonic shock tunnels.

The detached shock wave and the shock stand-off distance are clearly visible in Figs. 4 and 5. We have also analysed the complex flowfields around the large angle blunt cone numerically using the commercial CFD code CFX-TASCflow (AEA International Plc)[4,5]. This code solves the complete Navier-Stokes equations in the strong conservative form by an implicit pressure based method. Coupled solutions of mass, momentum and energy are obtained using a novel finite element based finite volume method. About 200 time steps were required for 4 orders of average residual reduction using the upwind differencing scheme which took approximately 10 hours of CPU time on a RS5000 processor based Silicon Graphics workstation O2 running IRIX 6.3. The computed Mach contours of the Mach 5.75 hypersonic flow around the 120° apex angle blunt cone model are shown in Fig. 7. The curved shock in front of the body has been well captured by the simulation. The shock wave visualized using the electrical discharge technique shown in Fig. 4 matches very well with the numerically predicted shock shape for the 120° blunt cone at zero incidence. However, the matching of the measured stand-off distance with the numerically predicted 6mm is poor. This is essentially because of the inaccuracy in measuring the shock stand-off distance from the photographs as its value is very small compared to the body radius. The accuracy of measuring the stand-off distance can be improved by scanning the negative of the photograph using a densitometer which will help in locating the position of the shock wave and the model surface accurately or using a CCD camera to record the shock wave.

4.CONCLUSIONS

We have presented a flow visualization technique based on the electrical discharge phenomenon to visualize the flowfields around hypersonic models tested in short duration hypersonic tunnels. The technique is applied to visualize the detached shock waves in front of blunt bodies at flow Mach number of 5.75 in HST2 shock tunnel. The visualized shock shape agrees very well with the numerically computed detached shock wave for a blunt body of 120° apex angle at zero degree angle of attack. This inexpensive technique is very simple to apply and can be improved further to experimentally measure the shock stand-off distance for complex body shapes in hypersonic flows. In addition, this technique can used for studying the flow starting process in the nozzle of a hypersonic shock tunnel by striking the discharge at regular intervals starting from the rupture of the secondary diaphragm. This application requires a CCD camera capable of recording at an interval of about 10 μs.

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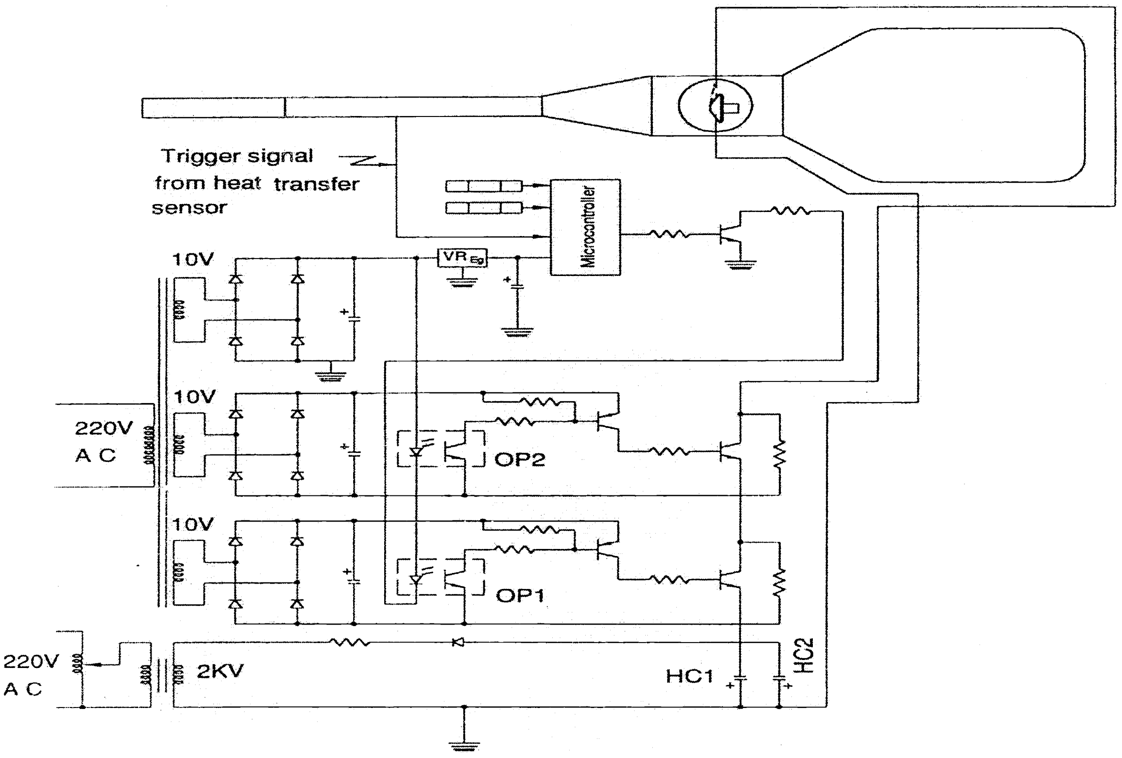

Fig.1 Schematic diagram of the experimental set up used for flow visualization in hypersonic shock tunnel HST2 using electrical discharge technique.

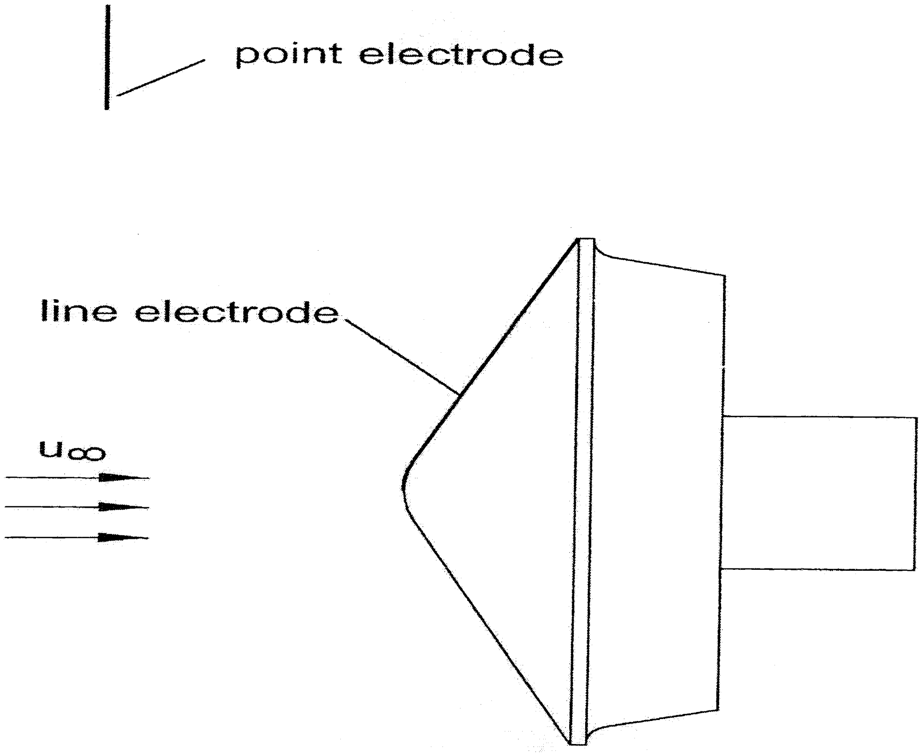

Fig.2. Schematic diagram of electrode arrangement used for flow visualization around large angle blunt body.

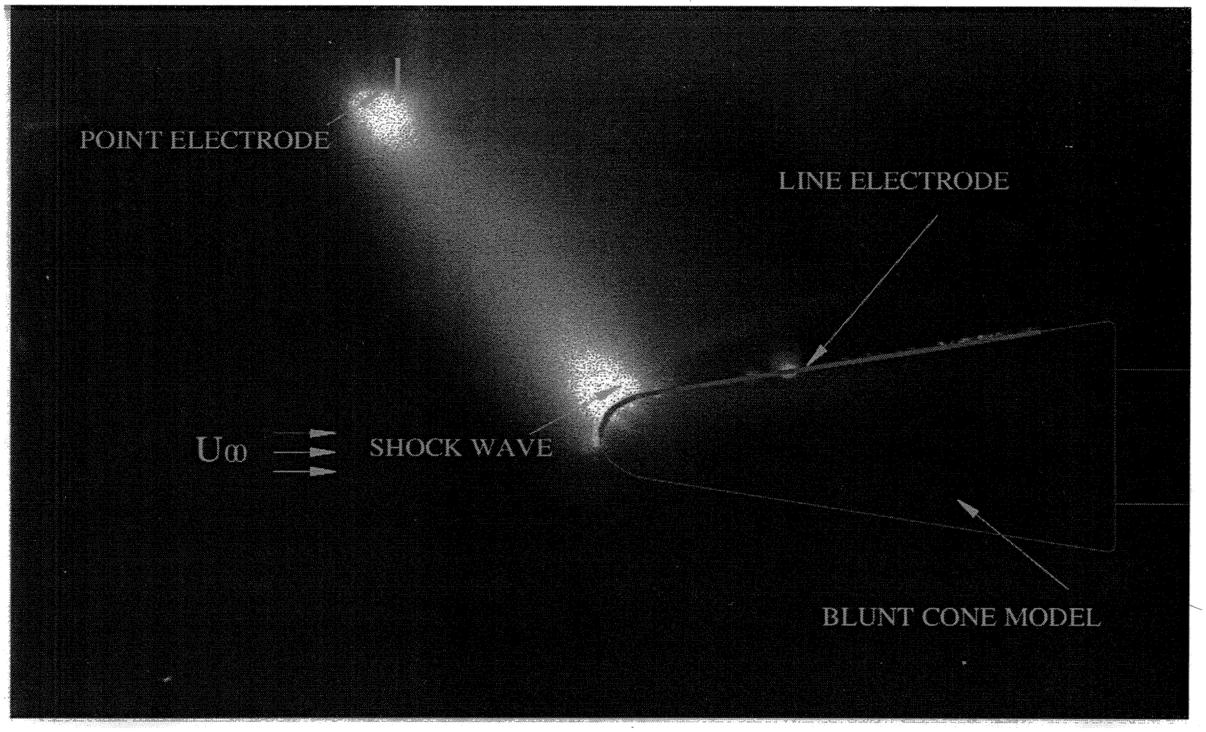

Fig.3. Shock wave around a 20° apex angle cone at zero degree angle of attack in Mach 5.75 hypersonic flow.

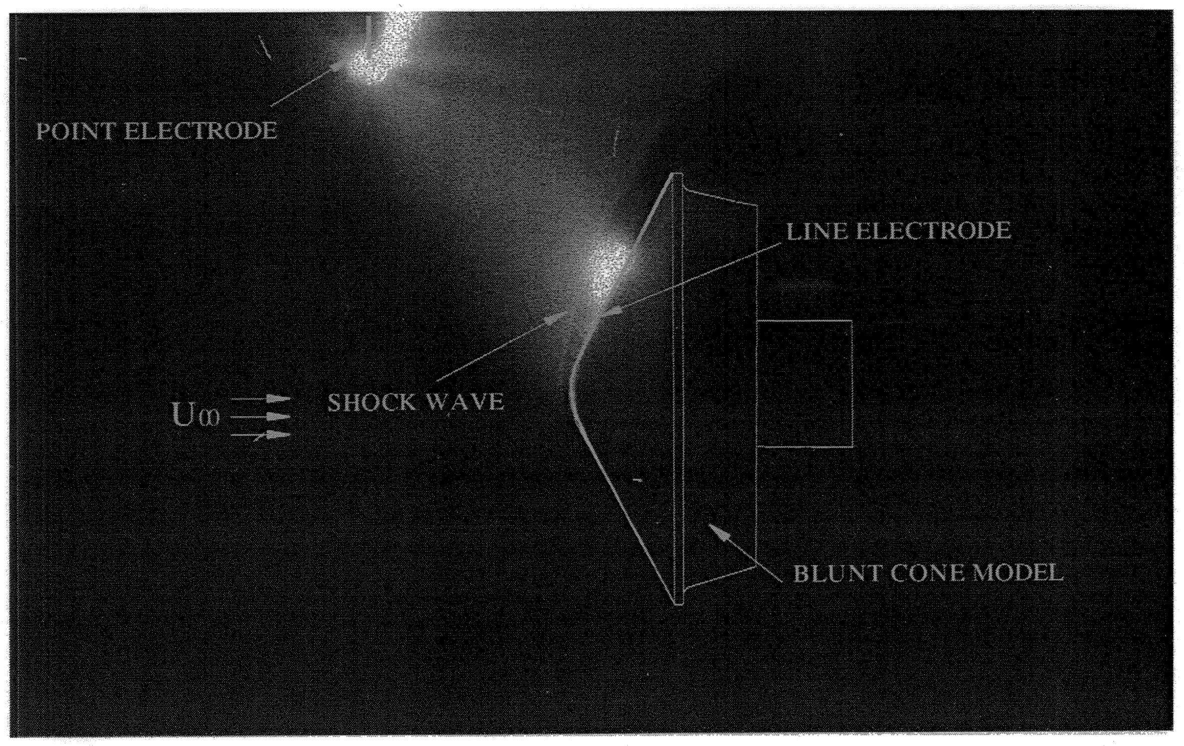

Fig.4. Detached shock wave ahead of a 120° apex angle blunt cone at zero degree angle of attack in Mach 5.75 hypersonic flow.

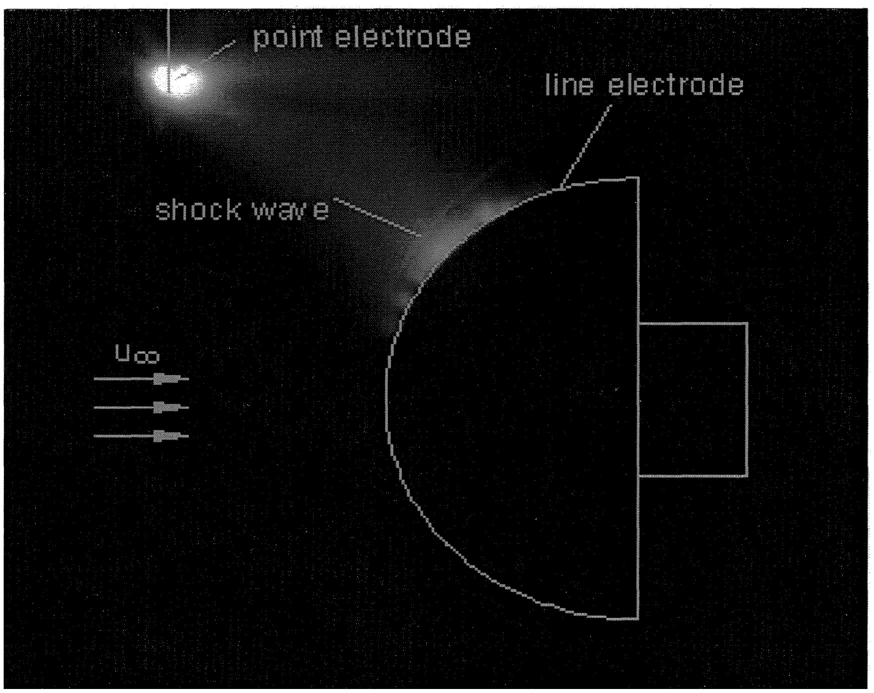

Fig.5. Detached shock wave ahead of a semi-sphere at zero degree angle of attack in Mach 5.75 hypersonic flow.

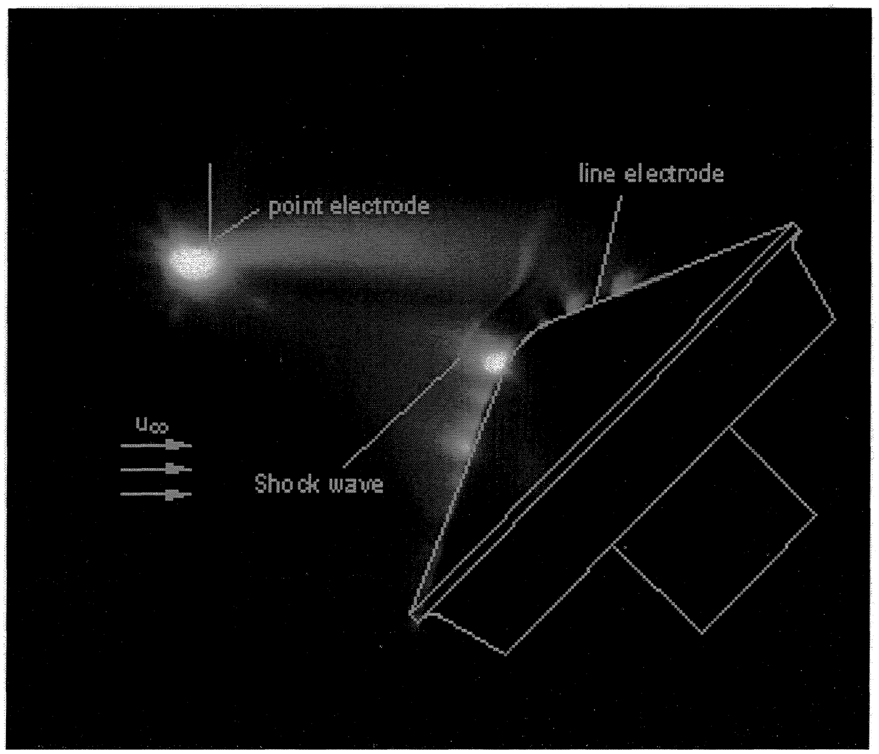

Fig.6. Shock wave pattern ahead of a 120° apex angle blunt cone at 45° angle of attack in Mach 5.75 hypersonic flow showing shock-shock interaction.

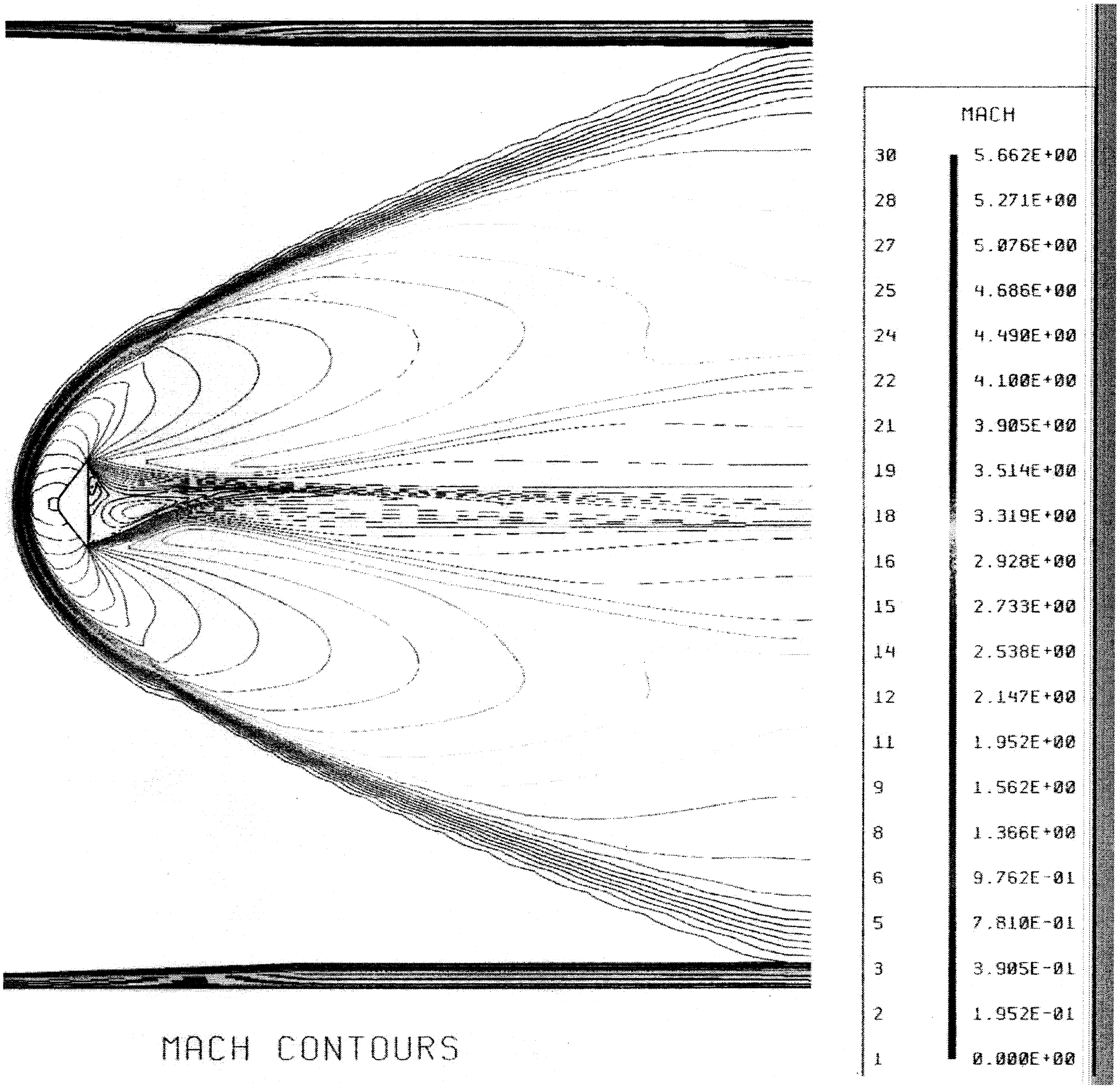

Fig.7. Mach contours around a 120° apex angle blunt cone at zero degree angle of attack in Mach 5.75 hypersonic flow generated using a CFD code.