Separated Flow at an axisymmetric compression corner in a supersonic freestream

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ABSTRACT

Fluorescence imaging and thermometry is used to investigate separated flow at an axisymmetric compression corner in a supersonic freestream. The experimental data are compared with computational fluid dynamic simulations, which assume axially symmetry. Discrepancies between CFD and experiment are observed and attributed to the fact that the flow was not perfectly axisymmetric due to imperfect alignment of the model.

1. INTRODUCTION

Shock-wave/boundary-layer interactions are fundamental research problems of significant scientific importance and have been the subject of numerous experimental investigations[1]. This paper investigates one of these fundamental problems, flow at an axisymmetric compression corner in a supersonic freestream.

Previous work[1] has demonstrated that steady separated flow over a two-dimensional model could be achieved within the flow duration of a free-piston shock tunnel. Our work seeks to build upon that earlier work using planar laser-induced fluorescence (PLIF) to both visualize the flow and produce maps of the temperature field for comparisons with computational fluid dynamic (CFD) simulations. The experimental conditions are chosen on the basis of their suitability for PLIF-based thermometry and ease of computational modelling, based on the following considerations: avoidance of line interference and saturation effects; ensuring minimum laser beam attenuation; good signal-to-noise ratios; good temperature sensitivity and perfect gas behaviour. It was intended that an axisymmetric compression corner, perfectly co-axially aligned with the freestream flow axis, would allow the experimental simulation of a perfectly axisymmetric separated flow. However, this could not be achieved and the body was at incidence and yaw to the oncoming flow. Ideally, this flow should be compared with a CFD simulation for the same incidence and yaw or the experiment repeated with perfect alignment. However, this was not possible because of time and resources limitations, so that we have been limited to simulating the perfectly axially symmetric case with CFD and comparing those results with experimental results from our imperfectly aligned model.

2. EXPERIMENTAL CONSIDERATIONS

The research problem is illustrated in Fig.1, which shows a hollow cylinder with a sharp leading edge upstream of an axisymmetric compression corner in a supersonic flow for the ideal axisymmetric case. A boundary layer grows on the cylinder, causing a leading edge shock wave to be produced. Provided the internal flow through the hollow cylinder doesn't choke, this leading edge shock will be relatively weak. In the absence of viscous effects, a conical shock wave would be situated at the compression corner. This shock wave produces an adverse pressure gradient, which interacts with the boundary layer, resulting in flow separation. Our experiment was performed in the T2 free-piston shock tunnel [2] using PLIF visualization and thermometry to produce data for comparison with CFD simulations at low enthalpy freestream flow conditions. An illustration of the model is presented in Fig. 2. To ensure that the internal flow doesn't choke during the experiment, a number of relief holes were included in the model as shown. Preliminary experiments confirmed that these worked effectively.

3. NUMERICAL METHODS

The T2 free-piston shock tunnel is described elsewhere and its freestream conditions have been well characterized[2]. It has a converging-diverging nozzle with a throat of 7.0 mm diameter and an exit of 67.6 mm diameter. The existing of a viscous boundary layer in the nozzle reduces this to an effective half angle of 6.8°. The existence of a viscous boundary layer in the nozzle reduces this to an effective half angle of 7.5°. The excimer-laser-pumped dye-laser apparatus used in the NO PLIF imaging system has been described previously [2] and is shown in Fig. 3.

Figure 1 Axisymmetric compression corner flow: (b.l.) boundary layer; (l.e.s.) leading edge shock; (s.p.) separation point; (s.f.) separated flow; (r.p.) re-attachment point; (r.b.l.) re-attached boundary layer; (s.s.) separation shock; (s.l.) shear layer.

Figure 2 Compression corner model.
4. EXPERIMENTAL TECHNIQUES

4.1 PLIF imaging

PLIF is suitable for both qualitative flow visualization and quantitative measurements of complex three-dimensional flow fields. It provides species and quantum-state specific information with very good spatial and temporal resolution. It involves illuminating the flow with a thin sheet of laser light tuned to excite electronic transitions in a chemical species in the flow. Here the species is nitric oxide (NO) which is naturally generated by the shock reflection process in the nozzle. The fluorescence induced by this illumination is focussed onto an intensified charge-coupled device (ICCD) camera to produce an image of the fluorescence in that region. Such an image is useful for visualizing flow features of interest in the illuminated plane, providing an understanding of flow behaviour[2]. With judicious choice of transition and subsequent image processing, the technique can be extended to yield measurements of temperature[2]. In the current work, we produce visualization images by exciting the $^1P_{12}(2.5)$ transition and imaging the subsequent fluorescence on an ICCD camera.

4.2 PLIF thermometry

The thermometry method used is the two-line technique[2]. A fluorescence image probing a rotational level with quantum number $J'$ and energy $F_{J'}$ is compared with a fluorescence image probing a rotational level with quantum number $J''$ and energy $F_{J''}$. Under such circumstances, the rotational temperature is given by[2]:

$$T = \frac{F_{J''} - F_{J'}}{k\ln \left( \frac{S_{J''}B_{J''}(2J'' + 1)/S_{J'}B_{J'}(2J' + 1)}{} \right)}$$

where: $S_j$ is the fluorescence signal obtained when probing state $J'_j$; $S_j$ is the fluorescence signal obtained when probing state $J'_j$; $B_j$ and $B_j$ are the Einstein B coefficients of the respective states; and $k$ is Boltzmann's constant. Furthermore, $E_1$ and $E_2$ are the energies of the laser pulses used when probing the respective states. It is assumed that the transitionional area of the laser sheet is the same when probing the different states, which was satisfied in our experiments. The absorption lines used are the $^1P_{12}(2.5)$ and $^1R_{22}(28.5)$ transitions in the $A'\sum_--X^1\Pi(0,0)$ band of NO. They have a large difference in rotational energies, have similar Einstein absorption coefficients, are spectrally isolated, provide adequate signal and have the same vibrational energies. As described previously[2], the images were corrected for dark noise, Mie scattering, Rayleigh scattering, scatter off model surfaces, flow luminosity and laser sheet intensity variations, which depends on the assumption that the fluorescence signal is linearly dependent on laser intensity[2]. This assumption was true in the current work because the irradiance of the laser sheet was much less than the saturated irradiance for each transition used. For visualization purposes, six tunnel runs were completed and images recorded for the $^1P_{12}(2.5)$ transition. The number of images recorded was to account for shot-to-shot fluctuations in the field of view. Previous work[2] has established that six samples is the lower limit required for statistical significance. After this, images were recorded for three runs of the shock tunnel using a test gas of 100% N₂, which doesn't produce fluorescence, but provides images with laser scatter and background luminosity[2] that can be used to subtract the average background luminosity from the average PLIF signal from each transition.

For the thermometry experiments, six tunnel runs were completed and images recorded for each NO transition. Runs of the shock tunnel were used to capture images of the fluorescence when probing the $J'_j$ and $J''_j$ states successively, assuming flow reproducibility. The camera gain used for each of the transitions was calibrated by PLIF experiments in a static test cell, which produced 40 images for each gain setting, with a different gain setting used for each transition to ensure adequate signal levels.

<table>
<thead>
<tr>
<th>Location</th>
<th>x(mm)</th>
<th>T(K)</th>
<th>p(kPa)</th>
<th>u(km/s)</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>n.e.</td>
<td>254</td>
<td>416</td>
<td>7.60</td>
<td>2.83</td>
<td>7.10</td>
</tr>
<tr>
<td>l.e.</td>
<td>258</td>
<td>411</td>
<td>7.29</td>
<td>2.83</td>
<td>7.14</td>
</tr>
<tr>
<td>c.c.</td>
<td>318</td>
<td>351</td>
<td>4.24</td>
<td>2.86</td>
<td>7.81</td>
</tr>
</tbody>
</table>

Table 1 Freestream conditions

The freestream conditions were calculated by STUBE and are given in Table 1, which gives the freestream conditions at various axial locations x downstream from the nozzle throat.
In Table 1, n.e. indicates the nozzle exit; l.e. the leading edge of the model; c.c. the compression corner; \( p, T, u \) and \( M \) are the static pressure, static temperature, flow speed and Mach number, respectively. From this, we note that there is a significant variation in flow conditions from the nozzle exit to the compression corner. In particular, the Mach number varies by 10% over this region. The Reynolds number at the separation point is calculated to be \( \text{Re}_{s.p.} = 1.33 \times 10^5 \).

Even if the boundary layer at our Reynolds number is laminar before separation, disturbances generated in the separated region could travel upstream producing turbulence, invalidating the laminar flow assumption made in the CFD. Unfortunately, our ability to resolve any turbulent structures that might be present in the flow is limited by the thickness of the laser sheet, which is between 250 and 500\( \mu \)m.

5. RESULTS

Figure 4 presents the temperature field as determined by the CFD simulation. This is used later for comparison with the experimentally measured temperature. However, it is also useful for determining the theoretical values for geometric flow parameters such as those in Table 2, where CFD and experimental values are compared. Figure 5 presents a PLIF visualization image produced through the excitation of the \( ^1P_g(2.5) \) transition, plus a temperature map produced by the two-line PLIF thermometry method. In Table 2, \( \alpha_{l.e.s}, \alpha_{s.l}, \alpha_{s.s.} \text{ and } \alpha_{r.s.} \) are the angles, with respect to the horizontal, of the leading edge shock, shear layer, separation shock and re-attachment shock, respectively. \( z_{s.p.} \text{ and } z_{r.p.} \) are the distances from the leading edge to the separation point and re-attachment point, respectively. \( \delta_{s.p.} \) is the boundary layer thickness at the separation point and \( \Delta_{c.c.} \) is the size (height) of the separated flow at the compression corner.

Figure 6 compares CFD and experimental (EXP) temperature profiles. The profiles are along vertical cuts for different axial locations on the model. Comparing the profiles, we note that the CFD simulation underpredicts the size of the separated region and the peak temperature, as seen in Fig.6 (a) which shows that PLIF measures a peak temperature around 2100K, whereas the CFD simulation predicts it to be around 1300K.

The comparison is much the same in Fig. 6 (b), which shows that PLIF measures a peak temperature around 2300K, whereas CFD predicts it to be around 1200K.

### Table 2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>EXP</th>
<th>CFD</th>
<th>% Diff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha_{l.e.s} ) (°)</td>
<td>15.6</td>
<td>8.5</td>
<td>-45.5</td>
</tr>
<tr>
<td>( \alpha_{s.l} ) (°)</td>
<td>7.3</td>
<td>4.5</td>
<td>-38.4</td>
</tr>
<tr>
<td>( \alpha_{s.s.} ) (°)</td>
<td>12.2</td>
<td>9</td>
<td>-26.2</td>
</tr>
<tr>
<td>( \alpha_{r.s.} ) (°)</td>
<td>8.2</td>
<td>8</td>
<td>-2.5</td>
</tr>
<tr>
<td>( z_{s.p.} ) (mm)</td>
<td>23</td>
<td>32</td>
<td>-10.7</td>
</tr>
<tr>
<td>( z_{r.p.} ) (mm)</td>
<td>77.5</td>
<td>70.0</td>
<td>-10.7</td>
</tr>
<tr>
<td>( \delta_{s.p.} ) (mm)</td>
<td>0.75</td>
<td>0.75</td>
<td>0</td>
</tr>
<tr>
<td>( \Delta_{c.c.} ) (mm)</td>
<td>4.85</td>
<td>2.8</td>
<td>-73</td>
</tr>
</tbody>
</table>

This trend continues up to Fig 6(d), where CFD predicts a peak temperature around 1200K and experiment measures around 1800K.

Theoretical and experimental peak temperatures are somewhat closer in Fig. 6(e), but the spatial temperature profiles from theory and experiment are noticeably different.

Since the CFD assumed axisymmetric flow, the discrepancy between theory and experiment suggest that the axes of the model and nozzle were not perfectly aligned with respect to each other during the experiments (possibly a result of impulsive loading of the model or tunnel recoil).

In related work[2], it is shown that the model is at an angle of 1.5 ± 0.5° towards the laser and at a sideslip angle of 3.1 ± 0.5° away from the camera, with the camera and laser sheet at 90° to the flow. The inclination towards the laser would have resulted in a weaker leading edge shock on the upper surface with a subsequent decrease in the measured temperature. The (larger) sideslip inclination away from the camera would have resulted in a stronger leading edge shock on the surface facing the camera with a subsequent increase in the measured temperature or an underprediction of the temperature by CFD.
6. Uncertainties

For Table 2, uncertainties are ±0.5° for angles and ±0.3 mm for lengths. The main cause of uncertainty in the temperature measurements was random fluctuations in the longitudinal laser mode structure between laser pulses[2]. This was determined through pulse-to-pulse variation of PLIF signal in a static cell containing a mixture of 1% NO in N₂ at pressures between 1 and 50 kPa.

This showed that the standard deviation in PLIF signal due to mode fluctuations varies from 10% to 15% depending on the pressure, and is some 10% less than the fluctuations measured in the shock tunnel. The largest sources of systematic error for two-line PLIF thermometry in free-piston shock tunnels are absorption of the laser sheet at different rates by different transitions, differences in response to saturation by different transitions and interference with the PLIF signal by flow luminosity[2]. The effects of absorption and saturation have been minimized by careful choice of excitation transition. The influence of luminosity was minimized by operating the tunnel at low enthalpy conditions.

In order to determine the significance of mode fluctuations in our work, we compared the standard deviation in thermometry PLIF images with the test-cell measurements. The standard deviation of the test-cell measurements was found to be: ± 15% at 2 kPa, compared to the measured standard deviation in the freestream of ± 23% for the ⁰P₁₂ (2.5) transition and: ± 29% for the ⁰P₁₁ (33.5) transition. The sample size for the thermometry images of 6 shots per transition is on the borderline of statistical significance, but in agreement with earlier work[2].

Because a free-piston shock tunnel is a short duration pulsed facility with a long turn-around time, it was difficult to make more than six measurements.

Calculations indicate that the systematic error due to saturation on measured temperature is less than 1% and the systematic error due to absorption is nowhere greater than 3% for all regions of the flow. The careful selection of the NO transitions has ensured that the systematic errors remain relatively small when compared with random errors in the temperature due to longitudinal-mode fluctuations of the laser and shot-noise of the camera. To estimate these random errors, we performed a statistical analysis of an 11×11 pixel region in various parts of the flow, from which we determined that the random error was: 2.5% in the free stream; 3.2% in the leading edge shock layer; 5.3% in the separation shock layer and 16.5% in the separated flow region.

7. Conclusions

Laminar flow over an axisymmetric compression corner model in a diverging supersonic freestream produced by a conical nozzle was simulated by CFD. PLIF visualisation and thermometry experiments were attempted for the modelled flowfield, but model misalignment meant that perfect axial symmetry wasn’t achieved. Further work is required to produce better agreement between CFD and experiment, either by improved experiments or accounting for the misalignment in a three dimensional CFD simulation. A turbulent flow CFD simulation should also be performed to determine whether the observed descrepancy is a result of turbulence.

Acknowledgments

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REFERENCES


