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ABSTRACT

High enthalpy flow separation over bodies at hypersonic speeds continues to intrigue researchers, since considerable differences are observed between experiments and CFD. In the present study the separated flow field around a double cone has been investigated at nominal stagnation enthalpies of 4.2 MJ/kg and 1.6 MJ/kg. The flow around a double cone (first cone semi-apex angle = 25°; second cone semi-apex angle=68°) has been visualized using high-speed image converter camera (IMACON) and double exposure holographic interferometry in the Shock Wave Research Center's (SWRC) free piston driven shock tunnel at Mach 6.99. Presence of a triple shock structure in front of the second cone, and non-linear unsteady shock structure oscillation in the flow field, are the significant results from visualization studies.

Further surface convective heat transfer measurements have been carried out at a nominal Mach number of 5.75 in the Indian Institute of Science (IISc), hypersonic shock tunnel HST-2. The surface heat transfer in the vicinity of transmitted shock impingement point on the second cone surface fluctuates between 100 W/cm^2 – 400 W/cm^2 (± 10 %) for nearly identical (± 8 %) free stream conditions, indicating the severe unsteadiness in the flow field. Similar unsteady fluctuations in the heat transfer and oscillatory shock structure in the flow field around the double cone are also observed in the numerical simulations carried out by solving the axi-symmetric Navier-Stokes equations.

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INTRODUCTION

The role of non-equilibrium real gas effects on hypersonic flow separation induced by shock wave boundary layer interaction is still not clear. Also the influence of flow separation on the basic aerodynamic coefficients like lift, drag and pitching moment is unclear. Notwithstanding the great strides made by CFD techniques the ability to predict large-scale separated flow features especially at high enthalpy hypersonic flow conditions is rather poor. More often than not the separation length measured during experiments does not agree well with CFD results [1]. The separation length computed by different CFD codes taking into account various real gas effects at high enthalpy flow situations appear to be different and the actual cause for such variations is not very clear. On the other hand reliable experimental database for separated high enthalpy flows that can be used for CFD code validation studies is rather limited.

The interaction between a shock wave and boundary layer often results in local regions of separated flows. Upstream facing corner formed by a deflected control surface on a hypersonic re-entry vehicle, internally generated shock wave impinging on a boundary layer in hypersonic air breathing propulsion system and separation bubble induced by control surface deflection are some of the typical scenarios where precise knowledge of separated flow features are essential. Recently [2] new correlation parameter has been deduced for high enthalpy flows based on the experimentally measured separation length, for a 2-D double wedge configuration. Wright et al [3] have also investigated type IV and V type shock interaction processes using a double cone model in a gun tunnel at Mach 8. However there is no reliable experimental database for 3-D separated flow situations at high enthalpy conditions, which will be useful in validating the CFD codes used for simulating the dissociated hypersonic flows.

A double cone model is a useful configuration for studying the 3-D separated flow features under severe adverse pressure gradient. Depending on the first and second cone apex angles the flow field around the double cone will comprise of several classical viscous flow features such as shock wave / boundary layer interaction, triple shock interaction, unsteady shear layers and non-linear shock oscillations. A schematic representation of the viscous hypersonic flow field around a double cone is shown in Fig. 1. An oblique shock emanating from the leading edge of the first cone, a recompression shock from the separation zone and the bow shock in front of the second cone are some of the main features of the flow around the double cone. These three shocks intersect ahead of the second cone resulting in the formation of a triple point. Following the triple shock interaction a transmitted shock emerges from the triple point impinging on the second cone. This shock impingement on the surface of the second cone results in instantaneous pressure spike, which in turn will further enhance flow separation. But then the gas that is reversed into the separation zone must flow out of the shear layer near the edge of the separation zone. However as the second cone angle is increased, the impinging transmitted shock becomes more normal and more gas is reversed into the separation zone. Eventually a steady shear layer cannot eject enough mass and the flow becomes unsteady and begins to oscillate and is highly non-linear. On the other hand even small changes in the position and shape of the bow shock ahead of the second cone will result in the shifting of the triple point, which in turn will dictate the size of the separation zone. Although most of these basic gas dynamic features are known, what really happens at high enthalpies in dissociated flow environment is not clear. There is no experimental database on the unsteady shock oscillations in hypersonic separated flow situations over bodies, which will help in validating the results from numerical studies.

In this backdrop the present collaborative study between Shock Wave Research Center (SWRC) and Department of Aerospace Engineering, Indian Institute of Science (IISc), has been undertaken with the following objectives:

1. Visualization of the separated flow field at Mach 6.99 around a double cone (first cone semi-apex angle = 25°; second cone semi-apex angle=68°) using (a) Double exposure holographic interferometry, (b) Schileren, (c) Shadowgrphy and (d) High speed photography using IMACON camera in SWRC.
2. Determination of surface convective heat transfer coefficient on the double cone at Mach 5.75 conditions using platinum thin film sensors deposited on Macor substrate in IISc.
3. Simulation of the separated flow features around double cone using axi-symmetric Navier-Stokes equations at both low and high enthalpy flow conditions in SWRC.

While the experiments at high enthalpy (4 MJ/kg) were carried out in the SWRC free piston driven shock tunnel the low enthalpy (1.6 MJ/kg) tests were conducted in the IISc hypersonic shock tunnel HST2. The details of the experimental set-up, diagnostic techniques used along with important results have been described in the subsequent sections.

EXPERIMENTS

Flow visualization at high enthalpy

One of the primary goals of the visualization experiments is to characterize the nature of flow field around the double cone in dissociated hypersonic flow. A schematic diagram of the brass double cone model used in the study along with the photograph is shown in Fig. 2. Since the model erosion was quite significant new model is used for every run. The experiments are carried out in the SWRC free piston driven shock tunnel. The facility is 13 m long comprising of a high-pressure reservoir (volume of 0.07 m^3), 6 m long compression tube (internal diameter of 100 mm with 50 mm wall thickness), a stainless steel shock tube (2.04 m long; internal diameter 38 mm; wall thickness of 20 mm), a Mach 7 conical nozzle, test section and dump tank. A 3.078 kg piston is used for accelerating the driver gas in the compression tube. In the present experiments air is used as the test gas. Typical dissociated air after expansion from the conical nozzle to the test section consists of 67.5% Nitrogen, 13.1% Oxygen, 19.3% of NO. The nominal test flow conditions are listed in Table 1. All the experiments are carried out at zero angle of incidence. For further details on the SWRC free piston driven shock tunnel see Reference [4]

Double exposure holographic interferometry

Holographic interferometry is a very powerful optical technique, which can be used for quantitative characterization of the flow field. Both finite and infinite fringe interferometry of the separated hypersonic flow over the double cone model have been carried out. Further the precise location of the separation point on the first cone is also attempted using shadowgraphy and schlieren techniques. Multiple optical techniques have been used in this study to precisely locate the separation point on the first cone and also to quantify the density field around the double cone. The optical set-up used for double exposure holographic interferometry is shown in Figure 3. A 694nm wavelength ruby laser (Lumonics HL33, 30 ns pulse duration) is used as the light source for all the visualization experiments. A beam splitter is used for dividing the light beam into object and reference beams. For details of the optical set-up for holographic interferometry see Reference [5].

The infinite fringe interferogram of the high enthalpy flow around the double cone is shown in Figure 4. The separation point is clearly seen on the surface of the first cone along with the bow shock of the second cone. Although the number of fringes denoting the isopynics are limited in this case the separated flow region is clearly visualized. In order to quantify the density field further finite fringe interferometry was carried out. The visualized flow field is shown in Figure 5. It is quite difficult to make out the precise location of the separation point from this photograph. Fringe analysis is also rather challenging and efforts are currently underway in SWRC to precisely derive the relative density distribution around the double cone using Fourier transform and Abel deconvolution techniques. Recently [6] manual fringe analysis procedure was used to identify the 0.5 order fringes in the flow field to locate the secondary disturbances in the separated flow region. The visualized flow field around the double cone using shadowgraphy is shown in Figure 6. From both infinite fringe interferometry and shadowgraphy the ratio of separation point from the leading edge to the face length of the first cone is found to be 0.3.

However these interferometric studies revealed that the shock structure recorded at various time instants during the steady flow test window to be different. This implies that the flow field should be unsteady with oscillating bow shock ahead of the second cone. But the location of the separation shock was almost same in all the runs. It is important to note here that precise identification of the separation point on the first cone is possible only with surface heat transfer or pressure measurements. In order to experimentally visualize the unsteady shock oscillations further visualization studies were carried out using high-speed image converter camera (IMACON, DRS Hadland Ltd.). The sequential flow field features captured by the IMACON at 30μs time intervals are shown in Fig.7. The average test time in the SWRC tunnel is ~ 300 μs. These results reveal severe shock oscillation and later movement of the transmitted shock impingement on the second cone surface. The non-linear behaviour of the shock interaction process is observed in many runs and at this point of time we are not sure about the total time duration of the unsteady shock oscillations. Although the spatial resolution of the photographs is not very good the gross shock structure in the flow field is clearly visualized.

Now some of the questions which arise are: 1) Is this shock oscillation a function of flow Mach number? 2) How long does this unsteady oscillations last in the flow field? 3) What is the role-played by vibrational, rotational and translational temperatures in the separated flow fields? and finally 4) Will we observe similar behaviour in lower stagnation enthalpy and Mach number? In case this behaviour is purely a result of the inviscid shock interaction dynamics then the shock oscillation process will last till the flow adjusts itself to the amount of adverse pressure gradient induced by the second cone angle. But this aspect cannot be verified in short duration facilities which have a test window of few ~ms at the most. Hence schlieren and pressure measurements have to be carried out in a hypersonic wind tunnel where the possible test window will be ~ 1000 ms. Nevertheless in order to experimentally determine the surface convective heat transfer rates on the double cone further tests were carried out in the IISc hypersonic shock tunnel HST2 at Mach 5.75.

Heat transfer measurements

The shock tube portion of HST2 consists of a 50mm diameter stainless steel driver and driven sections separated by 1.5 mm thick aluminum diaphragm. The shock wave velocity is monitored by with the help of platinum thin film thermal sensors located at the end of the shock tube. The dynamic pressure behind the primary and the reflected shock waves is measured using a pressure transducer (PCB, Piezotronics) located at the end of the driven section. The wind tunnel portion of the HST2 comprises of a truncated conical nozzle terminating into a 30 cm $\times$ 30 cm size test section. The typical test conditions of the experiments are shown in Table 2. The tunnel is capable of producing a reservoir enthalpy of up to 5 MJ/kg and has an effective test time of about 800 μs. A transient PC based data acquisition system with requisite software is used for recording and processing of the data.

Platinum thin film sensors are deposited on the ceramic glass Macor inserts, which in turn are embedded in the metallic blunt cone model. Thin film sensors are deposited on the Macor using platinum 05-X metallo-organic ink (M/s Englehard-Clal, UK). The sensors are connected through the analogue network circuitry, to the PC based data acquisition system. The details of the instrumentation used in heat transfer measurements along with the detailed data reduction methodology have been explained elsewhere [7].

Initially experiments are carried out using the double cone model with first cone semi-apex angle of 25° and second cone semi-apex angle of 68°. The geometric dimensions of the model is exactly similar to one used in the flow visualization experiments. Surface heat transfer rates are also measured on one more double cone model having a first cone semi-apex angle of 15° and second cone semi-apex angle of 35°. The photographs of the instrumented double cone models are shown in Figs 8 (a) and (b). The surface heat transfer is measured on the double cone (25°/68°) surface at six different locations. The measured convective heat transfer on the double cone model is plotted in Fig. 9. The measured heat transfer rates in 7 different shots with almost identical (± 8 %) free stream conditions are plotted along the cone surface. Since we were not able to deposit many gauges on the first cone surface it is not possible to precisely locate the flow separation point. What is interesting from these measurements is the wild fluctuations measured in gauge no.4 located on the second cone. It is very clear that this location corresponds to the transmitted shock impingement point. As the bow shock oscillated the transmitted shock is also displaced and it oscillates along the second cone surface. Depending on the location of the transmitted shock impingement point and platinum thin film sensor either higher or lower values of surface heat transfer is recorded. The uncertainty associated with these measurements is ± 10 %. Efforts are underway to sputter the platinum thin film gauges on Macor to further improve the accuracy of the unsteady heat transfer measurements. When we reduced the second and first cone angles as expected the measured values of the surface heat transfer were lower. The heat transfer on the double cone model having a first cone semi-apex angle of 15° and second cone semi-apex angle of 35° is shown in Fig. 10. In this case the heat transfer is measured at 10 different locations along the model surface. The unsteady peak heat transfer measured on the second cone surface has come down to ~ 65 W/cm^2 as compared to ~ 400 W/cm^2 measured in the other double cone (25°/68°) model. Numerical results are also shown on the same graph. Although the agreement between experiment and CFD is satisfactory on the first cone, considerable differences are observed in separated flow region. Heat transfer measurements will have to be carried out in high enthalpy conditions before we can clearly identify the role played by the dissociation temperatures on the shock oscillation and separation. In order to complement the experiments illustrative numerical study was undertaken where in efforts were made to simulate the flow features both at high and low enthalpy conditions.

NUMERICAL STUDY

The laminar axi-symmetric Navier-Stokes equations are solved by the finite volume method on a solution-adaptive unstructured quadrilateral grid [8]. The MUSCL-Hancock scheme is used to determine the inviscid flux through interfaces. The gradients or slopes of primitive variables are calculated by the least square method. In order to maintain the monotonicity constraint the slopes are modified using the minmod limiter. The HLLC approximate Riemann solver is used. The viscous terms are solved by the central difference scheme. Initially a rather coarse grid that covers the whole domain is generated, and during computation the grid cells are locally divided around the solid boundary, shock waves, slipstreams, and vortices. The minimum height of mesh in the boundary layer is about 0.025mm, and the aspect ratio is ranging from 1 to 20. The grid cells with such a low aspect ratio are used to be able to resolve the separation point precisely.

Initially using the free stream conditions shown in Table 1 the flow features around the double cone (25°/68°) is simulated. The sequential numerical interferograms at different time instants are shown in Fig. 11. The results qualitatively confirm the trend we observed in the visualization studies (Refer Fig.7). Actually the numerical results were obtained before the experiment. Further using the free stream conditions for low enthalpy conditions (Table 2) the surface heat transfer rates on the double cone (25°/68°) in low enthalpy conditions were simulated. The unsteady surface convective heat transfers as a function of time are plotted in Fig.12 at different gauge locations. Although we observe similar trends there is no agreement between experiments and CFD absolute values of measured heat transfers. Considerable difficulties were encountered in the convergence of solutions. Efforts are currently underway in SWRC to sort out the issues of solution convergence in CFD codes for these kinds of flow situations. Moreover the effects of flow dissociation have been neglected in the current simulations. The future study will focus on clearly characterizing the unsteady shock oscillation cycle time around the double cone model at hypersonic speeds.

CONCLUSIONS

The separated flow field around a double cone has been investigated at nominal stagnation enthalpies of 4.2 MJ/kg and 1.6 MJ/kg. The flow around a double cone (25°/68°) has been visualized using IMACON and double exposure holographic interferometry in the SWRC free piston driven shock tunnel at Mach 6.99. Presence of a triple shock structure in front of the second cone, and non-linear unsteady shock structure oscillation in the flow field, are the significant results from visualization studies. Further surface convective heat transfer measurements are made at Mach 5.75 in the IISc, hypersonic shock tunnel HST-2. The surface heat transfer in the vicinity of transmitted shock impingement point on the second cone surface fluctuates between 100 W/cm^2 – 400 W/cm^2 (± 10 %) for nearly identical (± 8 %) free stream conditions, indicating the severe unsteadiness in the flow field. Similar unsteady fluctuations in the heat transfer and oscillatory shock structure in the flow field around the double cone are also observed in the numerical simulations carried out by solving the axi-symmetric Navier-Stokes equations.

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Table 1 Nominal test conditions in SWRC free piston driven shock tunnel

H_0(MJ/kg)	U_∞(m/s)	T_∞(K)	ρ_∞(kg/m³)	M_∞	Specific ratio	$Re_\infty \times 10^5$ /model Diameter
4.8	2750	387	0.02	6.99	1.399	1.48

Table 2 Nominal test conditions in IISc shock tunnel HST2

H_0(MJ/kg)	U_∞(m/s)	T_∞(K)	ρ_∞(kg/m³)	M_∞	P_o (kPa)	$Re_\infty \times 10^6$ /m
1.6	1478.4	164.52	0.0102	5.75	586.38	1.4784

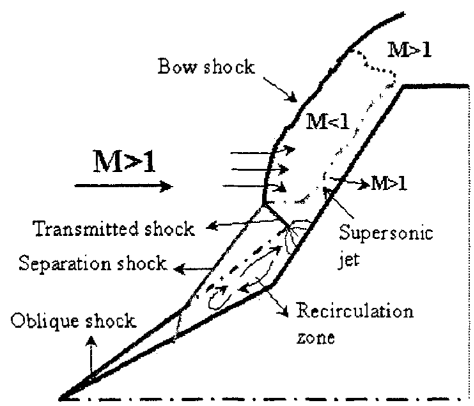

Fig. 1 Schematic representation of viscous hypersonic flow over a double cone.

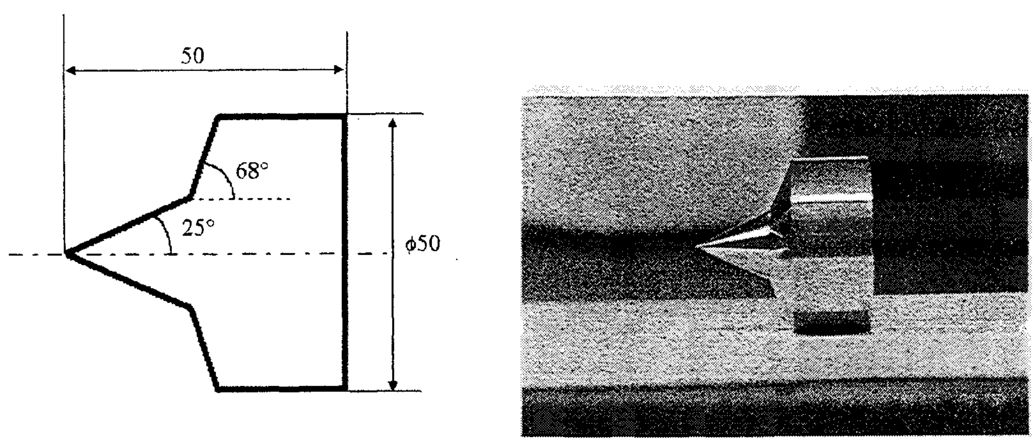

Fig.2 Schematic diagram and photograph of the double cone model used in the visualization experiments

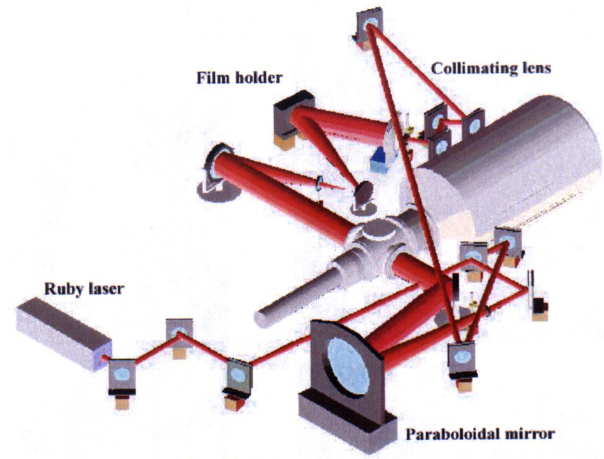

Fig. 3 The optical set up used double exposure holographic interferometry experiments.

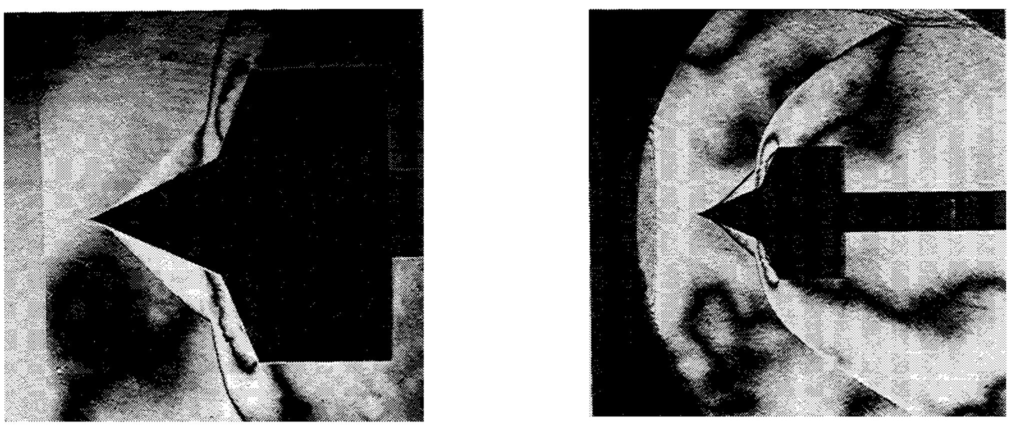

Fig. 4 Infinite fringe interferometry of the flow field around the double cone at Mach 6.99

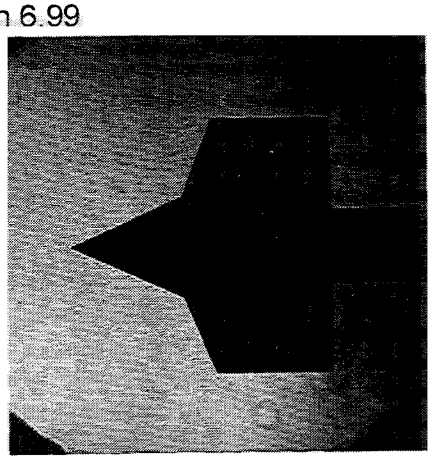

Fig 5 Finite fringe interferogram of the flow flow field around double cone.

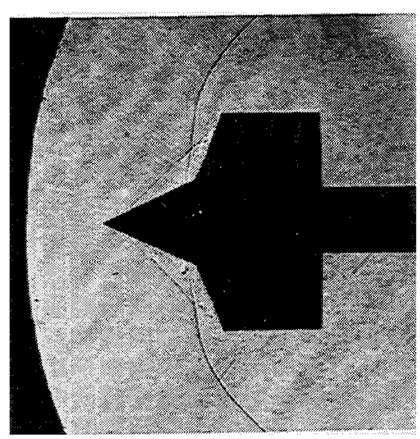

Fig.6 Shadowgraph depicting the features around the double cone.

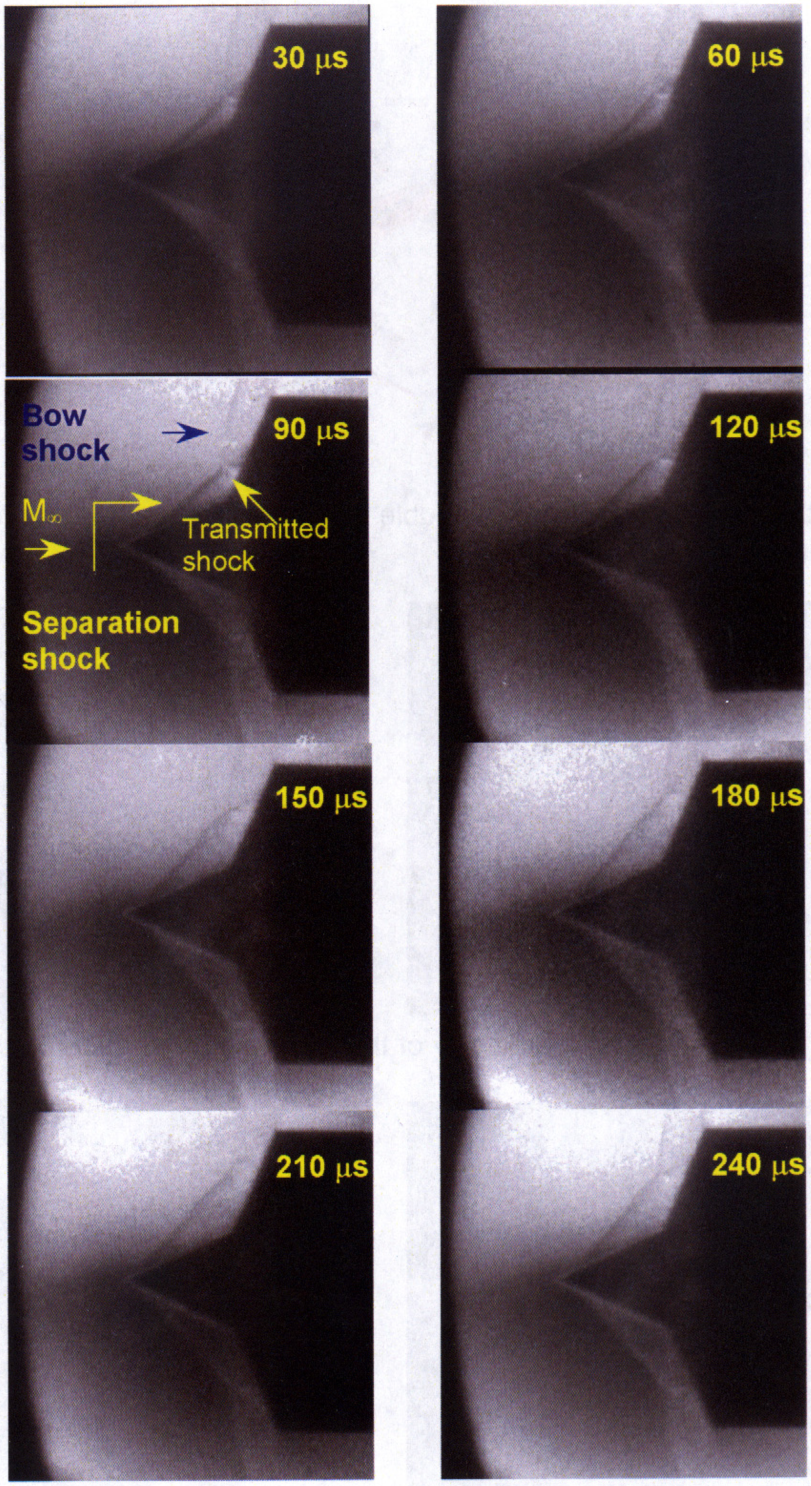

Fig.7 Sequential images of the flow field around the double cone recorded using IMACON camera. (All the frames are recorded in a single run).

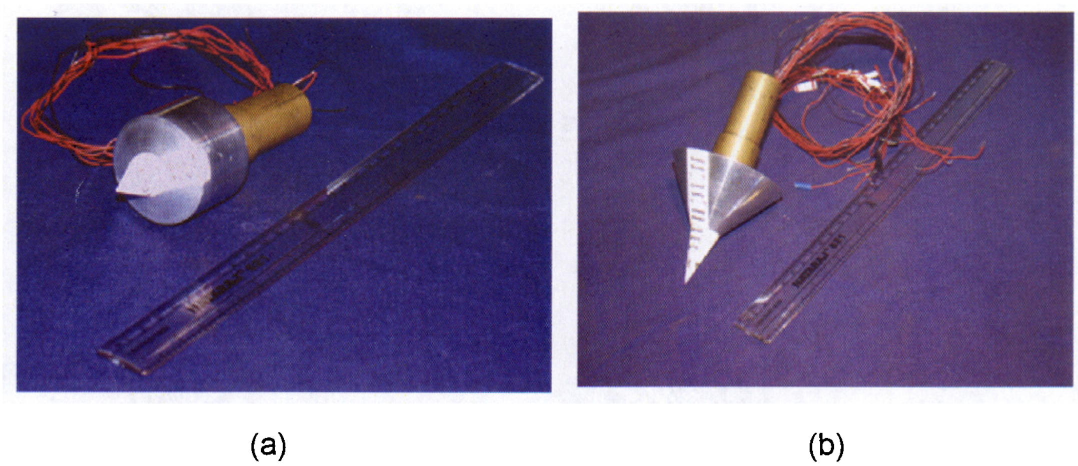

Fig. 8 Photographs of the double cone models with platinum thin film sensors deposited on Macor inserts; (a) first cone semi-apex angle = 25°; second cone semi-apex angle=68° (b) first cone semi-apex angle = 15°; second cone semi-apex angle=35°.

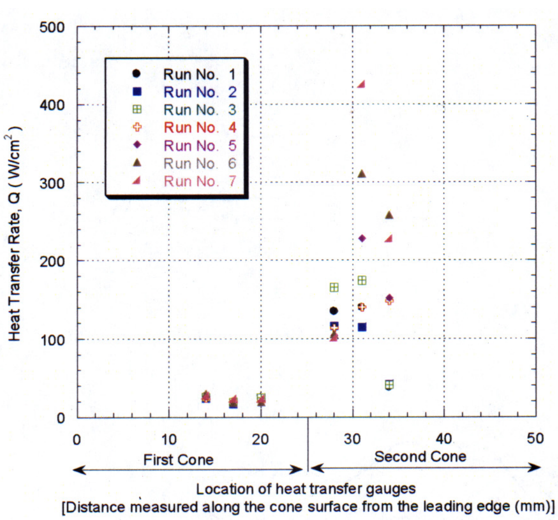

Fig. 9 Heat transfer measurements on the double cone; first cone semi-apex angle = 25°; second cone semi-apex angle=68°

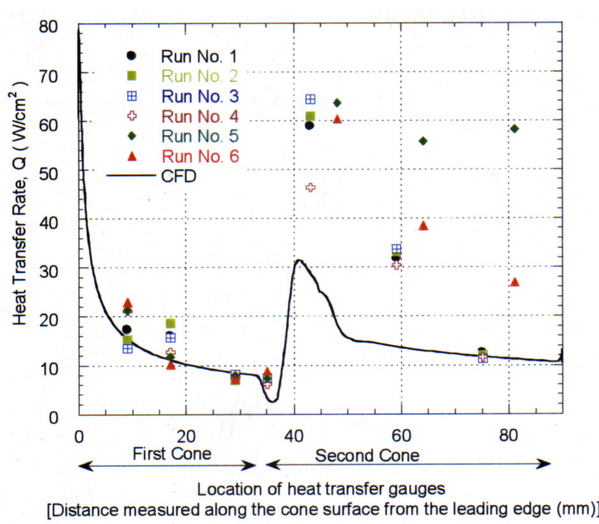

Fig. 10 Heat transfer measurements on the double cone; first cone semi-apex angle = 15°; second cone semi-apex angle=35°

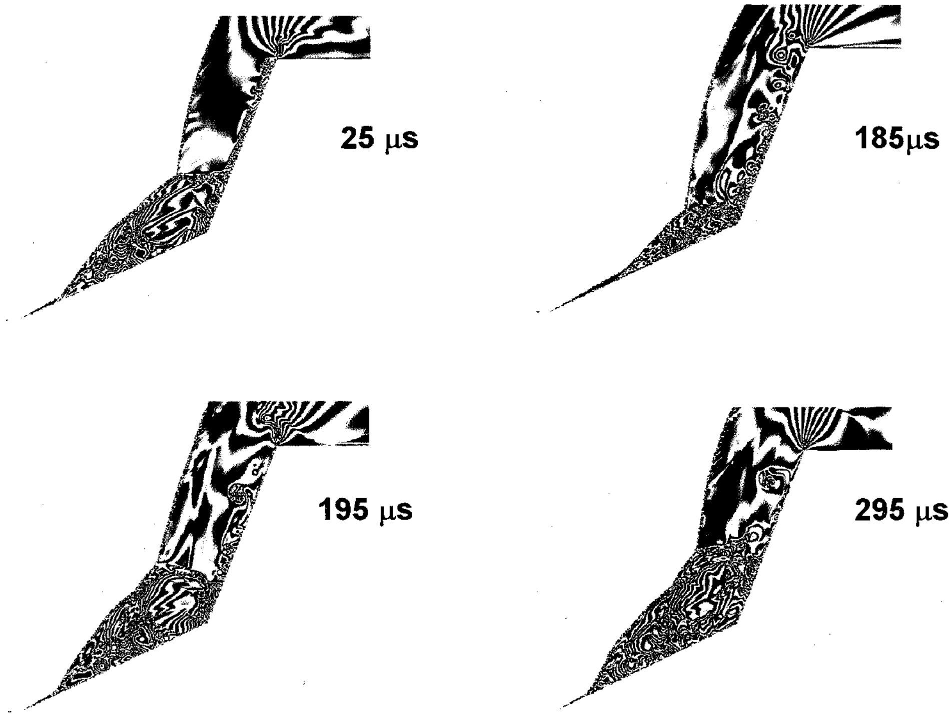

Fig. 11 Sequential numerical interferograms of the flow field around the double cone model; first cone semi-apex angle = 25°; second cone semi-apex angle=68°

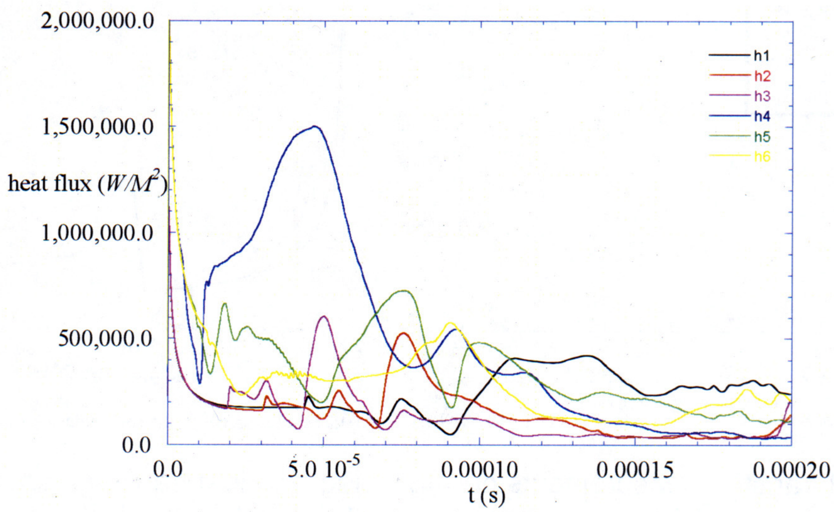

Fig.12 Numerically calculated heat transfer rates on the surface of the double cone; first cone semi-apex angle = 25°; second cone semi-apex angle=68°.