Measurements in Laminar Regions of Shock/Shock and Shock/Boundary Layer Interaction over Cylindrical Leading Edges, Cone/Cone and Hollow Cylinder Flare Configurations for DSMC/Navier-Stokes Code Validation

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Abstract. Detailed measurements of the distribution of heat transfer and pressure, as well as Schlieren photographs, have been obtained in a series of experimental studies designed to provide measurements with which to evaluate the capabilities of the current numerical simulation techniques to predict the detailed characteristics of regions of shock/shock and shock/boundary layer interactions in laminar hypersonic flows. These experimental studies were conducted for a range of Mach numbers and Reynolds numbers to obtain fully laminar flows at conditions through the interaction regions that could be predicted with both DSMC and Navier-Stokes numerical schemes. In the first part of this paper, we present the model configuration, test condition and surface and flowfield measurements obtained in regions of shock/shock interaction over a highly instrumented cylindrical leading edge. In part two, only the model configurations, test conditions, and sample surface measurements are presented on two models — an axisymmetric cone/cone and a hollow cylinder flare configuration. The measurements that have been made on these configurations are being retained until the results of predictions with the DSMC and Navier-Stokes codes have been completed.

INTRODUCTION

Recently, in connection with code validation efforts associated with the AGARD/AFOSR Working Group on Hypersonic Flows (Ref. 1), experimental measurements and numerical predictions have been made over a series of cylinder/flare and cone/flare configurations for low Reynolds number flow conditions where both DSMC and Navier-Stokes solution techniques could be applied. Comparisons (Moss et al, Ref. 2) between the most recent numerical schemes developed in Europe and America and the experimental measurements obtained by Chanetz, et al (Ref. 3) have demonstrated a strong sensitivity to the numerical grid and discrepancies between the measured and predicted pressure distributions. Similarly computations and measurements over cone/cone configurations (Holden, Ref. 4) have revealed significant numerical problems in describing flows with combined shock-induced separation and shock/shock interactions. Computations by Olejnieczak and Candler (Ref. 5) and Gnoффo (Ref. 6) demonstrated that the flow solvers may be prone to oscillation in predicting these complex flows and that mesh generation and refinement schemes must be handled with extreme care. Such regions of shock/shock and shock/boundary layer interaction have traditionally been the testing ground for prediction techniques. Viscous inviscid interaction phenomena were first treated by boundary layer methods by Lighthill (Ref. 7) and subsequently using integral techniques Lees and Reeves (Ref. 8) and Holden (Ref. 9) were first to develop solutions to describe shock interaction regions in adiabatic and highly cooled flows, respectively. Later, Holden (Ref. 10) demonstrated that conventional boundary layer theory was inadequate to describe such flows and added normal pressure gradient terms into the integral equations. These techniques were rendered obsolete when the stable numerical techniques developed by MacCormick (Ref. 11) were employed to directly obtain solutions to the Navier-Stokes equation. Hung and MacCormack (Ref. 12) obtained one of the first successful solutions to predict the detailed flowfield and surface characteristics of regions of laminar separated flow over a flat-plate/wedge compression corner for comparisons with measurements with heat transfer, pressure skin friction and measurements obtained earlier by...
Holden (Ref. 13). Later, Rudy, et al (Ref. 14) examined the performance of a series of Navier-Stokes solvers in an extensive set of calculations accounting for three-dimensional effects by running the full 3D solution. From these calculations and those by Vemanganti, et al (Ref. 15), who demonstrated the importance of carefully gridding the leading edge region and the flow close to reattachment, it was generally concluded that computational methods could be successfully employed to calculate complex laminar interaction flows in the absence of flowfield chemistry. The subsequent problems in predicting laminar interacting hypersonic flows encountered by Moss (Ref. 2) and Candler (Ref. 5) have caused the community to reevaluate the performance of DSMC and Navier-Stokes code in predicting laminar low-density flows. As a result of this controversy, we designed and constructed two new sets of experiments over cone/cone and cylinder flare configurations. In part one of this paper, we present and review measurements made in regions of shock/shock interaction for fully laminar flows; a situation which is extremely difficult to achieve because of the susceptibility of the free shear layers to transition. We then present model configurations and freestream conditions for measurements made in fully laminar flows over (1) a sharp and blunted cone/cone configurations and (2) a hollow cylinder flare configuration with two different flare lengths. Although we present an example set of heat transfer and pressure measurements over two cone/flare configurations, we will delay the publication of the measurements made in these studies until numerical predictions employing Navier-Stokes and DSMC techniques have been completed as part of an AGARD/Air Force Office of Scientific Research (AFOSR) code validation study.

EXPERIMENTAL FACILITIES, MODELS AND INSTRUMENTATION

Experimental Facilities – 48-Inch and LENS I and II Shock Tunnels

The ability to obtain experimental measurements in fully laminar regions of shock/shock and shock/boundary layer interaction in hypersonic flows requires the use of wind tunnel facilities capable of generating high quality, low Reynolds number flows. Over the past 40 years, since the development of the shock tunnel at Cornell Aeronautical Laboratory (CAL), a concerted effort has been placed on developing and using these facilities in fundamental studies in low Reynolds number shock/boundary layer interacting flows, with and in the absence of flowfield chemistry for the purpose of code validation. The 48-inch tunnel developed at CAL has been proven over its 40-year history to generate high-quality low Reynolds number flows, and the measurements made in the facility have been validated by flight tests from the Gemini to the space shuttle as well as in comparisons with well-established prediction techniques. The design of the LENS facility incorporates many of the key features learned from our earlier facility development as well as improvements in the tunnel components and a significant increase in the high-pressure, high-enthalpy (2,000 atm/12 MJ/kg) and test time performance of the tunnels. LENS Leg I and II are situated adjacent to each other, as shown in Figure 1. The two legs of the LENS facility share a common compressor, ballast tank, control room, and operating instrumentation. These tunnels are being employed in our Verification, Validation and Analysis (VV&A) programs for both facility and code validation, with the effort centered initially on comparing measurements in complex regions of shock wave/ laminar boundary layer interaction and separated flows developed on models tested in these facilities with the most current sophisticated prediction techniques.

The facility test conditions are established and validated by a combination of measurements in the reservoir region and test section of the tunnel. The stagnation pressure and enthalpy are obtained directly from pressure measurements behind the reflected shock and measurements of the incident shock Mach number. Conditions in the freestream are obtained from survey rakes containing pitot pressure probes, stagnation heat transfer gages on hemispherical cylinders, total temperature measurements with vented thermocouple probes (where applicable) and cone pressure measurements to establish, in conjunction with the aforementioned measurements, the static pressure in the flow. From these measurements, we can determine the accuracy of the freestream dynamic pressure of the freestream and the stagnation point heating to ± 5%, and the Mach number to ±1.5%.
Model Configurations for Shock/Shock Interaction Studies

A schematic diagram of the shock-generated/cylinder model is shown in Figure 2. In this study we employed cylinders with nose radii of 0.138, 0.375 and 1.5 inches, which were instrumented with high-frequency, thin-film instrumentation mounted on a streamwise continuous Pyrex strips. The 3-inch cylinder was also instrumented with high-frequency pressure and heat transfer instrumentation placed to give a spatial resolution within one degree in the area of key interest. A photograph of the heat-transfer instrumentation on the two smaller cylinders is shown in Figure 3. Because of the small size of the 0.138- and 0.375-inch radius cylinders, we employed only heat transfer gages on these models. The heat transfer instrumentation on these latter two cylinders is shown in more detail in Figure 3. Figure 4 shows the model support and shock-generated system for the 0.138-inch radius cylinder.

FIGURE 2 Schematic Diagram of Shock Generator/Model Support System for 1.5-inch Radius Cylinder

FIGURE 3 Heat Transfer Instrumentation Layout on 0.138 and 0.375-Inch Radius Cylinders
Model Configuration for the Cone/Cone Studies

The cone/cone configurations employed in these studies are shown in Figure 5. Although we employed a 60° flare in our original work to study real-gas effects, we lowered the flare angle to 55° for the majority of the new experimental studies to prevent potential flow oscillation, which was detected in the numerical analyses of this configuration. The length of the 55° cone was selected to provide a region of constant pressure downstream of the corner interaction region. The freestream conditions were also selected to ensure that attached flow was observed both upstream and downstream of the corner separated region so that the computations were bounded by regions of known boundary conditions.

Model Configuration for the Hollow Cylinder Flare Studies

The hollow cylinder flare configurations employed in this phase of the experimental program are shown in Figures 6 and 7. The length of the longest flare employed in the test program was again selected to provide well-defined boundary conditions downstream of the cylinder flare junction. Both the cylinder and flare were highly instrumented with high-frequency pressure and heat transfer instrumentation. The test conditions selected for the
measurements with the extended flare configuration will ensure that the flow remains fully laminar over the entire configuration and that there are well defined attached flow regions both upstream and downstream of the separated flow generated at the cylinder flare junction.

![Figure 6 Dimensions for Two Cylinder Flare Configurations employed in the CUBRC Experimental Studies](image)

**FIGURE 6 Dimensions for Two Cylinder Flare Configurations employed in the CUBRC Experimental Studies**

**FIGURE 7 Photograph of the Cylinder/Flare Model**

**Description and Accuracy of Heat Transfer and Pressure Instrumentation**

For these studies, we employed piezoelectric pressure gages and thin-film heat transfer instrumentation similar to those which were designed at Cornell Aeronautical Laboratory (CAL) in the late 1950s and refined over the past 40 years. The piezoelectric pressure transducers, manufactured by PCB, are a CAL-designed gage capable of measuring the low pressures obtained in our studies (\(O \sim 5 \times 10^{-3}\) psi) within \(\pm 3\%\). These transducers are mounted close to the surface so that “out-gassing” effects are negligible. The platinum thin-film heat transfer instrumentation employed in these studies has proven to be the most accurate measurement technique in hypersonic test facilities, particularly in the large heat-transfer gradients developed in shock interaction regions. We have calculated that the accuracy of heat transfer measurement is \(\pm 5\%\).

**RESULTS OF EXPERIMENTAL STUDIES**

**Part I – Measurements in Regions of Shock/Shock Interaction over Cylindrical Leading Edges**

Measurements were obtained at freestream Mach numbers from 10 to 15 of the distribution of heat transfer and pressure over a series of cylindrical leading edges with nose radii of 0.138, 0.375 and 1.5 inches. The measurements made in these studies in the low density flow regime demonstrated that the peak heating generated in regions of shock/shock interaction are significantly affected by viscous effects in the shock layer. While we measured enhancement factors resulting from shock/shock interaction of between 10 and 15 for high Reynolds number
laminar flows, in low density flows where the shock layer was strongly influenced by viscous effects, enhancement factors were typically a factor of 5 lower; and for these interactions in the low-density regime, it is difficult to define the characteristics in terms of Type III and IV flow geometries.

Measurements of the distribution of heat transfer and pressure in fully laminar regions of shock/shock interaction which were selected for the database are presented in Figures 8 and 9. In these low density flows where a large viscous region is generated in the shock layer, peak heating is observed when the interaction is roughly 18E below the axis. The peak heating decreases monotonically as the interaction is moved down around the leading edge, a feature which is characteristic of interactions which remain fully laminar. These and similar measurements under low Reynolds number conditions demonstrated that heating enhancement factors \( \frac{q}{q_{stag}} \) are less than 10 in Type III or IV interaction regions. For fully laminar interaction regions at shock layer conditions that are dominated by viscous effects, the peak-heating region occurs roughly between 15E and 25E below the model axis.

**Figures 8 and 9**: Distribution of heat and pressure in the shock interaction region in laminar flow over 1.5-inch radius cylinder.

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**Part II – Experimental Studies to Examine Laminar Interaction Regions in Hypersonic Flow over Cone/Cone and Cylinder Flare Configurations**

The experimental programs to examine the flow over cone/cone and flare and cylinder/flare configurations were conducted in a nitrogen freestream to remove effects of flowfield chemistry. The low Reynolds numbers selected for these experiments will enable DSMC, Hybrid and Navier-Stokes predictions to be made. To ensure that the experimental data selected was completely laminar, the studies were conducted over a range of Reynolds numbers so that we were able to confirm that the heat transfer coefficient downstream of the reattachment point decreased with increasing Reynolds number. The nominal test conditions for the studies over the 25°/55° cone/cone configuration are listed in Table 1 (Conditions A, B, C, D). In these studies, measurements were made at a nominal Mach number of 9.5 for a range of unit Reynolds numbers from \( 4.3 \times 10^4 \) to \( 7.8 \times 10^4 \). The preliminary test conditions for the cylinder/flare studies will be similar to those listed in Table 1. In these studies, measurements are being made at a nominal Mach number of 9.5 for a range of unit Reynolds numbers from \( 4.3 \times 10^4 \) to \( 7.8 \times 10^4 \) as well as for a Mach number of 11.5 at a unit Reynolds number of \( 4.3 \times 10^6 \). At these test conditions, the flow over the complete cylinder/flare configuration will be fully laminar and the measurements at the lowest Reynolds number will enable the computation of the flowfield with DSMC methods.
### TABLE 1. Nominal Test Conditions for Cone/Cone and Cylinder Flare Experimental Studies

<table>
<thead>
<tr>
<th></th>
<th>A: Mach #: 9.5</th>
<th>B: Mach #: 9.5</th>
<th>C: Mach #: 9.5</th>
<th>D: Mach #: 11.3</th>
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<tbody>
<tr>
<td></td>
<td>Re: 4.3e4 (ft⁻¹)</td>
<td>Re: 6.3e4 (ft⁻¹)</td>
<td>Re: 7.8e4 (ft⁻¹)</td>
<td>Re: 4.3e4 (ft⁻¹)</td>
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<tr>
<td>Mᵢ</td>
<td>5.212000e+00</td>
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<td>Re₀ (ft⁻¹)</td>
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As discussed above, we will not release the detailed measurements of heat transfer obtained on the cone/cone and cylinder/flare models until predictions with the DSMC and Navier-Stokes codes have been made as a part of the AFOSR/RTO Working Group efforts on Code Validation. However, one of the sets of heat transfer and pressure measurements which was not included in the database is from our cone/60E studies, because of the inadequate lengths of attached flow upstream and downstream of the interaction regions, is shown in Figure 10. These measurements were obtained with the 25E/60E cone/cone configuration equipped with a 0.25-inch radius blunt leading edge. For this large nosetip, bluntness boundary layer separation was induced close to the nose/cone junction and the reattachment point was close to the base of the 60E cone. This case was therefore not accepted, because we did not obtain a well-defined region of attached flow on both the 25E and 60E cones. However, measurements made on the 25E/55E cone/cone configurations for both sharp and blunted nosetips produced flows where attached regions were developed both upstream and downstream of the interaction and therefore are of much greater use in the code validation studies. It is this data for which numerical computations using both the DSMC and Navier-Stokes numerical schemes are currently being computed.

![FIGURE 10. Typical Heat Transfer and Pressure Measurements on Blunted 25°/60° Cone/Cone Configurations](image)

**CONCLUSIONS**

Experimental studies have been conducted to provide detailed heat transfer and pressure distributions in regions of laminar hypersonic flow developed by shock/shock and shock/boundary layer interactions over simple model...
configurations for DSMC and Navier-Stokes code validation. The measurements selected as typical of the characteristics of laminar regions of shock/shock interaction over cylindrical leading edges were from a large number of studies, the majority of which had transition in the shear layer and therefore were excluded from the database. Measurements of the detailed distribution of the heat transfer and pressure as well as flowfield geometry were obtained on a series of cone/cone and cylinder/flare configurations at Mach numbers between 9 and 11 for a range of freestream conditions. From these studies we have selected those with well defined boundary conditions where the flow both upstream and downstream of the interaction regions remained laminar and the pressures and heat transfer were obtained in well-defined regions of the flow. The measurements made in these latter studies will be released upon the completion of a series of numerical computations using both the DSMC and Navier-Stokes solvers. These calculations are currently being conducted under the auspices of the AFOSR and RTO Working Groups. A numerical tabulation of the experimental measurements made in these studies as well as the model configurations and test conditions are available on a CD compiled into the CUBDAT database. This data is available from the author upon request.

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**REFERENCES**