Aerodynamic Heating from Compression Corner Interactions in Hypersonic Flow

Eric E. Jo[*]
University of Maryland, College Park, MD, 20742, USA

Stuart J. Laurence[†]
University of Maryland, College Park, MD, 20742, USA

Localized thermal loads on hypersonic vehicles are often caused by geometric features that intensify compression and shock interactions. To better quantify this phenomenon, this study looks into the heating generated by compression corner shock interactions on a cone-flare model in Mach 6 flow. Experiments were conducted in a high-temperature Ludwieg tube hypersonic wind tunnel using various flare angles which depict a relationship between the local shock structures and surface heat flux. Temperature-sensitive paint applied on the surface of the cone-flare model spatially mapped heating measurements, with brightness changes recorded by a high-speed Phantom camera and converted to transient heat-flux data. Concurrently, schlieren imaging captured the shock structures, enabling direct comparison between shock-reattachment locations and regions of elevated heating. Results show a clear increase in surface heating near the flare junction corresponding to the compressive shock structures. These findings highlight how compressive features such as control surfaces can drive localized thermal loads, informing improved thermal protection strategies for future hypersonic vehicle designs.

I. Nomenclature

FPS = Frames Per Second
TSP = Temperature Sensitive Paint
q = Heat Flux
ρ_b = Density of the Cone-Flare
c_b = Specific Heat of the Cone-Flare
k_b = Thermal Conductivity of the Cone-Flare
T = Temperature
t_i = Time at index i
t_{i-1} = Time at index i-1
t_n = Total elapsed time
π = pi

II. Introduction

One of the primary challenges in hypersonic vehicle design is the proper management of aerodynamic heating. At hypersonic speeds, the kinetic energy of the flow is converted into thermal energy through compression shocks and viscous friction effects near the vehicle surface, resulting in extremely high heat fluxes. While average heating across a vehicle's surface can be estimated using existing analytical or computational methods, localized heating phenomena remain difficult to predict accurately. These localized thermal loads are a significant area of study because increased thermal loads can lead to unforeseen structural, mechanical, or operational failures in vehicles. Specifically, areas where a vehicle's geometry induces compression features are tied with elevated heating. Surface discontinuities such as flares, ramps, and control surfaces are some of the most common features seen in hypersonic vehicles which undergo increased heating.

---

[*] Undergraduate Student, Aerospace Engineering, Student AIAA Member 1926276
[†] Professor, Aerospace Engineering, 3179 Glenn L. Martin Hall

In order to study these effects, a cone-flare geometry was utilized. The flare provides an increase in the surface inclination, which generates a strong compression of the flow. This often causes shock-induced boundary layer separations which later reattach downstream.

In this study, experimental data obtained from a cone-flare model is extracted to investigate the aerodynamic and thermal behavior of the reattachment location of the shockwave. There are two main focuses for this work. First, the visualization of the surface heat flux distribution post the cone-flare is calculated to determine where peak heating occurs along the model surface. Second, the relationship between observed flow structures and visualized heating distribution is explored in order to track and identify the mechanisms behind the increase in heating.

III. Freestream Conditions & Testing Matrix

Below are the different freestream conditions, cone-flare set-ups, and video collection data tested on the High-Temperature Ludwieg Tube at the University of Maryland's High Altitude and Propulsion Laboratory.

Run #	M_∞	Re/m	Flare Angle [deg]	TSP FPS	Schlieren FPS
2	6	7.9×10^6	10	170,000	870,000
3	6	9.7×10^6	10	170,000	870,000
20	6	7.9×10^6	10	150,000	200,000
21	6	9.7×10^6	10	150,000	200,000
22	6	7.9×10^6	15	220,000	200,000
23	6	9.7×10^6	15	220,000	200,000

Table 2 Examined Test Matrix

IV. Thermal-Sensitive Paint Derived Heat Flux Extraction

Surface heat transfer measurements were obtained using temperature-sensitive paint (TSP) methods. TSP is a luminescent coating, where the emitted light's intensity varies with temperature, opening the door into non-intrusive ways to study the flow field. Due to the relatively short test time of the High-Temperature Ludwieg Tube, fast responding TSP is required to accurately obtain the transient heat distribution. This approach enables the extraction of the spatial heating on top of the cone-flare model's surface and clearly visualizes the "hot" and "cold" spots of the flow.

A. Thin Film Origins

Tracing its theoretical foundations in an early work by Schultz and Jones [1], this approach works under the assumptions of using the measured surface temperature history to then calculate surface heating with the one-dimensional transient heat conduction equation. Though the method described in Ref. [1] uses thin-film gauges, thermocouples, and optical measurement techniques, the same fundamental process can be used in TSP measurements. A numerical version of the heat flux time history equation is used as shown below [2]:

$$q(t_n) = 2\sqrt{\frac{\rho_b c_b k_b}{\pi}} \sum_{i=1}^{n} \frac{T(t_i) - T(t_{i-1})}{\sqrt{t_n - t_i} + \sqrt{t_n - t_{i-1}}} \tag{1}$$

Equation 1: Numerical Approximation of Heat Flux by Cook and Felderman

B. The Modern TSP Method

In an evolution to thin-film heat flux measurement methods, TSP light intensity measurements have become the modern way to accurately and non-intrusively extract heating data from a measured temperature history.

Demonstrated by more recent works by Ozawa and Laurence [3, 4], the extraction of surface heat flux using temperature-sensitive paint measurements have been successfully applied to hypersonic flow experiments in short-duration facilities. In these studies, high-speed Phantom cameras were used to capture the temperature and thus heat-flux evolution on the surface of test models of various shapes. Analytical approaches for converting TSP measurements into quantitative heat flux data have been developed in previous work [5] by Liu.

In the current study, TSP was applied to the surface of the cone-flare model in order to obtain time-resolved surface temperature measurements during each test run. Shot from the top down of the cone-flare model, various resolutions and frame rates were run in order to explore the fidelity of the spatial and temporal heat-flux resolutions needed to correlate with the schlieren runs which were shot simultaneously.

C. Post-Processing of Heat Flux Data

After examination of the raw heat data, high frequency noise can be found in the data which needs to be filtered out before any analysis can begin. Utilizing a moving mean algorithm, the data was smoothed in both the spatial and temporal dimensions in order to avoid features such as extreme and sudden gradients which are unrealistic to the flow. Additionally, with the schlieren data, the shock location can be mapped onto the heat flux visualization in order to see a direct qualitative comparison of the two results. Implementing heavy smoothing however is detrimental to the resolution of the data, therefore caution must be practiced in order to avoid over filtering data.

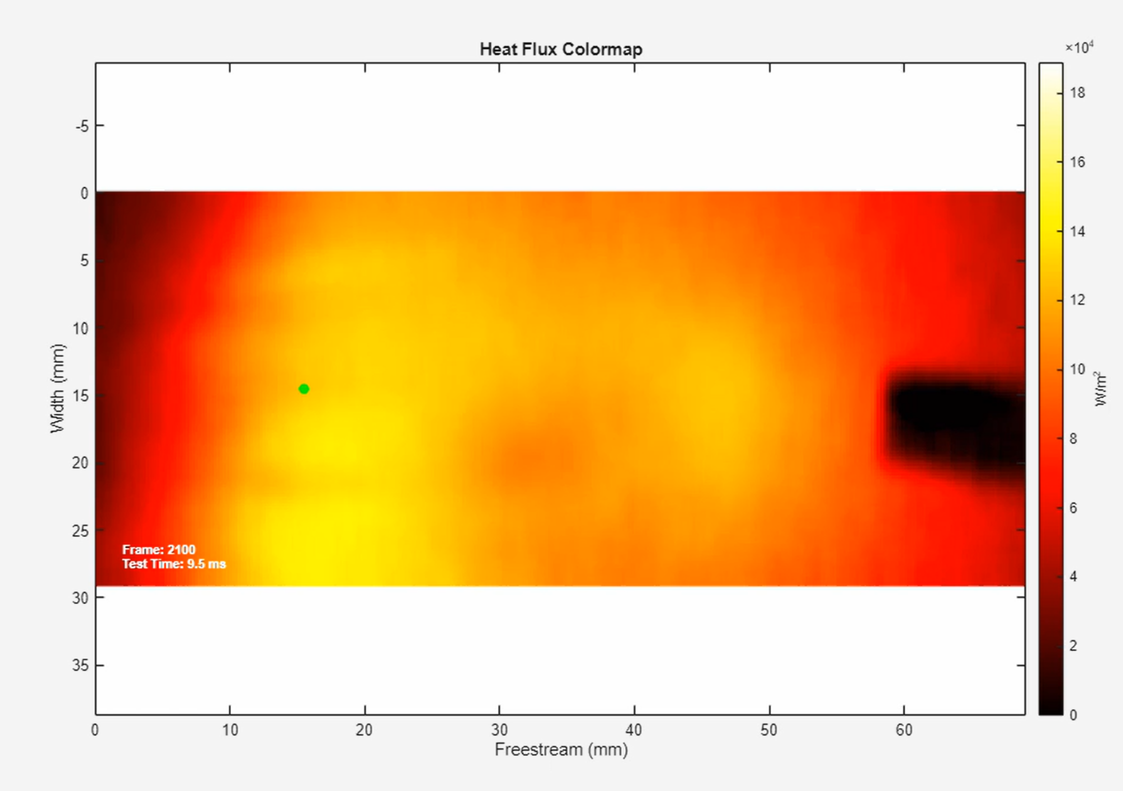

Fig. 1 Spatially resolved heat flux visualization of Run 23 with the shock reattachment shown as the green dot

V. Schlieren Measurements

Moving onto the flow structure measurements, schlieren imaging [6–8] was utilized to visualize the shock structures present in the flow around the cone-flare. Shot with a high speed Phantom camera, the videos provides full view of the top half of the cone-flare model showing both the flow before and after the flare. After implementing a bilinear rotation to place the flared surface on the bottom of the horizontal frame and cropping of the slow motion video to only capture the flared portion of the cone excluding the boundary-layer, the intensity values of the frame are extracted to track the shape of the shock. Similarly to the TSP post processing mentioned above, the shock shape is then smoothed with a moving mean calculation in order to filter out any extreme gradients or discontinuities in the shock structure.

A. Shock Reattachment Location Extraction

In regards to the main flow structure this study is examining, the shock reattachment point after the separation at the compression corner is difficult to quantify due to its vague and often times arbitrary definition. Two main methods were explored in order to accurately track the reattachment location.

1. Surface Proximity Method

The first method utilizes the local shock height or distance the shock curve is located from the lower cropped boundary of the frame. By defining a percent distance to the lower boundary of the frame, a virtual border is made such that if the shock curve's recorded values are below the lower border, it is classified as reattached to the cone flare. Though this method showed initial success, problems from noisy data or an improper definition of the lower boundary caused the border to either not detect the shock reattaching at all, the shock reattaching further downstream, or the border detecting the boundary layer as a shock. Due to the inconsistent nature of the method, a more reliable method had to be developed.

2. Shock Curve Gradient Analysis

The second method utilizes the numerical derivative or gradient of the shock curve in order to determine the reattachment location of the shock onto the flare. Because the flare has now been rotated to the lower border of the frame, the reattachment point should mathematically exist when the absolute value of the gradient of the shock is close to zero or is zero. Using the raw gradient also presents high frequency noise and so a moving mean is used to smooth the gradient curve before the reattachment point is ascertained. Unlike the previous method, this allows for a more consistent and reliable frame by frame shock curve tracking due to the fact that the gradient is now independent of the actual dimensions of the frame and rather shifts the analysis of the curve to its curvature rather than its location relative to the flare surface. Though there are still intermittent issues with tracking reattachment locations when the gradient of the shock never numerically reaches the set value near 0, this shift into the curvature space of the shock curve greatly increasing the accuracy and reliability of the reattachment point measurements.

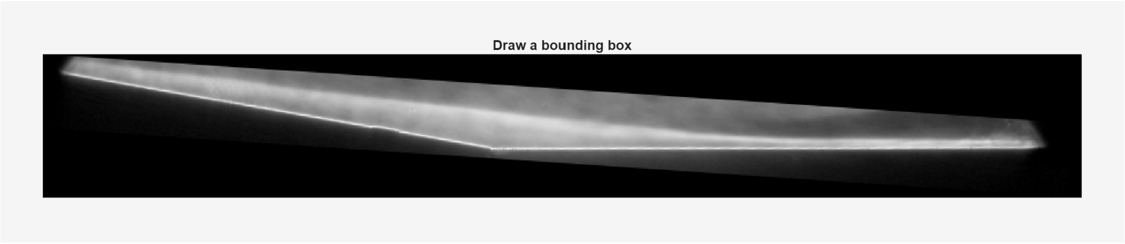

Fig. 2 Side-on Shot of the cone-flare in Run 23 after the bilinear rotation but before the cropping onto the flared "flat" region on the right

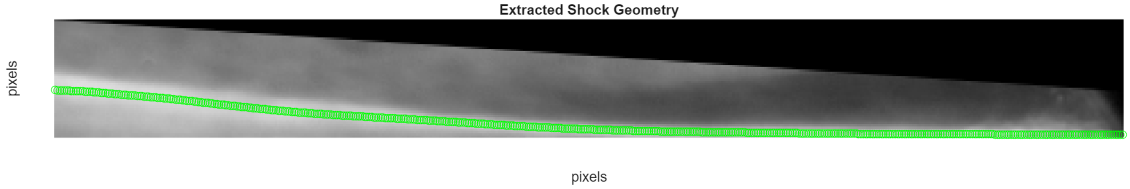

Fig. 3 Side-on Shot of the cone-flare in Run 23 with its shock shape plotted

VI. TSP & Schlieren Measurement Results

In order to examine the relationship between the heating on the cone flare and the shock structures around the body, the two data sets must now be accurately aligned to visualize any correlations between the two.

A. Spatial and Temporal Alignment

Since the TSP and schlieren measurements were shot top-down and side-on respectively, the appropriate region on where the schlieren data lives on the heating data must be accurately deduced. Due to the side-on frame of the schlieren imaging relative to the cone-flare, only a small mid-line region along the span of the cone-flare can be used to correlate the heat flux to the shock structures. Additionally, due to the differing frames per second (FPS) and resolution values of the two datasets, appropriate scaling and interpolation is needed in order to accurately map the location of the tracked shock reattachment to the midline of the heating data. The spatial scaling values used for all of the TSP and schlieren footage was 0.227 mm per pixel and 0.128 mm per pixel. The temporal differences were mapped using the ratio of the TSP to the schlieren videos in order to sample appropriately.

B. Correlations Between Heating and Shock Structures

In general observation, a loose relationship between the location of max heating along the mid-span line and the reattachment location of the shock can be found. In runs with smaller FPS discrepancies, a clearer correlation can be observed between the max heating and shock reattachment locations such as runs 20 to 23. Higher flare angles also appear to increase the correlation between the reattachment locations as seen in runs 22 and 23. However, as compression angles decrease and the FPS discrepancies increase, it becomes more difficult to extract a correlation between the two datasets. Runs 2, 3, 20, and 21 depict this phenomena as there exists a vertical displacement separating the max heating location to the shock structures. Run 23 correlates the most accurately between the two datasets clearly showing that the location of the max heat flux is coincident to the reattachment location when the flow is steady. Pockets of turbulence also tend to move both the shock reattachment and max heating locations wildly, making tracking during these periods nearly impossible. Lastly, for lower cone flare angles, the heating sometimes depicts streaks in the flow wise directions indicating a separate flow feature becoming the dominating factor in increasing the heating in those regions besides the shock reattachment. All of the correlated location plots can be found in the appendix below.

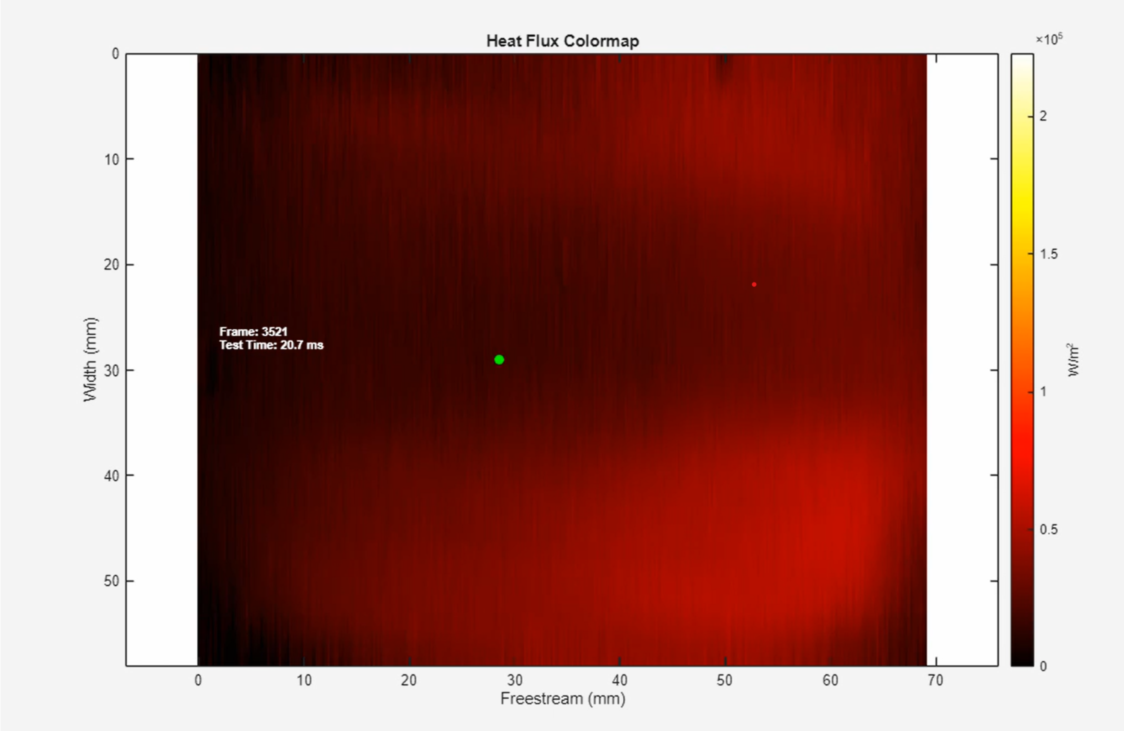

Fig. 4 Heat flux distribution on the cone-flare for Run 3 depicting streamwise streaks

VII. Conclusion

In summary, this study investigated the correlation between compression-corner shock interactions and localized aerodynamic heating on a cone–flare geometry in Mach 6 hypersonic flow. Data from the experiments conducted in the High-Temperature Ludwieg Tube at the University of Maryland utilized TSP to obtain top-down surface heat-flux, while simultaneously side-on schlieren imaging captured the corresponding shock structures in the surrounding flow.

Results indicate that the largest heat-flux values occur near the region where the separated flow reattaches onto the flare. For larger flare angles, the flow undergoes a more pronounced separation and reattachment, producing a clearer alignment between the shock reattachment locations and the peak heating observed on the surface.

At smaller flare angles, the relationship between the max heating and shock reattachment location become muddied. The spatial heating in these cases exhibit streak-like structures and momentary increases of heating in the streamwise direction, suggesting that additional flow features such as vortical structures may take over as the leading cause of heating. Due to the inconsistencies between the max heating locations and reattachment locations, it is very difficult to find correlations in these cases.

Future work may improve the robustness of the analysis by employing frequency-based filtering methods and more consistent imaging parameters across experimental runs.

Despite these limitations, the results demonstrate a clear relationship between compression-induced shock structures and localized aerodynamic heating on cone–flare geometries. Understanding this relationship is important for predicting and designing for thermal loads on hypersonic vehicles, particularly in regions where control surfaces, flares, or other geometric discontinuities introduce strong compression effects. The combined use of TSP measurements and schlieren imaging hold promise in correlating flow behaviors each cannot capture on their own. Meshing the two techniques together can potentially open up the analysis of more complex and detailed flow structures in the near future.

Appendix

Fig. 5 Midline Span Max Heat Flux and Shock Reattachment Location of Run 2

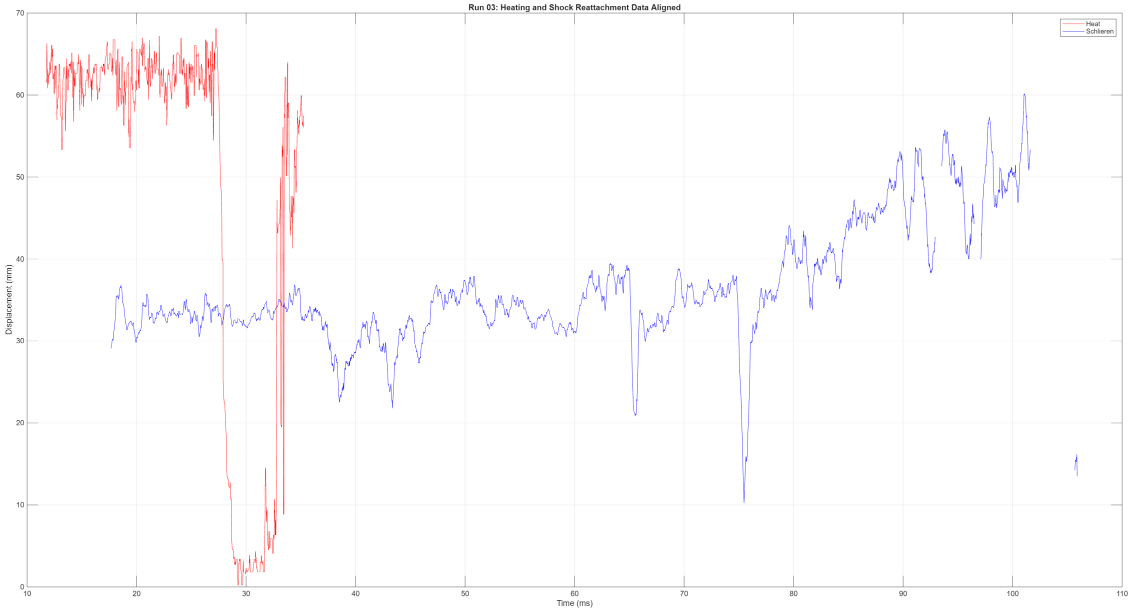

Fig. 6 Midline Span Max Heat Flux and Shock Reattachment Location of Run 3

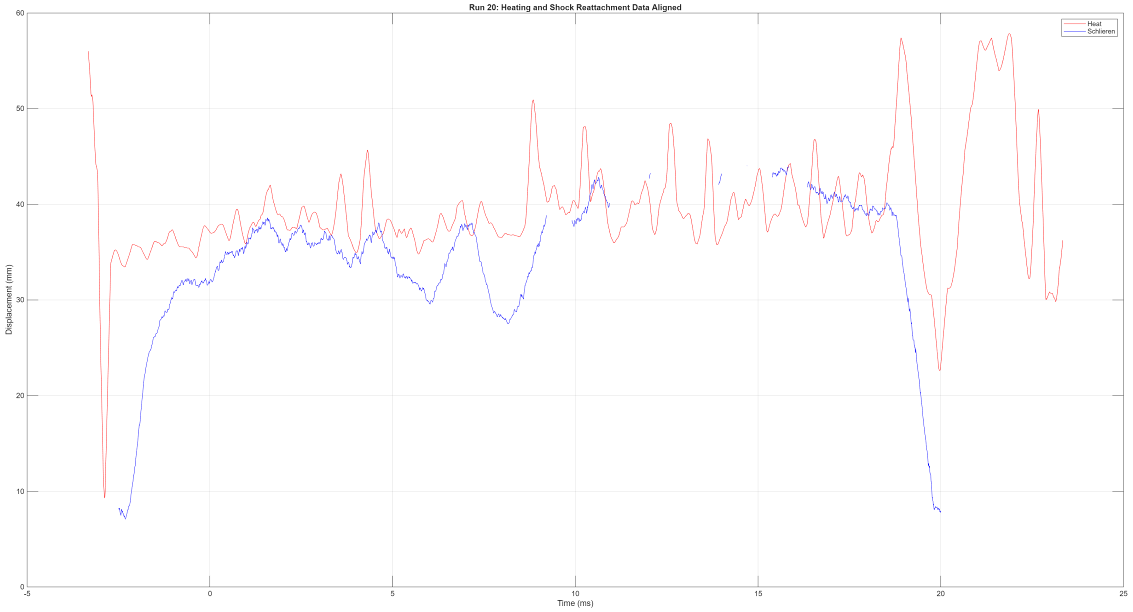

Fig. 7 Midline Span Max Heat Flux and Shock Reattachment Location of Run 20

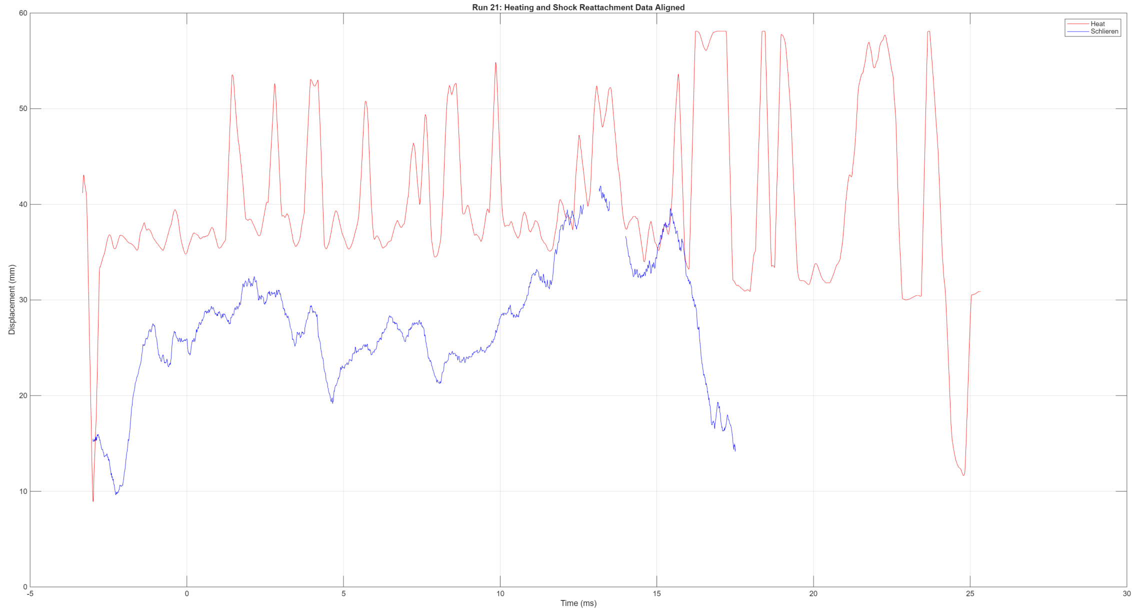

Fig. 8 Midline Span Max Heat Flux and Shock Reattachment Location of Run 21

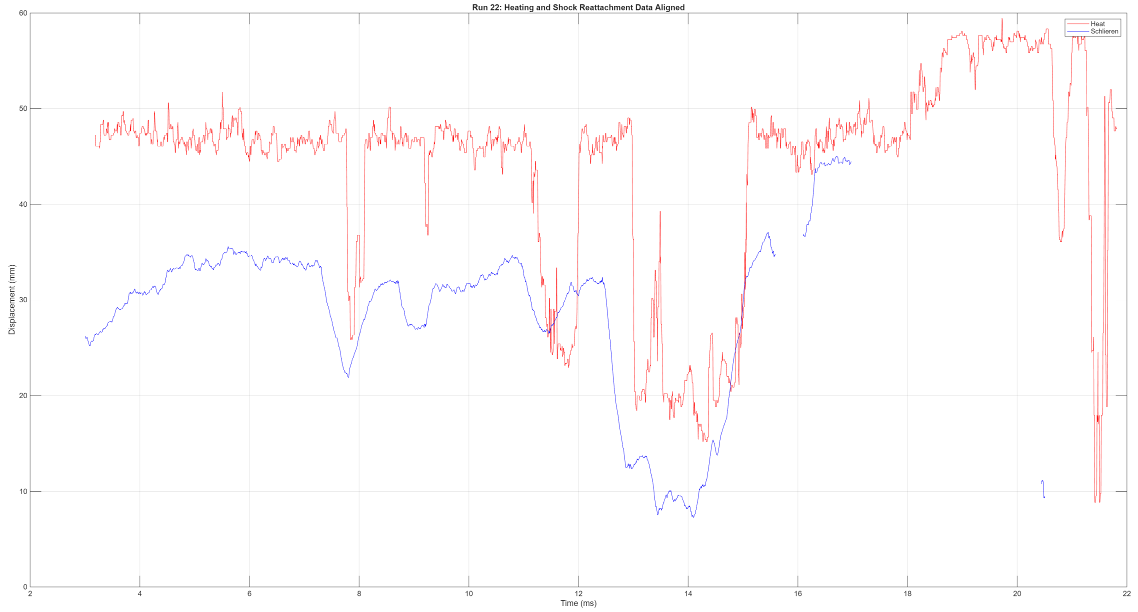

Fig. 9 Midline Span Max Heat Flux and Shock Reattachment Location of Run 22

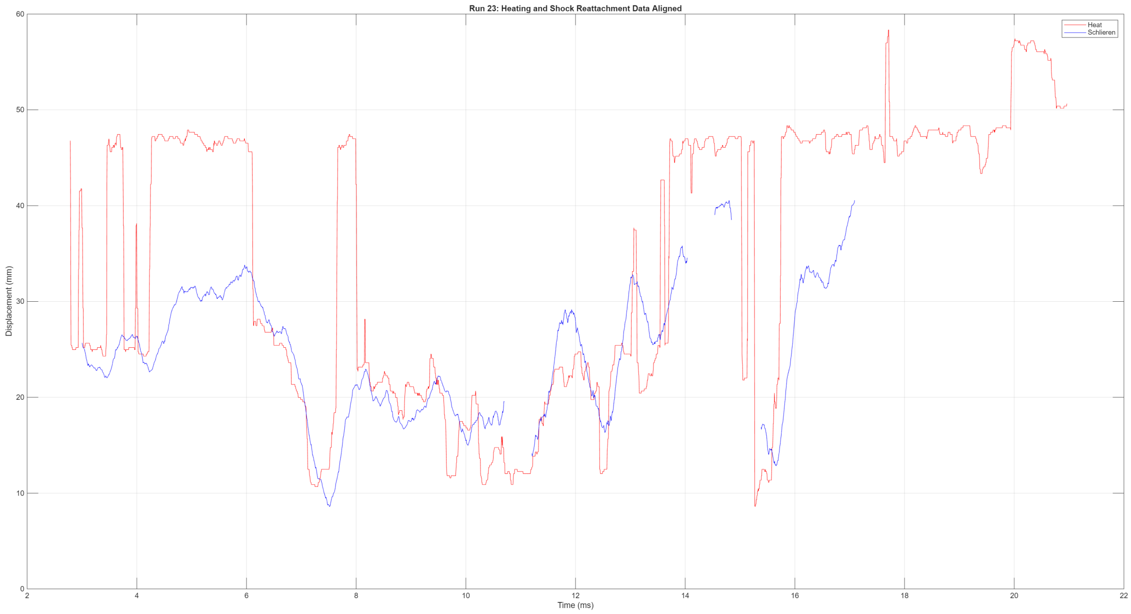

Fig. 10 Midline Span Max Heat Flux and Shock Reattachment Location of Run 23

Acknowledgments

The author thanks Grant Duemmel, Ryan De Silva, and Samuel Maszkiewicz for their assistance in the High Altitude and Propulsion Laboratory, including sharing run data and setting up the analysis code. The author also gratefully acknowledges the support and encouragement of his family.

References

[1] Schultz, D. L., and Jones, T. V., "Heat Transfer Measurements in Short-Duration Hypersonic Facilities," AGARDograph 165, AGARD, 1973.

[2] Cook, W., and Felderman, E., "Reduction of data from thin-film heat-transfer gages: a concise numerical technique," *AIAA Journal*, Vol. 4, No. 3, 1966, pp. 561–562.

[3] Ozawa, H., Laurence, S. J., Martinez Schramm, J., Wagner, A., and Hannemann, K., "Fast-response temperature-sensitive-paint measurements on a hypersonic transition cone," *Experiments in Fluids*, Vol. 56, 2015. https://doi.org/10.1007/s00348-014-1853-y.

[4] Ozawa, H., and Laurence, S. J., "Experimental investigation of the shock-induced flow over a wall-mounted cylinder," *Journal of Fluid Mechanics*, Vol. 849, 2018, pp. 1009–1042. https://doi.org/10.1017/jfm.2018.433.

[5] Liu, T., Cai, Z., Lai, J., Rubal, J., and Sullivan, J. P., "Analytical Method for Determining Heat Flux from Temperature-Sensitive-Paint Measurements in Hypersonic Tunnels," *49th AIAA Aerospace Sciences Meeting*, American Institute of Aeronautics and Astronautics, 2011. https://doi.org/10.2514/6.2011-1284.

[6] Toepler, A., "Über die Methode der Schlierenbeobachtung als mikroskopische Methode," *Annalen der Physik und Chemie*, Vol. 127, 1864, pp. 556–580.

[7] Settles, G. S., *Schlieren and Shadowgraph Techniques: Visualizing Phenomena in Transparent Media*, Springer, 2001.

[8] Merzkirch, W., *Flow Visualization*, Academic Press, 1987.