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Comparative surface heat transfer measurements in hypervelocity flow

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Experimental heat flux measurements are made using both thermocouple and thin film gages in high-temperature, hypersonic flows. Thermocouple and thin film gages have individually been extensively used in relatively high and low enthalpy conditions respectively. In this study, three test conditions with varying (intermediate) stagnation enthalpies, Mach and Reynolds numbers are created in an expansion tube facility, and temperature histories and heat flux measurements obtained using the two gage types are directly compared. Gage performance in terms of survivability, response, uncertainty, and signal-to-noise ratio is assessed for both blunt body and flat plate models.

I. Introduction

Reliable prediction of the high heat transfer rates experienced during the hypersonic portion of planetary entry and descent is critical to vehicle survival. While non-intrusive diagnostics can be used to obtain temperature field data around models, wall-mounted sensors are commonly used to measure the heat flux at the surface. Two types of sensors which can be used for this purpose are coaxial thermocouple gages and thin film resistance thermometers. Individually, both types of gages have been used successfully in extensive studies at Calspan-University of Buffalo Research Center (CUBRC),[1–8] NASA facilities,[9–14] Graduate Aeronautical Laboratories at Caltech (GALCIT),[15–18] and the University of Queensland,[19,20] among others. Both thermocouple and thin film gages measure surface temperature from which heat transfer can be calculated. Both have μs response times, and can be flush-mounted in models. Coaxial thermocouples are robust, and can survive challenging experimental conditions. Thin film resistance gages typically provide improved signal levels, but are less robust, and have to be individually calibrated. As discussed below, thermocouples are generally preferred at higher enthalpy conditions, while thin film gages are used at lower enthalpy conditions. As a result, there are few studies which directly compare measurements from the two types of gages. In the present work, we perform experimental measurements at a range of intermediate enthalpies in hypervelocity flow and make direct comparisons between heat flux data obtained from thermocouple and thin film gages.

Miller[9] performed a comprehensive review of thin film gages used in the NASA Langley Continuous Flow Hypersonic Tunnel (CFHT), comparing their performance to thick-skin calorimeters. Gage durability on both glass and ceramic substrates were tested. It was found that of the four glass substrate models, only one survived longer than one test. The ceramic models fared slightly better, with one surviving six tests, and the other surviving all nine tests it was subjected to. Since these tests were conducted in a continuous-flow facility the gages were exposed to test times three orders of magnitude longer than typical impulse facility test times. The method used to apply the gages to the substrate was significantly different than the current technique which could have significant effects of gage durability. Chadwick[7] performed a detailed review of the use of thin film heat transfer gages in the CUBRC 96 inch reflected shock tunnel facility. Heat transfer data are obtained at multiple run conditions with enthalpies ranging from 1.85 to 7.44 MJ/kg and Mach numbers from 10 to 16.

Kidd presents a detailed survey of the coaxial thermocouples used at Arnold Air Force Base, as well as many other facilities.[10] Some issues associated with the coaxial gages are quantified. The two major conclusions from this study were that coaxial thermocouples can be utilized at test times much longer than

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semi-infinite body assumption would allow, and also that the gage length does not need to be equal to the model wall thickness. In a later study, Kidd et al. investigated the effects of extraneous voltages caused by electrical connections between the model and the gage, and found that care must be taken to minimize the effects of such contact.[11]

Coaxial thermocouple gages are typically used in high stagnation enthalpy flows in the Caltech T5 reflected shock tunnel facility. Sanderson[15] originally developed a new coaxial thermocouple design in order to avoid fragility issues associated with thin film gages, and other issues with the more generally used coaxial wire thermocouples. Sanderson found that extraneous voltages produced from contact between the gage and the model were negligible with the new design. These thermocouples have been applied to other experiments in the T5 facility.[16,17,21] Marineau and Hornung[22] performed a numerical study of the gages designed by Sanderson. The response time and accuracy of the gages was found to be strongly dependent on the junction geometry. A simultaneous calibration procedure for multiple gages is proposed if individual calibration is desired.

Salvador et al. report on the development of coaxial thermocouple gages for use in the shock tunnel facilities at the Laboratory for Aerothermodynamics and Hypersonics in Brazil.[23] One important result from this paper is the demonstration of the dependence of gage response time on the connection properties between the two electrodes. It was found that simply by using different grit sandpaper to create the junction the response time could change by a factor of two.

While not focused on direct comparative measurements, there are a limited number of studies in which both thin film and thermocouple surface heat transfer data are available. In a recent study at the National Aerospace Laboratory in Japan, both coaxial and thin film thermocouples were used to compare the operation of the Hypersonic Wind Tunnel, the High Enthalpy Shock Tube, and the Hypersonic Shock Tube to establish guidelines for the use of the facilities.[24] The thermocouple data was found to be in good agreement with IR thermography, and the non-dimensional heat transfer agreed to within a few percent between all three facilities. Both thin film and thermocouple gages were used in two recent studies at CUBRC. The first study focused on real gas effects in both the LENS I and LENS X facilities for test gas enthalpies from 2 to 12 MJ/kg.[3] Heating rates measured by both gages were in good agreement with each other, however at high enthalpies the measured heat flux did not agree with either fully catalytic or non-catalytic wall predictions. The second study at CUBRC, conducted in the LENS I reflected shock tunnel, used the gages to investigate the role of catalytic effects on a sphere-cone model in both nitrogen and carbon dioxide. Tests were run at test gas enthalpies of 2, 6, and 8 MJ/kg. This study found good agreement between the gages, but found that all gage types measured heating levels higher than predicted assuming a non-catalytic wall, but less than that predicted assuming a fully-catalytic wall.[4]

Though these sensors have been used extensively for many years, their selection has relied on very general distinctions, where thin film gages are used for "low" enthalpy conditions, and coaxial thermocouples are used for "high" enthalpy conditions. In order to develop a more rigorous method for application of the gages, properties such as signal-to-noise ratio, durability, accuracy, and wall catalysis effects must be quantified for a range of flow enthalpies. Creating a database of these properties would allow researchers to determine the best gage for their application, and increase confidence in surface heat transfer measurements.

II. Experimental Setup

Hypervelocity flow conditions can be created using impulse ground testing facilities such as reflected shock tunnels (T5 at Caltech,[25] HLG at the Institute of Aerodynamics and Flow Technology in Germany,[26] LENS at CUBRC[27] and the 20 inch and 31 inch tunnels at NASA Langley[28]) and expansion tubes (X-series at University of Queensland,[29] JX-1 at the Institute of Fluid Science in Japan,[30] LENS-X at CUBRC[2]). In an expansion tube, the flow is accelerated by a shock followed by an unsteady expansion wave. A range of test conditions can be relatively easily accessed by changing initial pressures and gas compositions, and thermochemical freezing, a common problem in facilities which utilize nozzles, is minimized. Facility disadvantages include reduced test times and increased viscous effects.

The Hypervelocity Expansion Tube (HET) at the University of Illinois operates across a range of Mach numbers from 3.0 to 7.5 and stagnation enthalpies from 4.5 to 8.0 MJ/kg.[31] Heat flux data can be obtained using both thermocouple and thin film gages in this facility, allowing direct comparisons to be made between the two measurement techniques. The 9.14 m long facility consists of driver, driven, and accelerator sections all with a 150 mm inner diameter.[31] For this study, three test conditions with different stagnation enthalpies were selected. Steady, perfect gas dynamic calculations are used to predict test gas conditions, shown in Table 1.

Table 1: Theoretical parameters for HET run conditions.

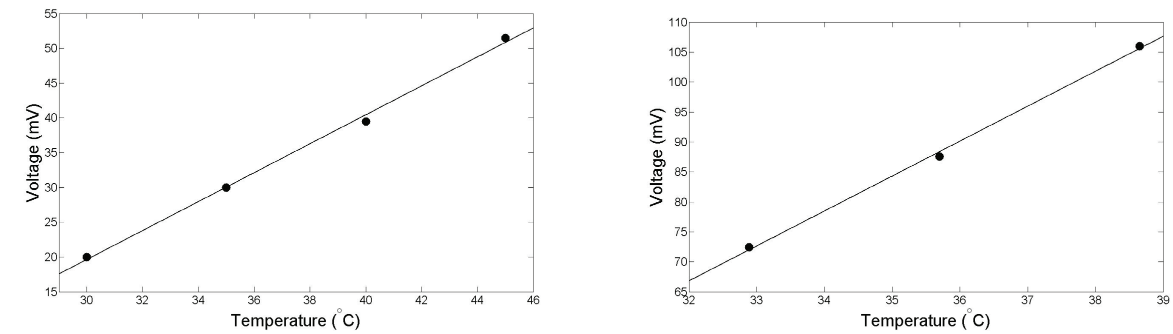
	Air 4	Air 5	Air 6
Mach Number	5.12	7.45	5.73
Static temperature, K	676	642	909
Static pressure, kPa	8.13	0.77	1.86
Velocity, m/s	2664	3779	3457
Density, kg/m^3	0.042	0.004	0.007
Test Time, μs	361	163	242
Unit Reynolds Number, $1/m$	3.42E6	0.50E6	0.63E6
Enthalpy, MJ/kg	4.08	7.65	6.70
Initial Pressures, kPa			
Driver Section	2500	2500	2500
Driven Section	6.0	1.5	1.2
Expansion Section	0.08	0.02	0.07

The thermocouples used in these experiments are based on the design of Sanderson.[15] They are coaxial, 2.4 mm in diameter, type E (Constantan-Chromel), and mount flush with the surface of a model. The two coaxial elements are designed such that an extremely thin junction (on the order of 1 μm) is formed at the surface. This type of thermocouple gage is used extensively in the T5 reflected shock tunnel at GALCIT,[15–17] where the high enthalpy test conditions result in adequate signal levels and the robust design of the gages make them highly resistant to damage caused by particulates in the test gas as well as the large heat fluxes.[15] The output signal is processed by a differential amplifier circuit mounted exterior to the test section. This also serves to eliminate the effects of any extraneous voltages generated between the thermocouple and the model wall. The circuit gain is 1000 to maximize signal amplitude. Individual calibration of thermocouples is not necessary, since the temperature response of all common thermocouple types is well known. The NIST thermocouple reference tables were used to convert from voltage to temperature.[32]

Thin film gages produce higher signal levels than the thermocouples, however have been reported to be less durable. To the authors' knowledge, quantification of survivability has not been undertaken in an expansion tube facility. The thin film gages used in this study are based on the design of Adelgren,[33] Chadwick,[7] and Kinnear.[34] Gages are created by painting and firing a small strip of metallo-organic platinum paint on to an insulating substrate, such as ceramic or glass, to create very thin film resistors, whose resistance changes with temperature. Though it is this temperature-resistance relationship that makes the gage useful, resistance is a difficult measurement to make during an experiment. Instead, the gage is used as one arm in a basic Wheatstone bridge circuit. The voltage difference between the two legs of the bridge will be proportional to the change in resistance of the gage. A differential amplifier (the same design used in the thermocouple circuit) is then used to find the difference between the two bridge legs, and amplify it with a gain 100. A lower gain is used for the thin film gage signal amplification than for the thermocouple as the sensitivity of the gage is greater.

Each thin film gage must be individually calibrated in a static bath in order to determine the resistance-temperature relationship. During this calibration procedure, a bath of a non-conducting fluid (glycerol) is brought to a known temperature (measured with a commercial thermocouple). The gage is then immersed in the liquid and the temperature in the substrate is allowed to equilibrate, then a voltage reading is taken. This procedure is repeated for a range of temperatures between 25° C and 50° C, and a calibration curve is fit to these data points. An example of one of these calibration curves is presented in Figure 1a. To check the functionality of the gages, a constant heat flux source was applied to the calibrated gage. The temperature profile and resultant heat flux data are shown in Figure 2.

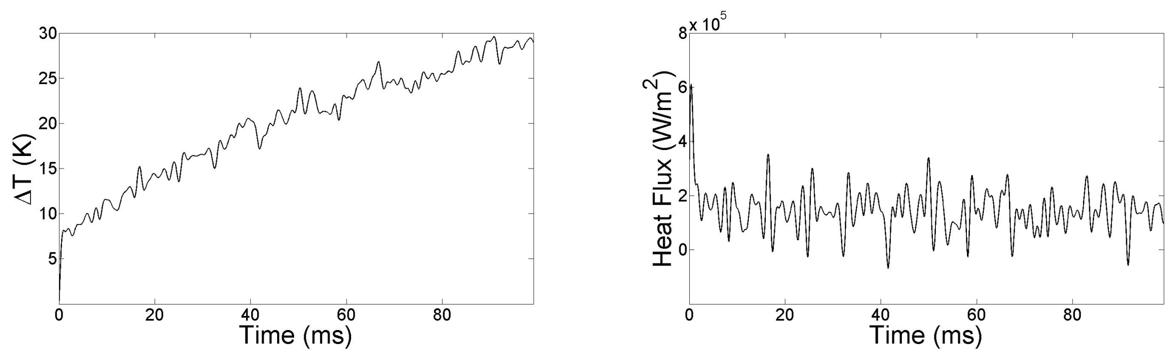
After initial experiments with an isolated gage, several thin film gages were painted onto a stagnation sphere model. Also, a special insert was made which could be mounted in a flat plate. This insert was 3 inches long and 0.5 inches wide, and was designed to have 12 thin film gages on the surface. Channels were cut in the side of the insert so that wires could be attached to each gage without affecting the surface of the model. The models were entirely immersed in the thermal bath for gage calibration. A calibration curve for a stagnation sphere gage is shown in Figure 1b.



(a) Calibration of an isolated thin film gage element.

(b) Calibration of a model-mounted thin film gage.

Figure 1: Thin film calibration curves.



(a) Temperature history.

(b) Surface heat transfer.

Figure 2: Thin film gage data obtained from an isolated gage element exposed to a constant heat flux.

A. Heat flux deconvolution

Two methods were investigated to deconvolve the heat flux from the gages, both of which assumed that the gage or substrate can be modeled as semi-infinite body during the test time. The first method uses Laplace transforms to solve the heat equation, and this solution is shown in Equation 1.[35] In order to solve this problem numerically, it is useful to use the discretized form, seen in Equation 2 (where the signal consists of $n+1$ measurements).

$$\dot{q}(t) = \sqrt{\frac{\rho c k}{\pi}} \int_0^t \frac{dT(\tau)}{d\tau} \frac{d\tau}{\sqrt{t-\tau}} \tag{1}$$

$$\dot{q}_n = \sqrt{\frac{\rho c k}{\pi}} \sum_{i=1}^{n} \frac{T_i - T_{i-1}}{\sqrt{t_n - t_i} + \sqrt{t_n - t_{i-1}}} \tag{2}$$

where $\dot{q}(t)$ is the heat flux as a function of time, ρ, c, k are density, specific heat and thermal conductivity of the material respectively, and T is the temperature. The second method was introduced by Sanderson.[15] The solution to the diffusion equation in a semi-infinite plate exposed to a surface heat flux is represented by a convolution integral

$$\Delta T(x,t) = \int_0^t g(x, t-\tau)\dot{q}(\tau)d\tau \tag{3}$$

where ΔT is the change in temperature and $g(x,t)$ is the impulse function, given by

$$g(x,t) = \frac{\partial \Delta T(x,t)}{\partial t} = \sqrt{\frac{\alpha}{\pi k^2 t}} \exp \frac{-x^2}{4\alpha t} \tag{4}$$

where α is the thermal diffusivity and x is the junction depth. By taking the Fourier transform of the equation, it is possible to solve for the heat flux, such that

$$\dot{q}_n = FFT^{-1}\left[\frac{S_n}{G_n}\right] \tag{5}$$

where S_n and G_n are the Fourier transforms of the temperature signal and the impulse function respectively. While the signal is in the frequency domain, a low-pass, 4th order filter is applied to it. The cut-off is set to 20 kHz, as previous reports have shown that the gages carry little to no signal above this frequency range.[15–17] Comparison of the heat flux calculated using both these methods showed that the spectral deconvolution method resulted in a less noisy signal, in agreement with the results of Sanderson.[15] It should be noted that Sanderson's method of spectral deconvolution is specific to the thermocouples of his design. Thus, The numerical integration method was used with the thin film gages, and spectral deconvolution was used with the thermocouples.

B. Comparison with theoretical prediction

In order to compare both gage types, it was necessary to expose them to a known heat flux while operating in the HET facility. Two model geometries were selected: a sphere and a flat plate. A self-similar solution was derived for heat transfer through a hypersonic boundary layer at the stagnation point of a sphere by Fay and Riddell.[36] A parametric study over a range of altitudes and velocities was carried out and an empirical curve to the data was obtained.[36] Two reduced expressions have been derived to simplify heat flux predictions. The first was derived by Sutton and Graves,[37] and is shown in Equation 6.

$$\dot{q} = K\sqrt{\frac{p_s}{R}}\left(h_{0,e} - h_w\right) \tag{6}$$

where p_s is the stagnation pressure, R is the sphere radius, $h_{0,e}$ is the test gas stagnation enthalpy, h_w is the wall enthalpy, and K is a constant based on the gas composition. Another reduced expression was reported by Filippis,[38] Equation 7.

$$\dot{q} = 90\sqrt{\frac{p_s}{R}}\left(h_{0,e} - h_w\right)^{1.17} \tag{7}$$

The equation derived by Filippis is valid solely for air, while the Sutton and Graves equation can be applied to any gas mixture, as long as the value of K is known. The Filippis equation was derived to extend the predictive range of the theory from a maximum flow enthalpy of 23 MJ/kg to 39 MJ/kg.[38] Though the experiments done here are within the 23 MJ/kg limit, the two equations still yield different results, and thus the experimental measurements were compared against both theoretical predictions.

Theoretical predictions for laminar flat plate heat transfer were calculated with the reference enthalpy method of Simeonides,[39] and predictions of turbulent flat plate heat transfer were made using the Van Driest II method.[40]

III. Error Analysis

In order to make comparative measurements between the two gages it was necessary to evaluate the error bars for each gage type. Davis[16] calculated the sources of uncertainty for the thermocouple gages designed by Sanderson. Two main sources of uncertainty were identified. First, there is error in the voltage-to-temperature conversion due to uncertainty in the NIST temperature conversion tables. Davis reports this to be 1.7% in the temperature change, which corresponds directly to a 1.7% error in the heat flux. Secondly, there is uncertainty in the thermal properties of the thermocouple materials. Davis was able to determine that the uncertainty of the thermal properties (as applied to the calculation of heat flux) was 8%. These values were used directly in this work since both the design and material choice were the same as used by Davis.

For the thin film gages the physical sources of uncertainty are the same as the same equation is solved when deconvolving the heat flux, but the magnitudes of the uncertainty are different. In order to determine the error in the voltage-to-temperature conversion it was necessary to evaluate the goodness of the calibration fit. It was decided to use a full scale error approach in the same way Davis calculated the thermocouple error. Since the calibration was done over a 50 degree range, the full scale was chosen to be 50 degrees. Each thin film gage was calibrated individually. Next, the average difference between the measured calibration point and the calibration curve was used as the error in the temperature measurement. This error was different for each calibrated gage, and was again assumed to carry through directly to the heat flux. The error in the thermal property was taken from Miller.[9] Though his method is different than that used here, Miller cites an unpublished Calspan report which uses the same gage construction method used here, and found an uncertainty of 5% in the thermal properties.

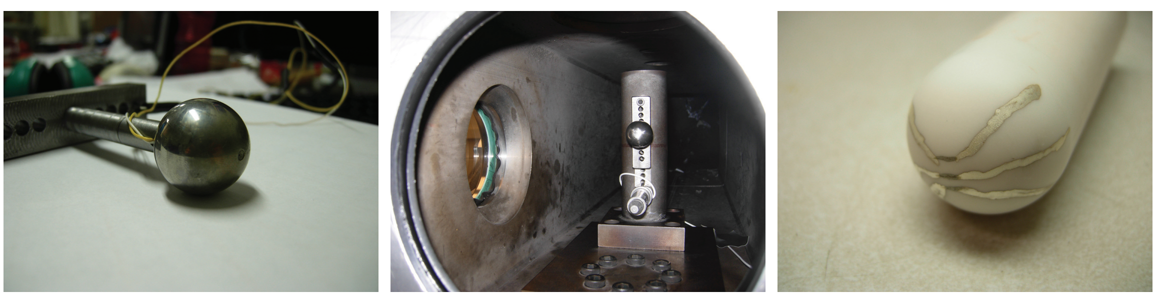
It is important to note that this error analysis takes into account the physical uncertainties associated with the gage alone. There is also shot-to-shot variability in the test conditions. Small variations in initial tube fill pressures can cause fluctuations in the free stream properties,[41] and therefore in the heat transfer. In addition, the free stream conditions have some unsteadiness during the test time. Heat transfer results presented here are averaged over the test time, which was experimentally measured using pitot probes.

IV. Results

A. Stagnation point results

To obtain directly comparable experimental results for both gages, two spherical models were designed. A thermocouple is mounted at the stagnation point of a 25.4 mm diameter stainless steel sphere, Figure 3a; this model can be seen sting-mounted in the test section of the HET in Figure 3b. For the thin film gages, a hemispherical blunt-body model with 25.4 mm nose diameter was created from the gage substrate material (in this case machinable ceramic MACOR®), then sleeve-mounted to the sting. Three gages were painted in the stagnation region, one at the stagnation point and two slightly offset. The MACOR thin film substrate model is shown in Figure 3c.

Thermocouple data were taken at three different test conditions with calculated stagnation enthalpies



(a) Thermocouple mounted at the stagnation region of a 25.4 mm diameter sphere model.

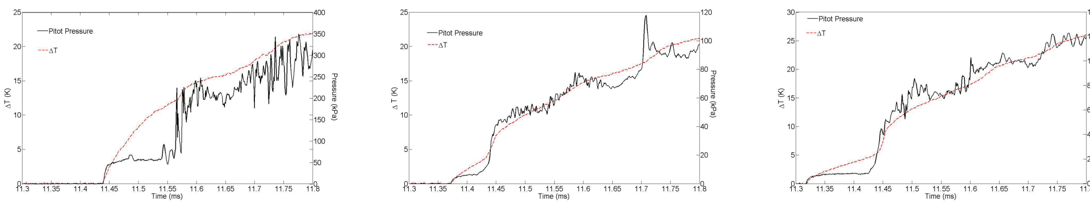
(b) Thermocouple stagnation sphere mounted in HET test section.

(c) Three thin film gages painted on the stagnation region of a 25.4 mm diameter MACOR substrate model.

Figure 3: Thermocouple and thin film heat transfer gages mounted on spherical models.

from 4.09 to 7.52 MJ/kg (listed in Table 1). Figure 4 shows the comparison between the temperature rise and the pitot pressure trace over a time period which encompasses the test gas. In all three plots, the temperature trace shows the arrival of the initial shock, accelerator gas, and contact surface, and the response time compares very well with the pitot pressure histories. The response time of the thermocouple gage was found to be sensitive to the degree of sanding used to create the thin thermocouple junction. The experimentally measured heat fluxes for each condition, and the theoretical predictions are listed in Table 2.

It is evident that in every case the heat transfer is under-predicted by theory. This is consistent with the results obtained by Marineau and Hornung while calibrating a new conical nozzle in the T5 facility.[42] The equation developed by Filippis provides the best prediction of the heat flux, with a 23% deviation in Air-4, a 26% deviation in Air-5, and a 35% deviation in Air-6.



(a) Air-4 Temperature Rise vs. Pitot Pressure.

(b) Air-5 Temperature Rise vs. Pitot Pressure.

(c) Air-6 Temperature Rise vs. Pitot Pressure.

Figure 4: Comparisons of temperature traces with pitot pressure data.

Table 2: Comparison of experimental heat transfer with theoretical predictions.

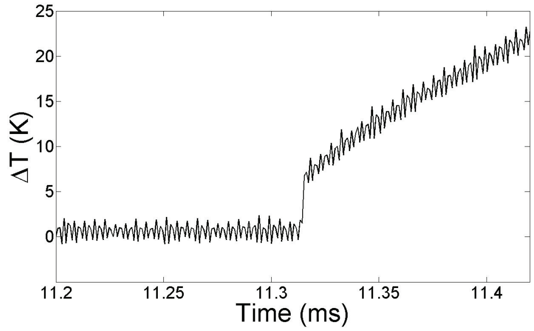
	Experimental Heat Flux	Sutton and Graves	Filippis
Air-4	7.845 MW/m^2	6.29 MW/m^2	6.397 MW/m^2
Air-5	7.743 MW/m^2	5.407 MW/m^2	6.146 MW/m^2
Air-6	8.498 MW/m^2	5.657 MW/m^2	6.284 MW/m^2

For the thin film gages, initial data was taken with the HET operating as a shock tube. The stagnation region gage was able to capture the initial shock and subsequent temperature rise very well. The temperature trace and calculated heat transfer data from this shot are shown in Figure 5. Shock arrival can be seen at 11.31 ms, referenced from the primary diaphragm rupture. The temperature history is presented unfiltered. Low-pass filtered data was used for the subsequent heat transfer calculation. The average heat flux over the steady state temperature rise is 2.95 MJ/m^2.

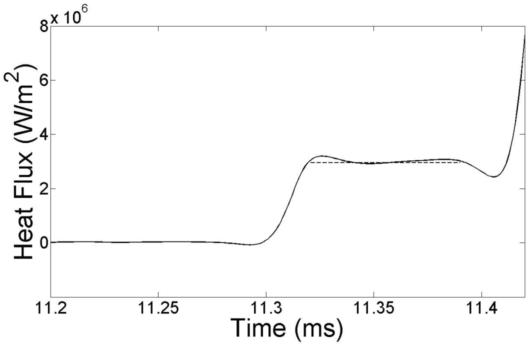
Thin film gage survival at the stagnation point was zero under expansion tube conditions. When measured between successive shots, changes in resistance were typically on the order of 500%. This is most likely due to gage damage from the high temperatures, shear forces, and debris that the model is exposed to during an experiment. This large resistance change calls into question the accuracy of any calibration curve for the gage. Since it is not known at what point in the experiment the gage was damaged, it is impossible to say if the calibration curve was still accurate during the test time. A second problem arose due to the exposed connection between the silver leads and the wire connection. Since this connection was exposed to the flow it had significant effects on the signal-to-noise ratio, decreasing confidence in the measurements. Two flat plate models were next instrumented with thin film and thermocouple gages.

B. Flat plate results

A flat plate was chosen as the second model geometry due to both its simplicity and the existence of theoretical predictions of heat flux. Also, the flat plate solved both issues discussed in Section A that were experienced with the stagnation point thin film gage. With the flat plate design the connection between the silver leads and the feedthrough wire were shielded from the flow, and the parallel mounting direction of the gages decreased the chances of damage from high temperatures and particulates in the flow. Figure 6 shows both the thermocouple and thin film flat plate models. These models were designed such that the same leading edge could be utilized for both the thin film and the thermocouple gages. Figures 7, and 8 show the comparison of the thin film data to the thermocouple data for the three run conditions. All three conditions show good agreement between gages near the leading edge, and measurements are in good agreement with theoretical predictions. It should be noted that both the thermocouples and thin film gages show an increase over the theory with increasing x-location on the plate. This may be due to the beginnings of transition on



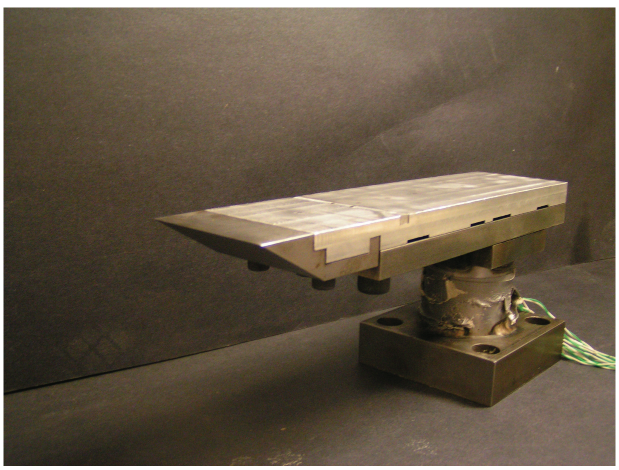
(a) Raw temperature history.



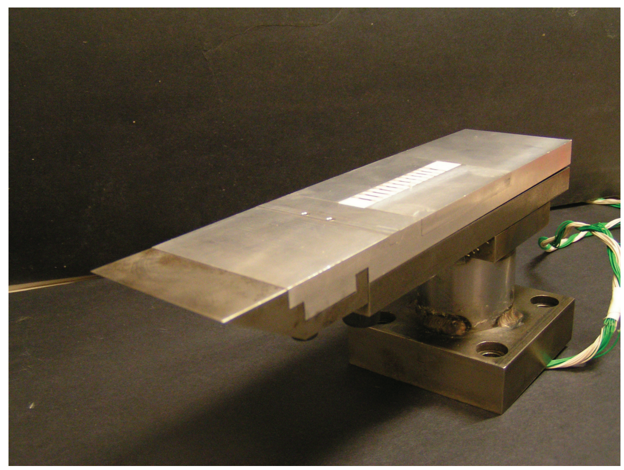
(b) Surface heat transfer.

Figure 5: Initial thin film data obtained in the HET after shock wave passage.

the plate. Transition was not anticipated at the lower Reynolds numbers of Air 5 and Air 6, and further experiments are required to address this issue.



(a) Thermocouple flat plate model.



(b) Thin film flat plate model.

Figure 6: Flat plate models.

V. Conclusions

Thermocouples and thin film gages are used extensively for surface heat transfer measurements in hypersonic impulse facilities. Coaxial thermocouples are robust, can survive challenging experimental conditions, and are typically used in higher enthalpy flows. Thin film resistance gages provide improved signal levels, but have to be individually calibrated and are less robust, and are typically used in lower enthalpy flows. The goal of this work is to make directly comparative measurements in flow fields accessible to both gage types with stagnation enthalpies between 4.09 and 7.52 MJ/kg.

We report on the design and construction of both coaxial thermocouples and thin film resistance thermometers. Gages are mounted on equivalent spherical and flat plate models. Thermocouple gages are internally mounted, while thin film gages are directly painted and fired onto a MACOR model which acts as the gage substrate, and calibrated in situ.

Both gages have been successfully used in the HET. Tests demonstrate that thermocouple gages are preferable for use in stagnation regions due to the extremely poor survivability of thin film gages. Both gages show good agreement in the flat plate case, though thin film gages have less noise, a higher signal level, and more consistent response time. Thus, in mounting locations where survivability is not an issue,

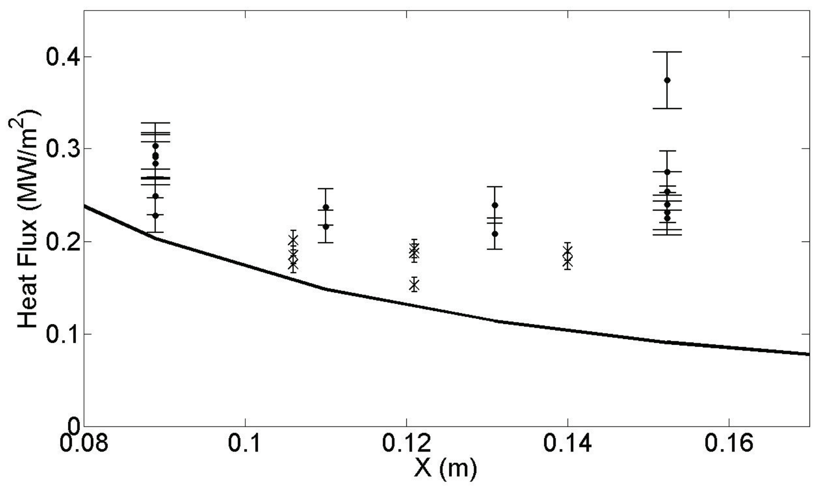


Figure 7: Comparison of thin film (×) and thermocouple (•) heat flux data in Air-4 (leading edge at x=0).

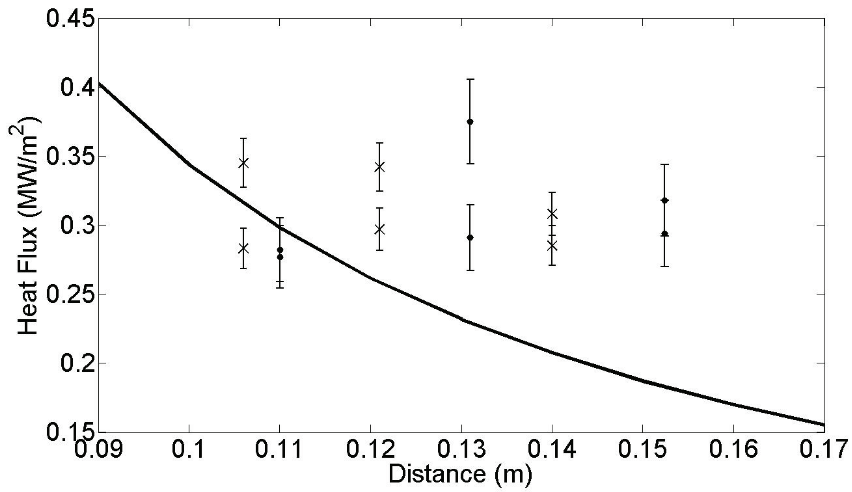


Figure 8: Comparison of thin film (×) and thermocouple (•) heat flux data in Air-6 (leading edge at x=0).

thin film gages are the preferred gage type.

Acknowledgments

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References

[1] Holden, M. S., Wadhams, T. P., Smolinski, G. J., Maclean, M. G., Harvey, J., and Walker, B. J., "Experimental and Numerical Studies on Hypersonic Vehicle Performance in the LENS Shock and Expansion Tunnels," *44th AIAA Aerospace Science Meeting and Exhibit*, January 2006.

[2]Holden, M. S., Wadhams, T. P., Maclean, M. G., Mundy, E., and Parker, R. A., "Experimental Studies in LENS I and X to Evaluate Real Gas Effects on Hypervelocity Vehicle Performace," *45th AIAA Aerospace Science Meeting and Exhibit*, January 2007.

[3]Holden, M. S., Wadhams, T. P., Maclean, M., Mundy, E., and Parker, R. A., "Experimental Studies in LENS I and X to Evaluate Real Gas Effects on Hypervelocity Vehicle Performance," *45th AIAA Aerospace Sciences Meeting and Exhibit*, January 2007.

[4]Maclean, M. and Holden, M. S., "Catalytic Effects on Heat Transfer Measurements for Aerothermal Studies with CO2," *44th AIAA Aerospace Sciences Meeting and Exhibit*, January 2006.

[5]Wadhams, T., Mundy, E., Maclean, M., and Holden, M., "Experimental and Analytical Study of Transition in High Speed Flows at CUBRC," *38th Fluid Dynamics Conference and Exhibit*, June 2008.

[6]MacLean, M., Holden, M., and Hollis, B., "Investigation of Blunt Bodies with CO2 Test Gas Including Catalytic Effects," *38th AIAA Thermophysics Conference*, June 2005.

[7]Chadwick, K. M., "Stagnation heat transfer measurement techniques in hypersonic shock tunnel flows over spherical segments," *32nd AIAA Thermophysics Conference*, June 1997.

[8]Wadhams, T. P., Maclean, M., Holden, M. S., and Smolinski, G. J., "Return to Flight Testing of a 3.5Model at Mach Numbers of 3.5 and 4.0," *44th AIAA Aerospace Sciences Meeting and Exhibit*, January 2006.

[9]Miller, C. G., "Comparison of Thin-Film Resistance Heat -Transfer Gages With Thin-Skin Transient Calorimeter Gages in Conventional Hypersonic Wind Tunnels," NASA Technical Memorandum 83197, NASA, 1981.

[10]Kidd, C. T., "Coaxial Surface Thermocouples: Analytical and Experimental Considerations for Aerothermal Heat-Flux Measurement Applications," *Proceedings of the ISA Aerospace Instrumentation Symposium*, 1990.

[11]Kidd, C. T., Nelson, C. G., and Scott, W. T., "Extreaneous Thermoelectrioc EMF Effects Resulting from Press-Fit Installation of Coaxial Thermocouples in Metal Models," *Proceedings of the ISA Aerospace Instrumentation Symposium*, 1994.

[12]Hollis, B. R., Berger, K. T., Horvath, T. J., Coblish, J. J., and Norris, J. D., "Aeroheating Testing and Predictions for Project Orion CEV at Turbulent Conditions," *46th AIAA Aerospace Sciences Meeting and Exhibit*, January 2008.

[13]Reddy, N. M., "Heat-Rate Measurements Over 30 and 40 (Half-Angle) Blunt Cones in Air and Helium in the Langley Expansion Tube Facility," NASA Technical Memorandum 80207, NASA, 1980.

[14]Hollis, B. R., Liechty, D. S., Wright, M. J., Holden, M. S., Wadhams, T. P., Maclean, M., and Dyakonov, A., "Transition Onset and Turbulent Heating Measurements for the Mars Science Laboratory Entry Vehicle," *43th AIAA Aerospace Sciences Meeting and Exhibit*, January 2005.

[15]Sanderson, S. R., *Shock wave interaction in hypervelocity flow*, Ph.D. thesis, California Institute of Technology, Pasadena, California, 1995.

[16]Davis, J.-P., *High-Enthalpy Shock/Boundary-Layer Interaction on a Double Wedge*, Ph.D. thesis, California Institute of Technology, Pasadena, California, 1999.

[17]Rasheed, A., *Passive Hypervelocity Boundary Layer Control Using an Ultrasonically Absorptive Surface*, Ph.D. thesis, California Institute of Technology, Pasadena, California, 2001.

[18]Leyva, I. A., *Shock detachment process on cones in hypervelocity flows.*, Ph.D. thesis, California Institute of Technology, Pasadena, California, 1999.

[19]Mee, D. J., "Boundary-Layer Transition Measurements in Hypervelocity Flows in a Shock Tunnel," *AIAA Journal*, Vol. 40, No. 8, Aug 2002, pp. 1542–1548.

[20]Capra, B. R., Levland, P., and Morgan, R. G., "Subscale Testing of the Fire II Vehicle in a Superorbital Expansion Tube," *42th AIAA Aerospace Science Meeting and Exhibit*, January 2004.

[21]Wright, M. J., Olejniczak, J., Brown, J. L., Hornung, H. G., and Edquist, K. T., "Modeling of Shock Tunnel Aeroheating Data on the Mars Science Laboratory Aeroshell," *Journal of Thermophysics and Heat Transfer*, Vol. 20, No. 4, 2006, pp. 641–651.

[22]Marineau, E. and Hornung, H., "Modeling and Calibration of Fast-Response Coaxial Heat Flux Gages," *47th AIAA Aerospace Sciences Meeting*, Jan 2009.

[23]Salvadaor, I. I., Minucci, M. A. S., Toro, P. G. P., Oliveira, A. C., and Jr, J. B. C., "Development of Surface Junction Thermocouples for High Enthalpy Measurements," *American Institute of Physics Beamed Energy Propulsion: Fourth International Symposium*, 2006.

[24]Kuchi-ishi, S., Watanabe, S., Nakakita, K., Koyama, T., Ueda, S., and Katsuhiro, "Comparative Heat Flux Measurments Between Three Hypersonic Test Facilities at NAL," *33rd AIAA Fluid Dynamics Conference and Exhibit*, June 2003.

[25]Hornung, H. G., "Performance data of the new free-piston shock tunnel at GALCIT," *17th AIAA Aerospace Ground Testing Conference*, July 1992.

[26]Hannemann, K. and Beck, W. H., *Advanced Hypersonic Test Facilities*, chap. Aerothermodynamics Research in the DLR High Enthalpy Shock Tunnel HEG, AIAA, Reston, VA, 2002, pp. 205–238.

[27]Holden, M. S. and Parker, R. A., *Advanced Hypersonic Test Facilities*, chap. LENS Hypervelocity Tunnels and Application to Vehicle Testing at Duplicated Flight Conditions, AIAA, Reston, VA, 2002, pp. 73–110.

[28]Micol, J. R., "Langley Aerothermodynamic Facilities Complex: Enhancements and Testing Capabilities," *AIAA Paper*, 1997.

[29]Morgan, R. G., "Development of X3, a superorbital expansion tube," *38th AIAA Aerospace Sciences Meeting and Exhibit*, January 2000.

[30]Sasoh, A., Ohnishi, Y., Koremoto, K., and Takayama, K., "Operation Design and Performance of a Free-Piston-Driven Expansion Tube," *37th AIAA Aerospace Sciences Meeting and Exhibit*, January 1999.

[31]Dufrene, A., Sharma, M., and Austin, J. M., "Design and Charachterization of a Hypervelocity Expansion Tube Facility," *Journal of Propulsion and Power*, Vol. 23, No. 6, Nov 2007, pp. 1185–1193.

[32]Croarkin, M. C., Guthrie, W. F., Burns, G. E., Kaeser, M., and Strouse, G. F., "Temperature-Electromotive Force Referance Function and Tables for the Letter-Designated Thermocouple Types Based on the ITS-90." Monograph 175, National Institute of Standard Technologies, 1993.

[33]Adelgren, R. G., *Localized Flow Control with Energy Deposition*, Ph.D. thesis, Rutgers University, New Brunswick, NJ, 2002.

[34]Kinnear, K. M. and Lu, F. K., "Design, Calibration and Testing and Transient Thin Film Heat Transfer Gauges," *AIAA Paper*, 1998.

[35]Schultz, D. L. and Jones, T. V., "Heat-transfer Measurements in Short-duration Hypersonic Facilities," Agardograph 165, AGARD, 1973.

[36]Fay, J. A. and Riddell, F. R., "Theory of Stagnation Point Heat Transfer in Dissociated Air," *Journal of the Aeronautical Sciences*, Vol. 25, No. 2, 1958, pp. 73–85.

[37]Sutton, K. and Graves, A. R., "A general stagnation-point convective-heating equation for arbitary gas mixtures," Tech. rep., NASA, 1971.

[38]Filippis, F. D. and Serpico, M., "Air High-Enthalpy Stagnation Point Heat Flux Calculation," *Journal of Thermophysics*, Vol. 12, No. 4, 1998, pp. 608–610.

[39]Simeonides, G., "Gerneralized reference enthalpy formulations and simulation of viscous effects in hypersonic flows," *Shock Waves*, Vol. 8, 1998, pp. 161–172.

[40]Driest, E. V., "Turbulent Boundary Layers in Compressible Fluids," *Journal of the Aeronautical Sciences*, Vol. 18, 1951, pp. 145–160.

[41]McGilvray, M., Austin, J., Sharma, M., Jacobs, P., and Morgan, R., "Diagnostic Modelling of an Expansion Tube Operating Condition," *Shock Waves*, Vol. 19, No. 1, 2009, pp. 59–66.

[42]Marineau, E. and Hornung, H., "Heat Flux Calibration of T5 Hypervelocity Shock Tunnel Conical Nozzle in Air," *47th AIAA Aerospace Sciences Meeting*, Jan 2009.