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Visualization of Unsteady Shock Oscillations in the High-Enthalpy Flow Field around Double Cones

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Abstract : The presence of an adverse pressure gradient, shock/shock interaction and shock wave/boundary layer interaction often induces flow separation around bodies. However, the effect of dissociated flow on separated flow characteristics, especially at hypersonic speeds, is still not clear, and considerable differences are observed between experiments and numerical simulations. In this investigation, the unsteady separated flow features around double cones are visualized in the Shock Wave Research Center (SWRC) free-piston driven shock tunnel at a nominal Mach Number of 6.99 using multiple optical techniques. The time resolved shock structure oscillations in the flow field around double cones (first cone, semi-apex angle = 25°; second cone, semi-apex angles=50°, 65°, 68° and 70°) have been visualized using a high-speed image converter camera (IMACON) at a nominal stagnation enthalpy of 4.8 MJ/kg. In addition, flow visualization studies around the double cone is also carried out using Schlieren and double exposure holographic interferometry in order to precisely locate the separation point and measure the separation length. The presence of a triple shock structure in front of the second cone and a non-linear unsteady shock structure oscillation in the flow field are the significant results from visualization studies on the 25°/65°, 25°/68°and 25°/70° double cones. On the other hand, the flow field around 25°/50° is relatively steady and Type V shock/shock interaction is observed. Illustrative numerical simulation studies are carried out by solving N-S equations to complement the experiments. The simulated flow features around a double cone agree well qualitatively with experiments.

Keywords : Visualization, Separated hypersonic flow, Shock tunnel.

1. Introduction

The interaction between shock wave and boundary layer often results in local regions of separated flow. The upstream facing corner formed by a deflected control surface on a hypersonic re-entry vehicle, the internally generated shock wave impinging on the boundary layer in a hypersonic air breathing propulsion system, and a separation bubble induced by a control surface deflection are some of the typical scenarios in which precise knowledge of the separated flow features is essential. However the role of non-equilibrium real gas effects on hypersonic flow separation induced by shock wave/boundary layer interaction and the influence of flow separation on basic aerodynamic properties, such as the lift, drag and pitching moment coefficients, remain unclear. Notwithstanding the great strides made in 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 (Chanetz B., et al., 1998). The separation length as computed by different CFD codes taking into account various real gas effects in high-enthalpy flow situations varies, and the actual cause of such variations is not clear. While considerable CFD and experimental efforts have been expended in understanding the shock interactions in the case of 2-D double wedge geometries at hypersonic Mach numbers (Rudy, et al., 1991; Olejniczak, et al., 1997), very few experimental investigations have been reported in the open literature. Recently (Jean-Paul Davis, et al., 2000) a 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. (2000) have also investigated type IV and V type shock interaction processes using a double cone model in a gun tunnel at Mach 8. However, no reliable experimental database exists for 3-D separated flow situations at high-enthalpy conditions, which would be useful for validating CFD codes used for simulating dissociated hypersonic flows.

A double cone model is a useful configuration for studying the 3-D separated flow features under a severe adverse pressure gradient. Depending on the first and second cone apex angles, the flow field around the double cone will comprise 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 an instantaneous pressure spike, which in turn will further enhance flow separation. However, the gas that is reversed into the separation zone must then flow out of the shear layer near the edge of the separation zone. As the second cone angle is increased, the impinging transmitted shock becomes increasingly 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, becoming highly non-linear. On the other hand, even small changes in the position and shape of the bow shock ahead of the second cone result in shifting of the triple point, which in turn dictates the size of the separation zone. Although most of the basic gas dynamic features are known, what will happen at high enthalpies in the dissociated flow environment is unclear. There exists no experimental database on the unsteady shock oscillations in hypersonic separated flow situations over bodies, which would help to validate the results from numerical studies. In the present investigation, the second cone angle is varied from 65° to 70° while maintaining the first cone angle at 25° to ensure large adverse pressure gradients in the double cone flow field. Against this backdrop, the present collaborative study between SWRC and the Department of Aerospace Engineering, the Indian Institute of Science (IISc), has undertaken the

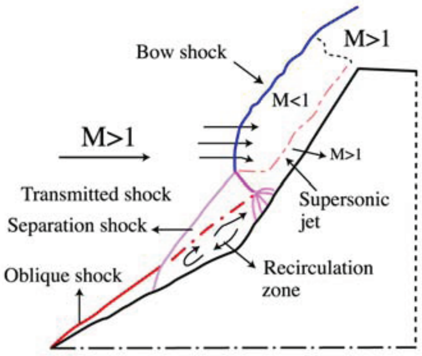

Fig. 1. Schematic representation of the flow field around a double cone.

following:

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=50°, 65°, 68° and 70°) using (a) double exposure holographic interferometry, (b) Schlieren photography, (c) shadowgraphy and (d) time-resolved high-speed photography using an IMACON camera.
2. Simulation of the separated flow features around the double cone using axi-symmetric Navier-Stokes equations at both low- and high-enthalpy flow conditions.

The experiments at high enthalpy (4.8 MJ/kg) were carried out in the SWRC free-piston driven shock tunnel. The details of the experimental set-up, the diagnostic techniques, and the important results have been described in subsequent sections.

2. Experiments

One of the primary goals of the visualization experiments is to characterize the nature of the flow field around the double cone in a dissociated hypersonic flow. A schematic diagram and a photograph of a typical brass double cone (25°/68°) model used in the present study is shown in Fig. 2.

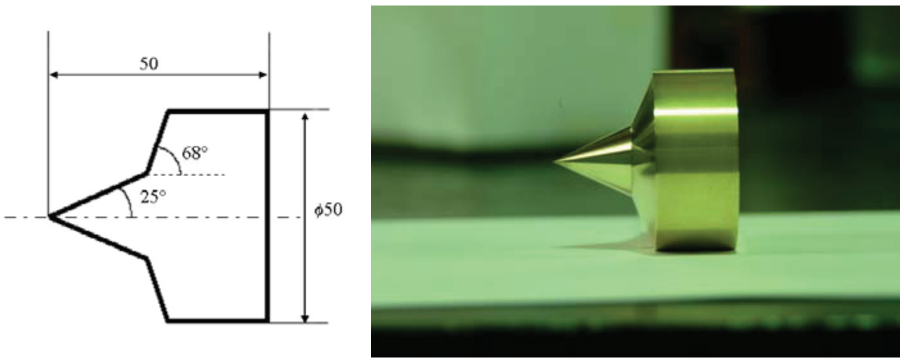

Fig. 2. Schematic diagram and photograph of the double cone model used in the visualization experiments.

Since the model erosion was quite significant, a new model was used for each run. The experiments were carried out in the SWRC free-piston driven shock tunnel, shown schematically in Fig. 3. The facility is 13 m in length and comprises a high-pressure reservoir (volume: 0.07 m^3), a 6-m-long compression tube (internal diameter: 100 mm, wall thickness: 50 mm), a stainless steel shock tube (length: 2.04 m, internal diameter: 38 mm, wall thickness: 20 mm), a Mach 7 conical nozzle, the test section and a dump tank. A 3.078-kg piston was used to accelerate the driver gas in the compression tube. In the present experiments, air is used as the test gas.

Typically, dissociated air after expansion from the conical nozzle to the test section comprises 67.5% Nitrogen, 13.1% Oxygen, and 19.3% of NO. The nominal test flow conditions are listed in Table 1. All experiments are carried out at zero angle of incidence. For further details on the SWRC free-piston driven shock tunnel, see Reference (Hashimoto, 2001)

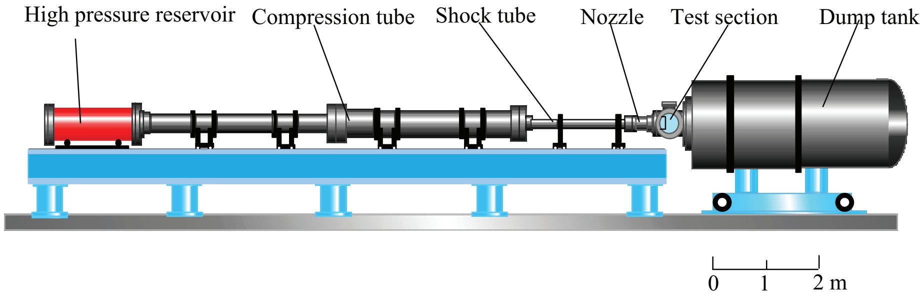

Fig. 3. Schematic diagram of the SWRC free-piston driven shock tunnel.

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

H_0 (MJ/kg)	U (m/s)	T (K)	Density (kg/m^3)	M	Specific ratio	$Re_\infty \times 10^5$ /model Diameter
4.8	2750	387	0.02	6.99	1.399	1.48

Multiple optical techniques, such as double exposure holographic interferometry, Schlieren photography and shadowgraphy have been used in this study to precisely locate the separation point on the first cone and to quantify the density field around the double cone. 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 were carried out. The schematic diagram of the optical set up used in the present investigations is shown in Fig. 4. A 694-nm-wavelength ruby laser (Lumonics HL33, 30 ns pulse duration) was used as the light source for all of the visualization experiments. A beam splitter was used to divide the light beam into object and reference beams. For details of the optical set-up for holographic interferometry see Takayama (1983).

The infinite fringe interferogram of the high enthalpy flow around a typical double cone is shown in Figure 5. The separation point is clearly seen on the surface of the first cone along with the bow shock of the second cone. Although the numbers of fringes denoting the isopynics are limited in this case the separated flow region is clearly visualized. 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.

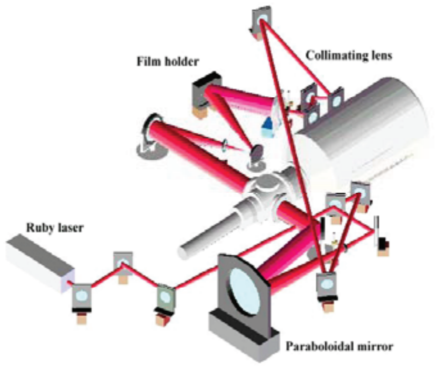

Fig. 4. Schematic diagram of the optical set-up used for holographic interferometery.

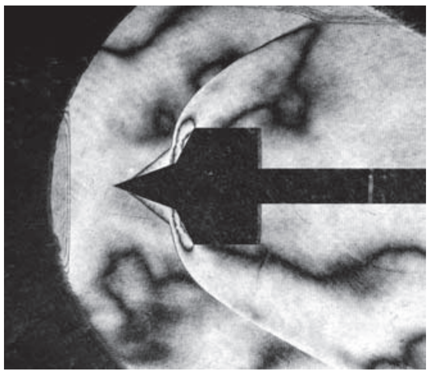

Fig. 5. Infinite fringe interferogram of the high-enthalpy flow around a (25°/68°) double cone.

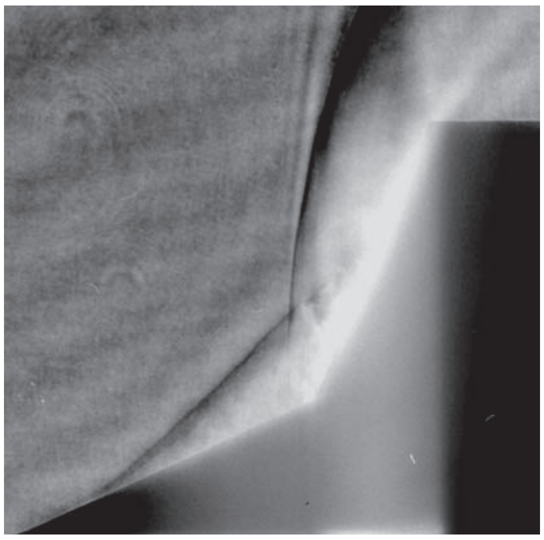

Fig. 6. Schlieren image of the high-enthalpy flow around a (25°/68°) double cone.

The flow field around the double cone visualized using the Schlieren technique 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. For details on the location of the separation point and the measured separation length, see Jagadeesh et al. (2002). However, these interferometric studies revealed the shock structure recorded at various times during the steady flow test window to be different. This implies that the flow field is unsteady with oscillating bow shock ahead of the second cone. However, the location of the separation shock was almost the same in all runs.

In order to experimentally visualize the unsteady shock oscillations, further time-resolved visualization studies were carried out using a high-speed image converter camera (HADLAND IMACON 468). The sequential flow field features captured by the IMACON camera around a 25°/68° double cone model at 30-μs time intervals are shown in Fig. 7. The average test time in the SWRC tunnel was ~ 300 μs. Figures 8 and 9 show the separated flow field around double cones with second cone apex angles of 65° and 70°. These results reveal severe shock oscillation and later movement of the transmitted shock impingement on the second cone surface. The non-linear behavior of the shock interaction process was observed in many runs, and, at this point in time, we are unsure about the total time duration of the unsteady shock oscillations. On the other hand, if the second cone angle is decreased to say 50° the flow field around the cone becomes steadier, as observed from Fig. 9. There is no triple shock interaction in this case, and only Type V (Edney 1968) shock interaction is observed. Although the spatial resolution of the photographs is not very good, the macroscopic features of the interacting shock structure in the flow field are clearly visualized. Further CFD studies are carried out in order to complement the experiments.

3. Numerical Study

The laminar axi-symmetric Navier-Stokes equations are solved by the finite volume method on a solution-adaptive unstructured quadrilateral grid [Sun 1999]. 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 squares 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 0.025 mm, and the aspect ratio ranges from 1 to 3. Grid cells having such a low aspect ratio are used in order to resolve the separation point precisely. Before simulating the high-enthalpy flow, the numerical code was validated using the heat transfer measurements in the IISc hypersonic shock tunnel at a stagnation enthalpy of 1.2 MJ/kg. For details on the heat transfer measurements see Jagadeesh et al. (2002). The surface heat transfer

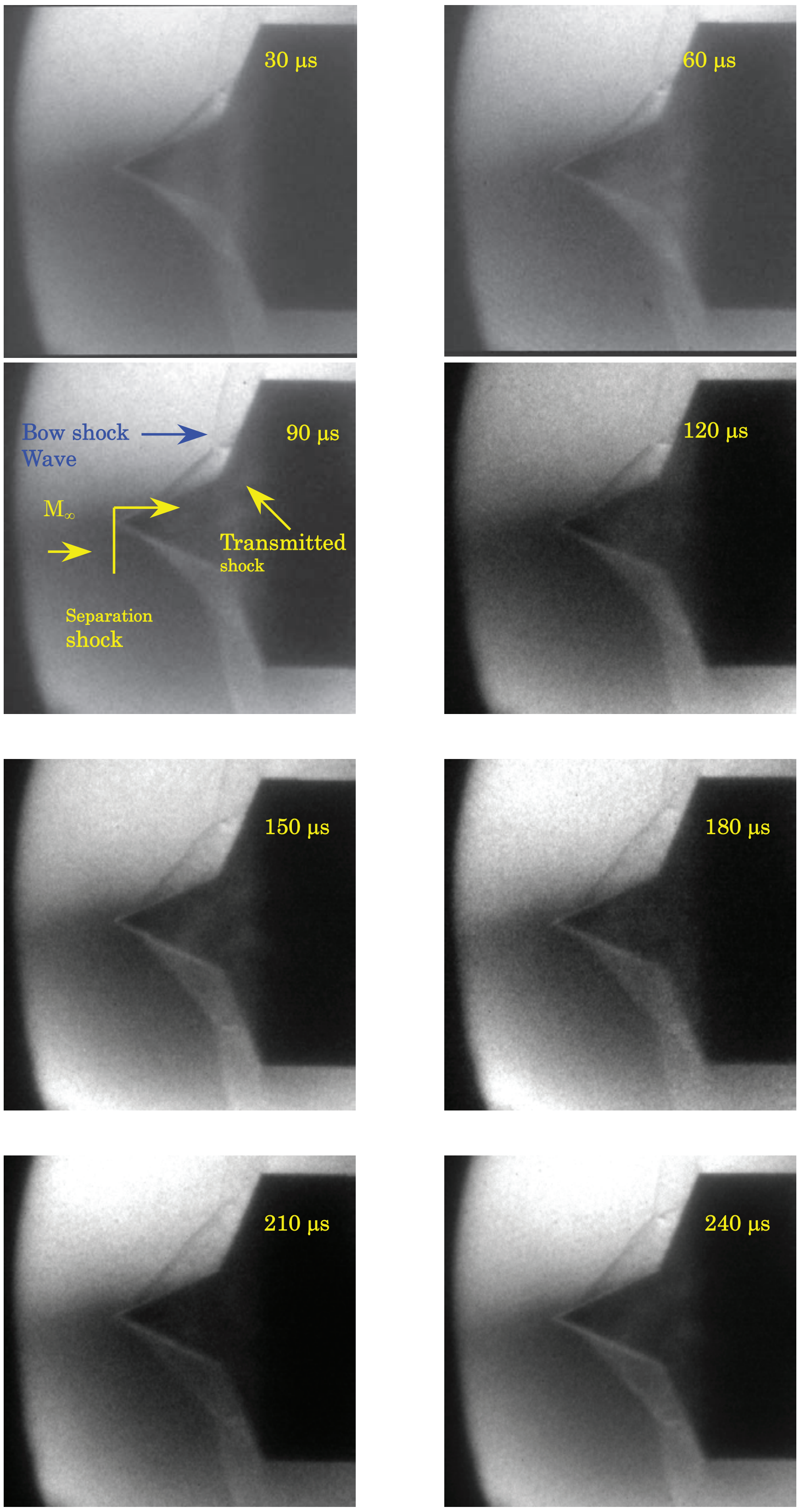

Fig. 7. Sequential images of the flow field around the double cone (25°/68°) recorded using an IMACON camera. (All frames were recorded in a single run).

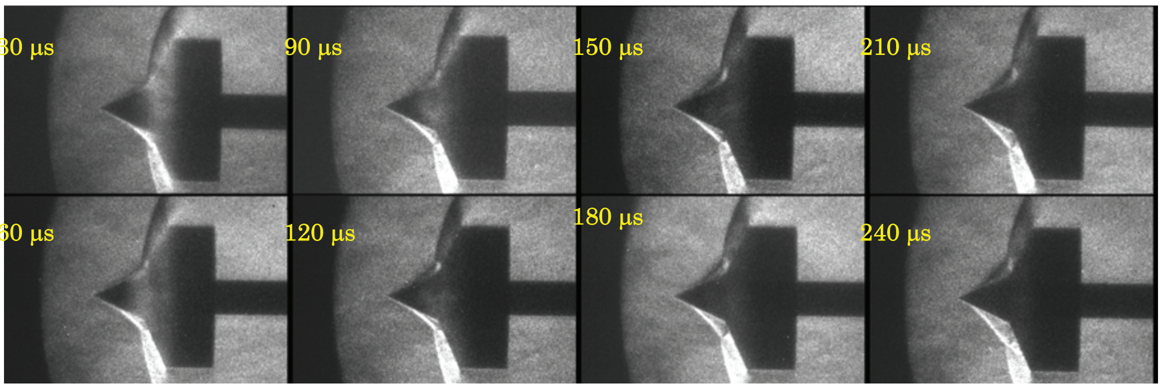

Fig. 8. Sequential images of the flow field around a double cone (25°/65°).

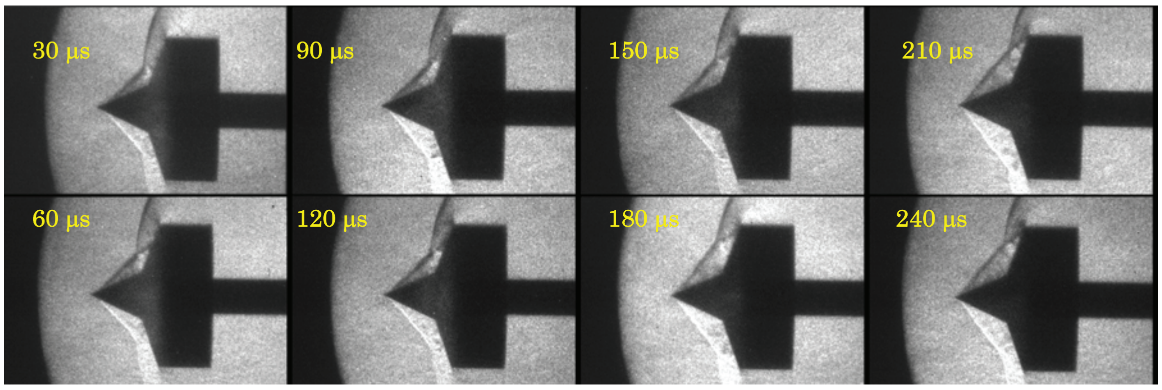

Fig. 9. Sequential images of the flow field around a double cone (25°/70°).

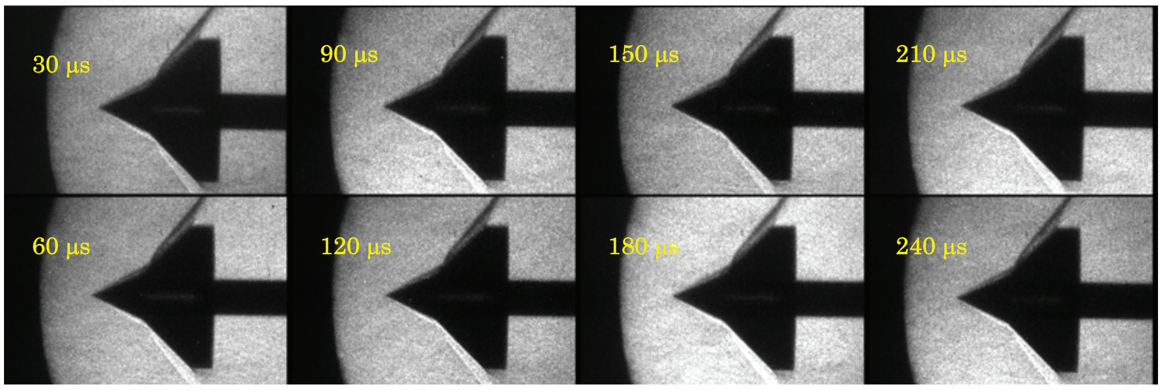

Fig. 10. Sequential images of the flow field around a double cone (25°/50°).

rates measured on a 15°/35° double cone and the numerical results are shown in Fig. 11. Although the agreement between experiments and CFD is very good for the first cone surface, considerable differences are observed in the separated flow region of the second cone. Again, using the free-stream conditions shown in Table 1, the flow features around the double cone (25°/68°) are simulated. The sequential numerical interferograms at different time instants are shown in Fig. 11. The results qualitatively confirm the trend observed in the visualization studies (Refer Fig. 7). 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. Future study will include both the effects of turbulence and dissociation in the numerical simulation.

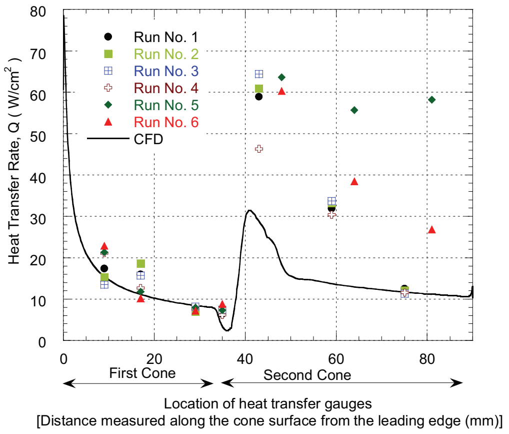

Fig. 11. Convective heat transfer rates measured on the surface of a 15°/35° double cone model using platinum thin-film gauges at Mach 5.75 along with the CFD results.

4. Conclusions

The separated flow field around a double cone has been investigated at nominal stagnation enthalpies of 4.2 MJ/kg. The time resolved shock structure oscillations in the flow field around double cones (first cone, semi-apex angle = 25°; second cone, semi-apex angles=50°, 65°, 68° and 70°) have been visualized in the SWRC free-piston driven shock tunnel at Mach 6.99, using a high-speed image converter camera (IMACON) at a nominal stagnation enthalpy of 4.8 MJ/kg. The presence of a triple shock structure in front of the second cone, and a non-linear unsteady shock structure oscillation in the flow field are the significant results from visualization studies on the 25°/65°, 25°/68° and 25°/70° double cones. On the other hand, the flow field around the 25°/50° cone is relatively steady, and a Type V shock/shock interaction is observed. Illustrative numerical simulation studies are carried out by solving N-S equations to complement the experiments. The simulated flow features around the double cone qualitatively match well experimentally obtained flow features. Future studies will focus on clearly characterizing the unsteady shock oscillation cycle time around the double cone model and will measure the surface pressure fluctuations at hypersonic speeds, preferably in a wind tunnel which will provide a longer steady state test duration.

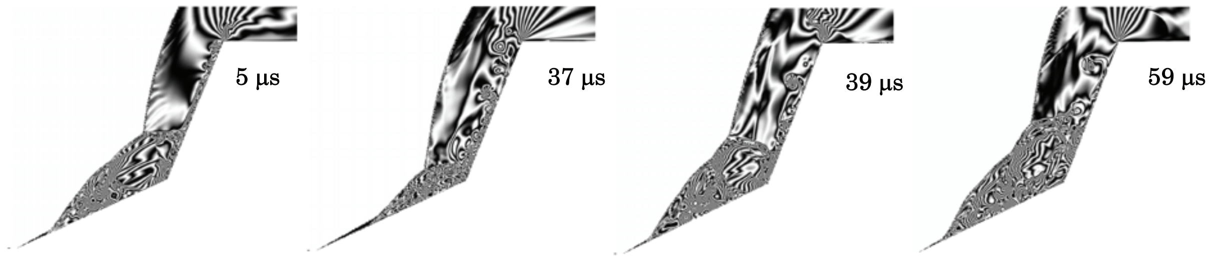

Fig. 12. Numerical interferograms depicting the flow field around the double cone (25°/68°) at Mach 6.99.

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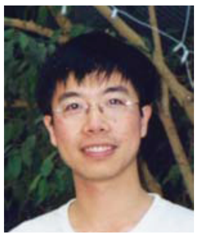

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