ASE 162M
Fall 2024

Laboratory 4
Application of Temperature-Sensitive Paint to a Space Shuttle Geometry
(Nov. 11)

Instructions

Before You Start:
You will use the images acquired in this laboratory to complete the associated homework assignment. Create a folder with your lab name in the lab computer and store all your images. Please make sure that at least one member of your lab group brings a flash drive or other suitable media to the lab for storing the images.

Objective:
This lab will serve as an introduction to our temperature-sensitive paint (TSP) measurement system. We will be using TSP to measure the temperature on the bottom of a space shuttle model. The shuttle model is made of cast aluminum (A384, k = 96.2 W/m-K) and mounted at a 15° angle of attack. The model has a length of 68 mm and a 47 mm wingspan.

Procedure: Some of the procedures might change due to the new set-up.
1. Discuss the provided Schlieren image of the space shuttle flow field with your TA.

2. The shuttle should be installed in the sidewall plug of the wind tunnel. Check the TSP coating for chips and cracks.

3. Make sure the type-J thermocouple is connected to AI-1 on the LabVIEW DAQ board and the switch on the board is set to “Thermocouple”. Additionally, make sure that the switch on AI-0 is set to “Temp Ref”. Make sure that the static pressure port on the sidewall plug is properly connected to the DAQ. Check that the pressure tap in the stagnation chamber is properly connected as well. (Ports AI-3 and AI-2, respectively)

4. Check that the photodiode next to the camera (and shielded with duct tape) is connected to the DAQ through port AI-4 and that the switch on the photodiode is set to “ON”.

5. Start LabVIEW and open the data acquisition VI. Note that the data collected is slightly different than in the previous two labs. We will be using pressure transducers to record the stagnation chamber pressure and test section static pressure and a thermocouple to record the surface temperature on the shuttle model. Additionally, we will use a photodiode to monitor the camera status LEDs to determine when the camera is acquiring.

6. Check to make sure that the Schott OG 570 colored glass filter is installed in front of the camera. Turn on the Apogee CCD camera. Wait 15 seconds and open the OMS Acquire software. Both fans should be running. Check that the camera is focused on the surface of the shuttle model.

7. Turn off the room lights and acquire a background image using the OMS Acquire software. The exposure duration should be approximately 750 ms.

8. With the room lights still off, turn on the UV LED. Acquire a "wind-off" reference image using the OMS Acquire software.

9. Conduct runs at M = 2, 2.5, and 3. It will be necessary to repeat steps 7 and 8 before each run. During each run, you will acquire pressure data, temperature data, and the photodiode signal using the LabVIEW VI. Additionally, you will record four "wind-on" images using the OMS Acquire software. For each image, the software will save each CCD color channel as a separate image file (Ch 0 = G, Ch 1 = R, Ch 2 = G, Ch 3 = B), resulting in a total of 16 images per wind tunnel run.

10. Open the OMS Lite software. Load wind-on and wind-off images from channel 1, which corresponds to the red CCD channel. Using the software, save the I_0/I images as Tecplot .dat data files.

11. After completing the lab, be sure to reinstall the blackout cover over the tunnel test section in order to prevent photodegradation of the TSP coating.

DATA gives $\frac{I_{ref}}{I} \Rightarrow$ invert $\Rightarrow \frac{I}{I_{ref}}$

Apparatus:

Aerolab Variable Mach Number Wind Tunnel: The test section is nominally 3”×3”. The Mach number is varied by sliding the lower block of the nozzle with a hand crank according to the calibration table provided by the manufacturer. The nominal operating range is $1.4 \leq M \leq 3.5$. The wind tunnel is equipped with stagnation and test section pressure gages.

TSP System: Two layers of paint are applied to the model surface. The first coat is a matte black paint that serves as an insulating layer and primer. The second coat is the UNICOAT TSP. The TSP is excited using a high-powered UV LED. The resultant fluorescence is captured with a low-noise, cooled, interline transfer, four-color-channel CCD camera (Apogee Alta F2000C).

Data Acquisition System: The pressure measurements are made using a series of pressure transducers. A pressure transducer is directly mounted on the tunnel to measure the stagnation pressure, while the others are placed in the pressure transducer and data acquisition box (it should be underneath the front optical table). The signals from the pressure transducers are recorded using an NI data acquisition card interfaced with the pressure transducers through a BNC NI adapter. The temperature at a point on the shuttle surface is measured using a type-J thermocouple mounted flush to the surface. The NI data acquisition card is mounted in the laboratory computer. Finally, the voltage outputs from the pressure transducers, thermocouple, and photodiode are acquired using a LabVIEW VI and are then saved in a data file. Note that the outputs are in Volts, so you need to convert them to their respective units using the proper calibration equations. The following calibration constants can be used for the pressure measurements (note that the readings are gage pressures):

1. Stagnation pressure: 4137 kPa/V
2. Surface/Static pressure: 1034 kPa/V

ASE 162M
Fall 2024

Laboratory 4
Application of Temperature-Sensitive Paint to a Space Shuttle Geometry

Assignment (90 pts)

Due three weeks after the day of your scheduled lab. A PDF uploaded to Canvas is due by 5PM on your scheduled lab day.

The assignment should be typed and no hand-written work will be accepted (including equations). A quantification of uncertainty should be performed, with uncertainties included in quoted measurements, but equations used for calculating uncertainty do not need to be included in the assignment. Points will be deducted for exceptionally sloppy or poorly-written assignments. Additionally, all images should portray the flow moving from left to right (standard convention).

1) Present the Schlieren image of the shuttle geometry in a supersonic flow and label and discuss the main flow features. (8 pts)

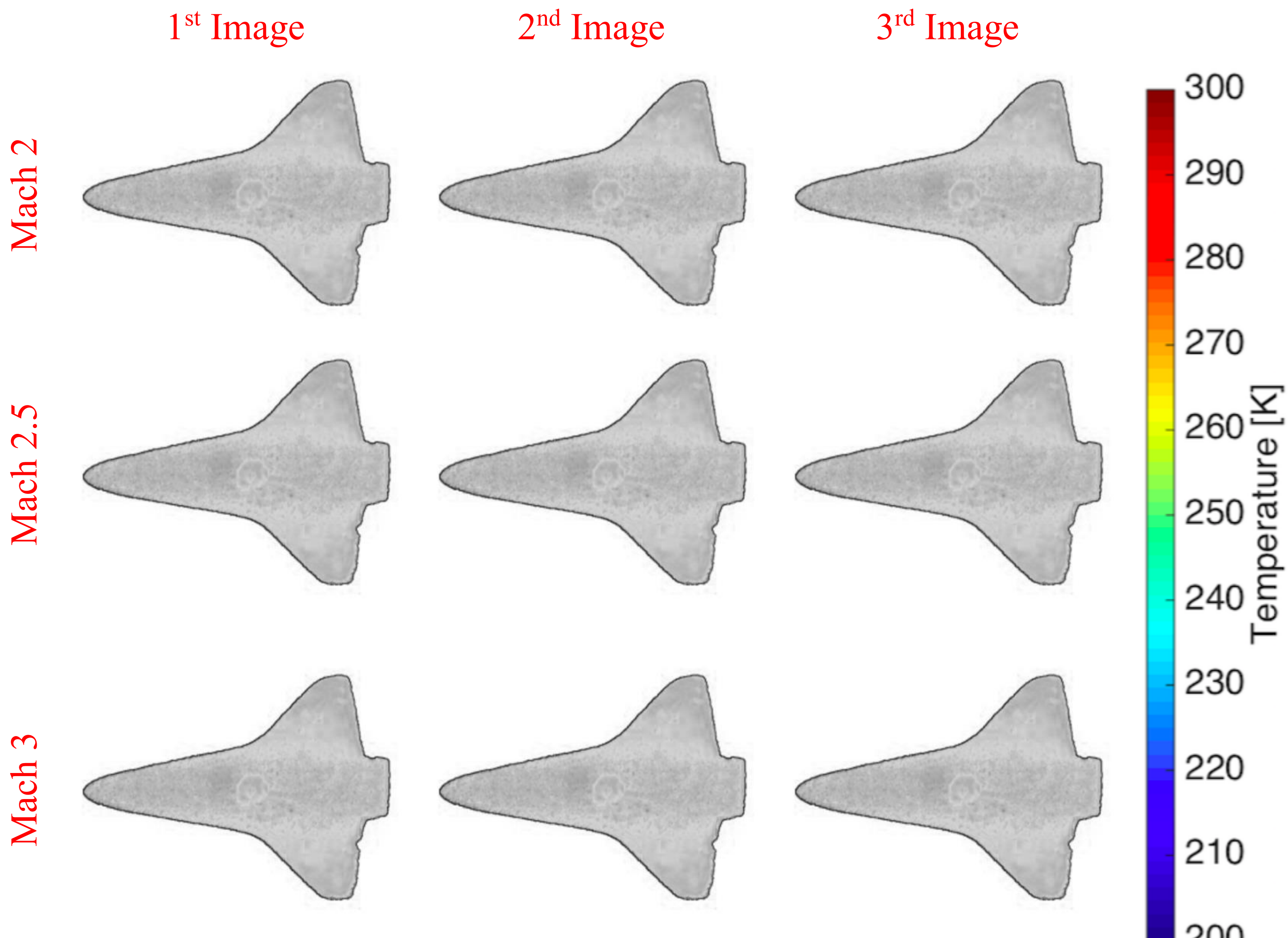
2) Make a detailed schematic of the TSP system used in this experiment. Describe the function of each part. (12 pts) Reminder: Show flow direction.

3) Convert the recorded pressure values to absolute pressure in kPa. On one plot with dual y-axes, present the recorded pressures and shuttle surface temperature for one of the three wind tunnel runs. (5 pts) Reminder: Calculate mach number using your instantaneous Pstagnation and Pstatic pressures and plot the Mach number curve on the top of pressure curves dual y axis.

4) Using the known temperature recorded by the thermocouple before and during each run as well as the known TSP intensity ratio near the thermocouple before (can assume to be 1) and during each run, make one plot of I/I_{ref} vs. T/T_{ref} containing data points from all three runs (nine data points in total). On top of this plot, plot a linear curve fit of the data and include the equation for the curve fit on the figure. (10 pts)

5) Use the calibration curve generated in question 4 to present the recorded TSP images of intensity ratio as 2D temperature maps (in Kelvin). Make sure you include a labeled color bar and that your color scale is set such that you can actually see variation in the temperature map. Present all three images from all runs. Feel free to filter the images to reduce random noise. (10 pts) (Reminder: For your image representation: 1. Do not compress or stretch your images. 2. Use same color scale in your all images. 3. The nose of the shuttle should point to the left. For your image representation you can refer to the following scheme. Note that the limits of the colorbar should be adjusted according to the global maximum and global minimum of all nine images where the region of interest is shown in gray.)

SAMPLE IMAGE FORMAT



6) Discuss the images presented in question 5. Is the model heating up or cooling down? Why? Does this make physical sense? Does it match what your thermocouple data is showing you in question 2? (5 pts)

7) Using oblique shock theory and assuming the shuttle is a 15° wedge, calculate the following values for each Mach number and present them in a table. Be sure to use your measured static and stagnation pressures and the calculated true Mach number for all of your calculations. Include uncertainty in your calculations (you may use sequential perturbation or root sum square of partials to propagate uncertainty, at your preference). To get full credit your calculation steps and equations used should be clearly shown on. (10 pts)

   a. Stagnation and static pressure behind the shock
   b. Stagnation and static temperature behind the shock
   c. Velocity behind the shock
   d. Density behind the shock (hint: ideal gas)
   e. Viscosity of the air behind the shock (use Sutherland's Law: http://www.cfd-online.com/Wiki/Sutherland's_law)
   f. For the model surface, assume a constant Reynolds number based on the half-length of the model. **Check your Re whether the flow is turbulent of laminar.** Calculate recovery temperature at the surface of the model and write the equation you used (Prandtl number which can be assumed to be 0.7 for air at standard conditions).

8) Use the Reynolds number found in question 7 to compute a Nusselt number to be applied to the entire model surface using the following empirical correlation for turbulent flow on a flat plate:

$$Nu_L = 0.0296 * Re_L^{4/5} * Pr^{1/3}$$

where *Pr* is the Prandtl number which can be assumed to be 0.7 for air at standard conditions.

With the value for Nusselt number calculated in the equation above, use the definition of the Nusselt number to determine the convective heat transfer coefficient, *h*, for this flow. Assume a thermal conductivity of $0.02\ [W/mK]$ for air. After determining *h*, calculate the convective heat flux [W/m^2] on the shuttle surface using

$$q = h * (T_r - T_s)$$

where T_r is the recovery temperature of the air at the surface of the model and T_s is the surface temperature of the model at the time the calculation is being made.

Present plots of convective heat flux on the model surface for the first image collected during each run. (12 pts)

9) For each wind tunnel run, calculate the heat transfer rate as a function of time using the thermocouple measurement, where

$$q(t) = h * \left(T_r - T_{tc}(t)\right)$$

where $T_{tc}(t)$ is the thermocouple measurement as a function of time, h is the convective heat flux coefficient you calculated in Question 8, and T_r is the recovery temperature that you calculated in question 7.

Present the results for each of the three Mach numbers tested on a single plot of q vs. time while the wind tunnel was running at the desired Mach number. What do we learn from the plot? (8 pts)

10) What do the results from questions 8 and 9 tell us about the heat transfer on the model surface? Is the heat transfer to or away from the model surface? When is the magnitude of the heat flux the largest for Mach 3? Why? Do certain parts of the shuttle surface experience higher heat transfer rates than others? Why or why not? (5 pts)

11) Considering the results you have presented in the previous questions, how is this situation similar (or different) to the heating experienced by an actual space shuttle during atmospheric reentry? Why? Is there a way we could make this a more realistic ground test? (5 pts)

Bonus

Revisit question 8 but instead of assuming a constant Reynolds and Nusselt number for the entire surface, calculate Re_x and Nu_x, where x is the streamwise coordinate and x equals zero at the leading edge of the shuttle surface. This should result in a 2D map of Nusselt number for the shuttle. Discuss the method you used for computing the new Nusselt number and present this 2D map as a figure. Next, use the values of Nusselt number to recompute the heat transfer coefficient (should now be dependent on x and y) and convective surface heat flux the same way as in question 8. Present new plots of convective heat flux for the first image collected during each wind tunnel run.

Compare these images to the ones presented for question 8. Do the images look different? Is any new information brought to light? Was it a good approximation to assume a constant value of Nusselt number for the entire surface? (15 pts)