Shock Standoff from Blunt Cones in High-Enthalpy Nonequilibrium Nitrogen Flow

S. L. Gai*
University College (U.N.S.W.), Australian Defence Force Academy, Canberra, Australia
and
P. R. A. Lyons†
Australian National University, Canberra, Australia

Measurements of standoff distance from blunted cones of various bluntness raio in high-enthalpy nonequilibrium nitrogen flow have been made. The results show that the nondimensional shock detachment distance is a function both of bluntness ratio and the relaxation distance. The results show that shock detachment is more influenced by flow nonequilibrium in the shock layer than the conical afterbody.

Introduction

IT is well known that the main parameters in the hypersonic blunt-body problem are the shock-wave standoff distance Δ and the shock density ratio $\epsilon(=\rho_\infty/\rho_s)$. In the frozen or equilibrium flow, it is known that the standoff distance is dependent on the density ratio ϵ, being proportional to it. There is also now enough evidence that flow nonequilibrium in the shock layer of a blunt body has a significant influence on the detachment distance.[1-3] In their investigations, Hornung and Smith[1] and Hornung and Houwing[2] show that real gas effects inhibit the development of shock detachment, yielding much less detachment for a given wedge or cone angle than for a perfect gas case, and they also found that the detachment distance grows gradually as the wedge or cone angle is increased. On the other hand, Miller[3] found that the nonequilibrium in the shock layer in front of a spherical nose in hypersonic hypervelocity flow tended to increase the detachment distance compared with equilibrium flow.

Hornung[4] has presented a detailed study of a dissociating nitrogen flow over circular cylinders. It is shown in that paper that the density field and the shock standoff exhibit strong scale effect. The paper also contains numerical calculations of the effect of nonequilibrium on the standoff in front of spheres. However, the experimental data presented are confined only to cylinders.

It was therefore of interest to study the effect of nonequilibrium flow on the shock detachment of spherically blunted cones, which are of considerable interest as hypersonic vehicles requiring high drag as well as moderate lift-to-drag ratios, such as Aero-assisted Orbital Transfer Vehicles (AOTV). Flow around cone spheres in hypersonic perfect gas helium flow has been studied by Johnson,[5] who showed that the detachment distance has a strong dependence on the model geometry and predicted that this result might be useful in studying real gas effects around blunt bodies. This point has been pursued by Hornung and Smith[1] and Hornung and Houwing,[2] who have studied in detail the effect of relaxation on shock detachment in front of large-angle sharp wedges and cones, as mentioned earlier. Johnson's experiments also showed that the detachment distance and shock strength depended on sphere-cone bluntness. It was therefore considered worthwhile to study the effect of relaxation on shock detachment on sphere-cones of varying bluntness ratio, which is a natural extension of studies in Refs. 1 and 2.

Analysis

Consider only the flow at distances within L from the cone apex, where L is the observation scale, and κ is the curvature of the cone tip (Fig. 1).

If $\kappa L \to 0$ and we consider flow at distances greater than L, then we see the flow past a sharp cone (equilibrium case). If we let $\kappa L \to \infty$ but observe within the distance L near the tip, then $1/\kappa \to 0$, and we again notice the flow past a sharp cone (frozen case). In between these two extremes, when $\kappa L = 0(1)$, we observe the details of the flow within a region of the order of the tip radius. Thus, if the observation scale L is of the order of relaxation distance l (vibration and dissociation relaxation), then for blunt cones whose radii are of the order of relaxation distance behind the shock, the detachment distance is affected by relaxation of the flow. Then, following Hornung and Smith,[1] the ratio of standoff distance Δ to nose radius a for a spherically blunted cone in a relaxing gas can be written as

$$\Delta/a = F(M, \gamma_\infty, \mu_\infty, l/a, a/b) \tag{1}$$

where M_∞, γ_∞, and μ_∞ are the freestream Mach number, specific heat ratio and kinetic-to-chemical energy ratio per unit mass, respectively; l is the relaxation length; and a/b is the bluntness ratio defined as the ratio of nose radius to cone base radius with cone angle being constant.

For constant freestream conditions, Eq. (1) simplifies to

$$\Delta/a = f(l/a, a/b) \tag{2}$$

In the present experiments, variation in (l/a) was achieved by changing a and hence the bluntness ratio, while keeping the base and cone angle constant.

Experiments

The experiments were conducted in the Australian National University free-piston driven shock tunnel T3 (Ref. 6) with nitrogen as the test gas. The flow was generated by a conical nozzle whose exit and throat diameters were 203 and 12.7 mm, respectively. The freestream was a dissociated nitrogen with a speed V_∞ and Mach number M_∞ of 7.0 km·s^{-1} and 6.7, respectively. The corresponding reservoir enthalpy was 40.0 MJ·kg^{-1}.

The freestream conditions were calculated at the exit plane of the nozzle using a computer program based on the method of Lordi et al.[7] for nonequilibrium gas expansions.

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*Senior Lecturer, Department of Mechanical Engineering. Member AIAA.

†Research Associate, Department of Physics and Theoretical Physics, Faculty of Science.

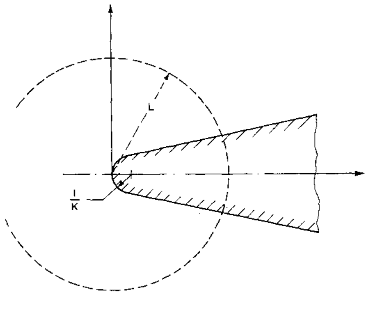


Fig. 1 Flow in the vicinity of the nose.

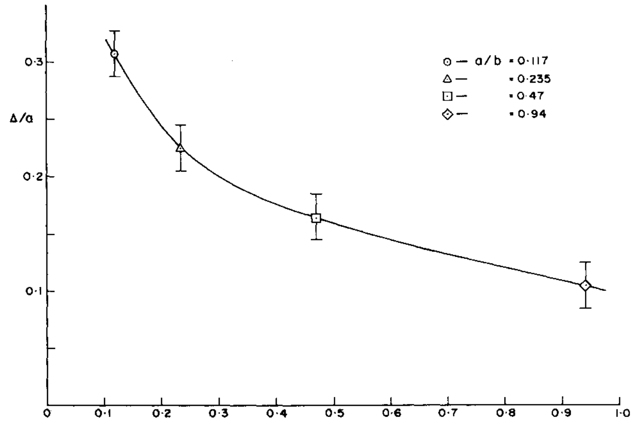


Fig. 2 Variation of shock standoff with respect to bluntness ratio in a dissociating nitrogen flow (0-deg incidence).

The models were all spherically blunted cones, all with semicone angle 10 deg and a common base diameter of 54 mm. The nose radius varied from 3.18 to 25.4 mm, giving a change in bluntness ratio from 0.118 to 0.94.

Self-luminosity photographs, taken with a fast electromechanical shutter (speed ≈ 800 cm$\cdot$s^{-1}) especially developed for these experiments,[8] were used to measure shock standoff distances. Enlarged prints of negatives were made, and readings from these enlargements were taken. Resolution on enlargements was sufficient in most cases, but for the smallest nose radius the uncertainties were larger. Measurements of Δ also were verified with densitometer scans of the negatives, and agreement with those obtained from enlargements was within 10%.

Results and Discussion

Figure 2 shows the ratio of measured shock standoff distance to nose radius plotted against the bluntness ratio. It is seen that (Δ/a) decreases monotonically with the bluntness ratio. Miller[3] observed similar results for a spherical nose and concluded that, for a nonequilibrium flow in the shock layer, Δ would be greater than that for equilibrium flow. In the present case, nonequilibrium effects would be greatest for the smallest nose radius cone where the nose radius is of the order of the relaxation distance. For the present experimental conditions, the relaxation distance l was calculated to be 2 mm.[9] As the nose radius is increased, l/a becomes smaller, and the influence of relaxation (hence nonequilibrium) on Δ becomes less and less. This is shown in Fig. 3.

Johnson's[5] experiments show that sphere-cones at 0-deg incidence having semicone angles less than 15 deg exhibit sphere body-flow characteristics in that the standoff is little affected by increasing the cone angle as long as the angle is below this critical value. His experiments were conducted in perfect gas helium; hence, no real gas effects would be present. However, it is surprising that he found no afterbody influence on shock detachment or shape. Results of Miller and Moore[10] show that

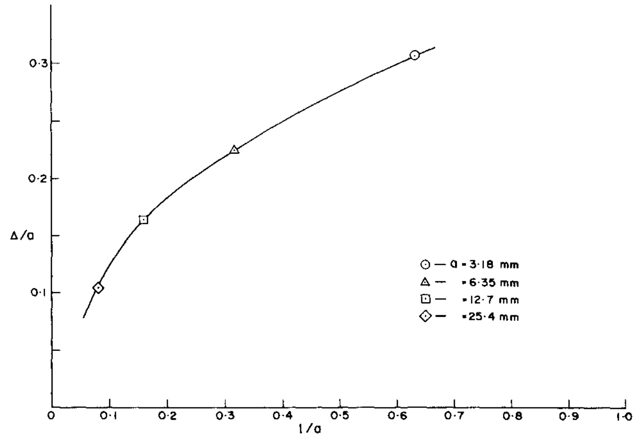


Fig. 3 Influence of relaxation on standoff.

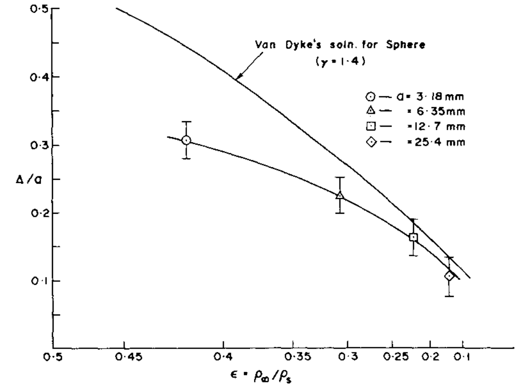
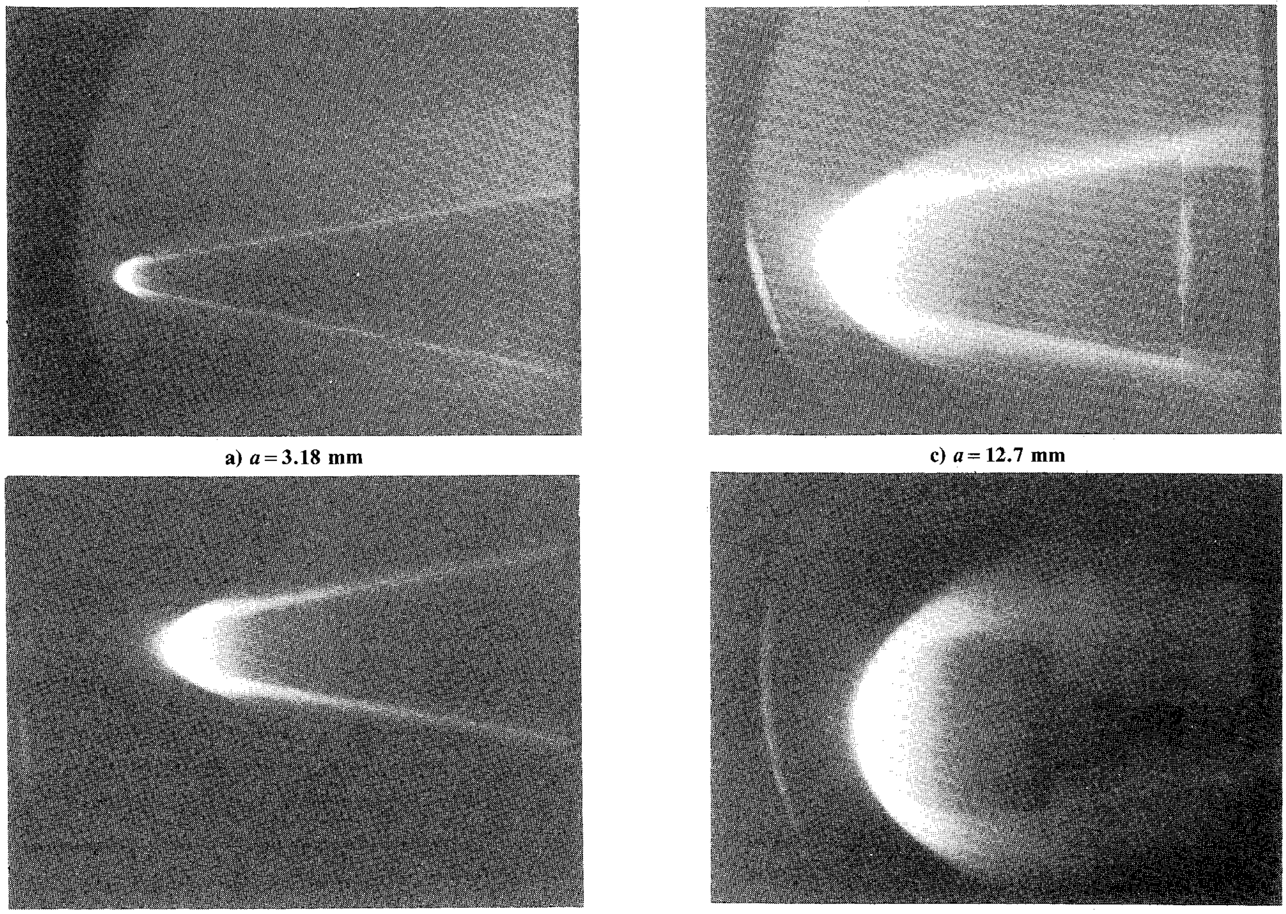


Fig. 4 Standoff distance vs density ratio in a dissociating nitrogen flow.

both shock detachment and shape are affected to some extent by body shape. These experiments took real gas effects into account. That the afterbody influence is there on shock detachment and shape even in the case of perfect gas flow is indicated by Hayes and Probstein,[11] who attribute this to the shape of the sonic line as well as location of the sonic point on the shock and the body. They show that the difference in shock detachment between a spherically blunted cone and a sphere of the same nose radius, all other flow conditions remaining the same, is about 10%, which, although small, is significant.

Thus, although it is difficult to decouple the nonequilibrium and afterbody effects in the present experiments, it is felt that the dominant influence on shock detachment has been the flow nonequilibrium. This point has been illustrated in Fig. 4, where the nondimensional detachment distance is shown plotted against ϵ. Also shown in the figure is Van Dyke's numerical prediction for standoff distance in front of a sphere,[11] in a perfect gas that has been shown to agree well with experimental data obtained in undissociated flow over Mach numbers ranging from low supersonic to hypersonic. The density ratios for the present experiments were computed using the empirical relationship $\Delta/a \approx 0.73/(\rho_s/\rho_\infty)$ proposed by Heybey[12] for a sphere traveling in a real gas and the measured shock detachment. It is seen that the difference between the real gas result and the perfect gas result is greatest for the smallest nose radius, which is of the order of relaxation length. The differences are least for the two larger-nose radii. This is consistent with the earlier inference that the smallest-nose radius is most affected by flow nonequilibrium. The results also are consistent with the fact that shock detachment in a real gas is more affected by nonequilibrium in the shock layer than the conical afterbody, and the detachment is less for a real gas than for the perfect gas, as postulated and observed by Hornung et al.[1,2] Figure 5 consists of photographs that clearly show the



a) $a = 3.18$ mm

c) $a = 12.7$ mm

b) $a = 6.35$ mm

d) $a = 25.4$ mm

Fig. 5 Dissociating nitrogen flow over spherically blunted cones at 0- deg incidence.

bow shock location and shape for the four nose radii with the body at 0-deg incidence.

An additional possibility exists that the detachment distance is affected by low Reynolds number effects, especially for cones with smaller-nose radii. The nose Reynolds number based on conditions behind the normal shock and nose diameter for all the models ranges from 10^3 to 10^4; thus, is it possible that the smallest nose radius (3.18 mm) cone results to some extent have been affected by rarefaction effects. However, since the nose surface temperature (~ 300 K) is many orders of magnitude smaller than the postshock temperature (~ 9000 K) for dissociating nitrogen at this enthalpy, the effect of the cold wall on the boundary layer on the nose is considerable and acts to reduce the boundary-layer thickness. The thick boundary-layer effect of rarefied flow therefore is unlikely to be significant, but the effect of shock thickness remains. As the Knudsen number ($K_{n\infty}$) based on the smallest nose radius and freestream mean free path is still only 0.014, it is expected that the shock thickness effects are also small. Anderson[13] suggests that the flow does not exhibit transitional behavior until $0.03 < K_{n_\infty} < 1.0$. It is therefore reasonable to assume the shock to be thin compared to Δ.

The present results have not been corrected for conicity effect of the nozzle. Calculations indicated them to be no more than 10%; consequently, they have not been considered.

Conclusion

Experiments with spherically blunted cones of various nose radii in a dissociated nitrogen flow have been described. The shock detachment was found to be affected by the flow nonequilibrium in the shock layer in the way it varied with the nondimensional relaxation distance.

Acknowledgment

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References

[1]Hornung, H. G. and Smith, G. H., "The Influence of Relaxation on Shock Detachment," *Journal of Fluid Mechanics*, Vol. 93, Pt. 2, July 1979, pp. 225–239.

[2]Hornung, H. G. and Houwing, A. F. P., "Shock Detachment from Cones in a Relaxing Gas," *Journal of Fluid Mechanics*, Vol. 101, Pt. 2, Nov. 1980, pp. 307–319.

[3]Miller, C. G., "Comparison of Measured and Predicted Sphere Shock Shapes in Hypersonic Flows with Density Ratios from 4 to 19," NASA TN D-8076, 1975.

[4]Hornung, H. G., "Non-Equilibrium Dissociating Nitrogen Flow over Spheres and Circular Cylinders," *Journal of Fluid Mechanics*, Vol. 53, Pt. 1, Jan. 1972, pp. 149–176.

[5]Johnson, R. H., "The Cone Sphere in Hypersonic Helium above Mach 20," *Aero-Space Engineering*, Vol. 2, Feb. 1959, pp. 30–34.

[6]Stalker, R. J., "Development of a Hypervelocity Wind Tunnel," *Aeronautical Journal*, Vol. 76, June 1972, pp. 374–384.

[7]Lordi, J. A., Mates, R. E., and Moselle, J. R., "Computer Program for the Numerical Solution of Non-Equilibrium Expansions of Reacting Gas Mixtures," NASA CR-472, 1966.

[8]Lyons, P., Kilpin, D., and Gai, S. L., "A New High Speed Electro-Mechanical Shutter," *Journal of Scientific Instruments*, Vol. 17, No. 1, Jan. 1984, pp. 108–109.

[9]Vincenti, W. G. and Krager, C. H., "Introduction to Physical Gas Dynamics," Wiley, New York, 1965, pp. 197–244.

[10]Miller, C. G. and Moore, J. A., "Shock Shapes of Blunt Bodies in Hypersonic Helium, Air and CO_2 Flows," *AIAA Journal*, Vol. 12, March 1974, pp. 411–413.

[11]Hayes, W. D. and Probstein, R. F., "Hypersonic Flow Theory—Inviscid Flows," Academic, New York, 1966, pp. 448–479.

[12]Heybey, W. H., "Shock Distance in Front of Symmetric Bodies," U.S. Naval Ordnance Lab., White Oak, MD, Rept. 3594.

[13]Anderson, J. D., "A Survey of Modern Research in Hypersonic Aerodynamics," AIAA Paper 84-1578, June 1984.