An Overview of the Patch Integral Method (PIM), a New Heat Transfer Analysis Tool for Hypersonic Wind Tunnel Facilities at NASA Langley

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Introduction and Background

- The NASA Langley Research Center hypersonic wind tunnels are heavily leveraged for planetary missions. The data collection method in these tunnels is thermography, whereby surface temperature measurements of the model surface are collected and reduced to produce surface heating data, as seen in Fig 1. However, during model injection, no temperature data are collected, and thus conventional, integral heat transfer methods cannot be used to solve for surface heating.
- A method was developed in the 1990s to reduce this data despite the data gap, known as the step approximation method. The method assumes that the film coefficient behaves as a step function, the model is semi-infinite, and thermal properties are constant. With these simplifying assumptions, a Laplace transform can be performed to result in an equation that takes the initial temperature of the model and a temperature at some point in time to back out the film coefficient at that time. This is the method that is used in the current thermographic data reduction software, IHEAT.
- While computationally light-weight, the step approximation has several issues associated with it. The time-history of temperature is not accounted for, which is vital as heat transfer is an integral process. Additionally, the required semi-infinite assumption is unnecessary and might be violated during runtime. Thermal variation of material properties can have a sizeable impact on heating results and are not modeled by the method. This method also takes multiple seconds to “collapse” to a steady state, which is undesirable from both a facility and data reduction standpoint. The method is also very sensitive to the “effective time” approximation, an approximation of when heating instantaneously starts (which is a nonphysical simplification), and a small variation in this value can result in an error in heating results.

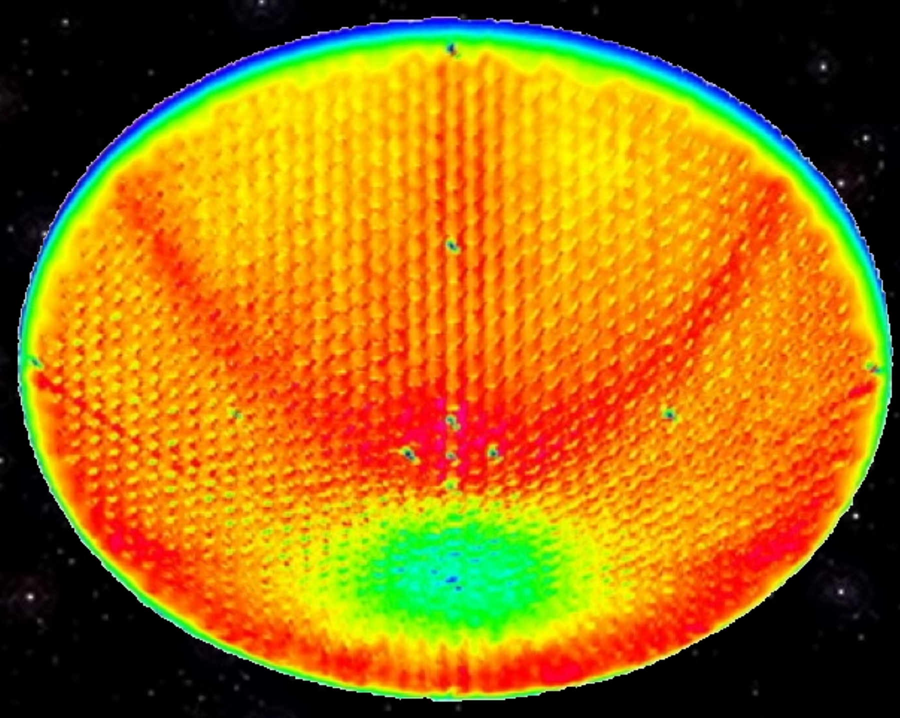

Figure 1: Heating Results for an Ablated Hex-comb TPS

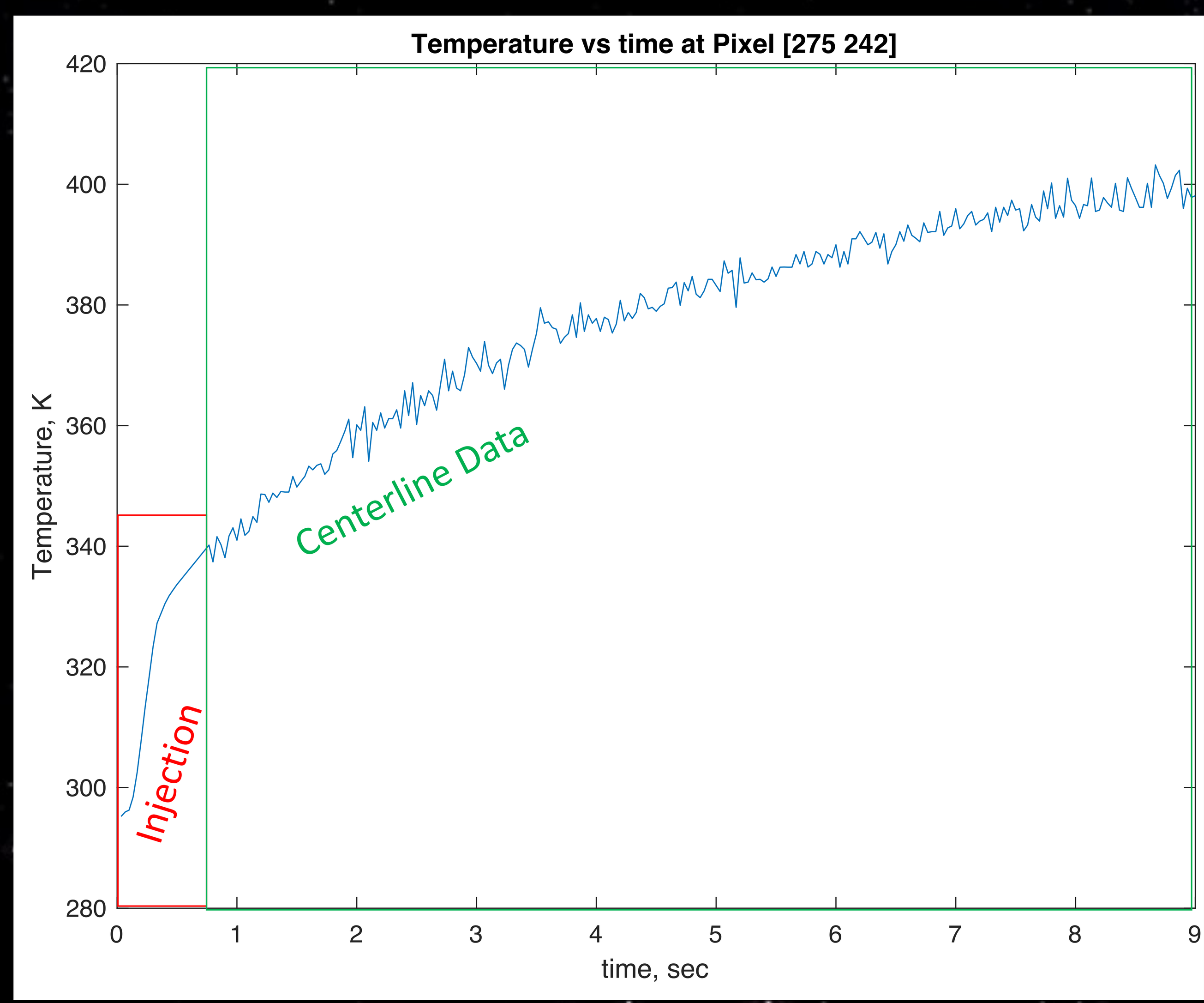

Figure 2: Illustration of PIM’s data patch. The patch is in the red box, while the centerline temperature data are in the green box.

Patch Integral Method (PIM) Overview

- These shortcomings led to a multiyear development of a new, improved method, known as the Patch Integral Method (PIM). PIM is a novel approach to the data gap problem and is composed of two main parts. First, the data gap is patched, which results in continuous temperature data, as seen in Fig 2. The construction of the patch is based on empirical, thin-film measurements and is based on prerun and centerline temperature measurements. Second, a conventional heat transfer analysis method is used to solve the heat equation directly, which accounts for the time-history of temperature as well as thermal variation in material properties, and the film coefficient is then solved for.
- After the data are patched, a 1-Dimensional, finite-difference Crank-Nicolson method is used to calculate surface heating. This method does not require any simplifying assumptions about the film coefficient, as the physics are modeled much more accurately, no “effective time” needs to be approximated as injection is directly modeled, heating is directly solved for entirely across both the spatial and temporal domain, and thermal property variations are accounted for and directly modeled.
- PIM is a much more resilient, improved method, which much more accurately and directly models the physics. Additionally, PIM “collapses” to a film coefficient value much more quickly than the step approximation method, as seen in Fig 3, and it offers a significant improvement over the currently used heat transfer analysis method, which is denoted as IHEAT in comparison plots.

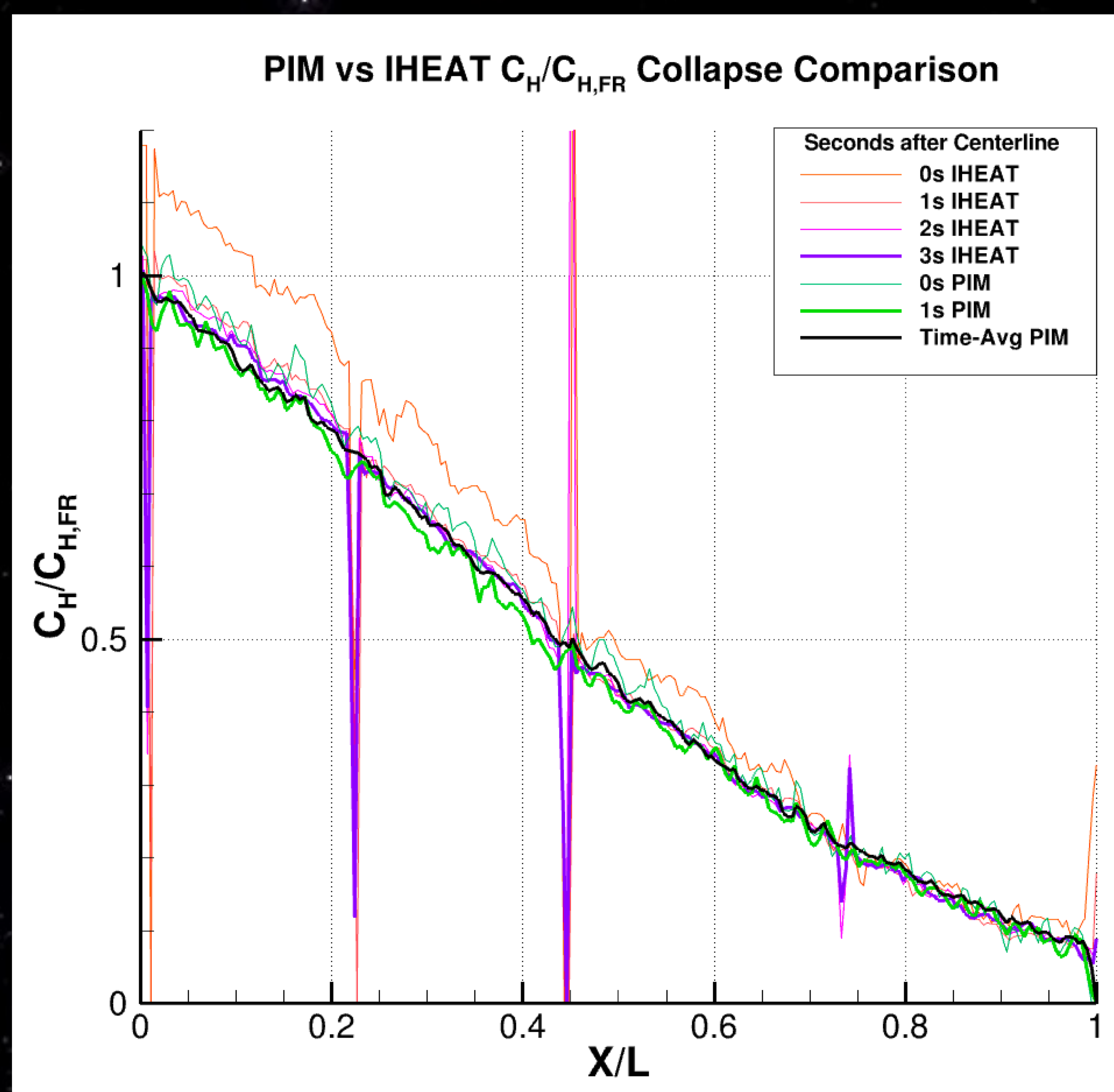

Figure 3: Comparison of C_H collapse between IHEAT and PIM for a smooth hemisphere. Each curve represents a line cut taken at different times after the model reaches centerline.

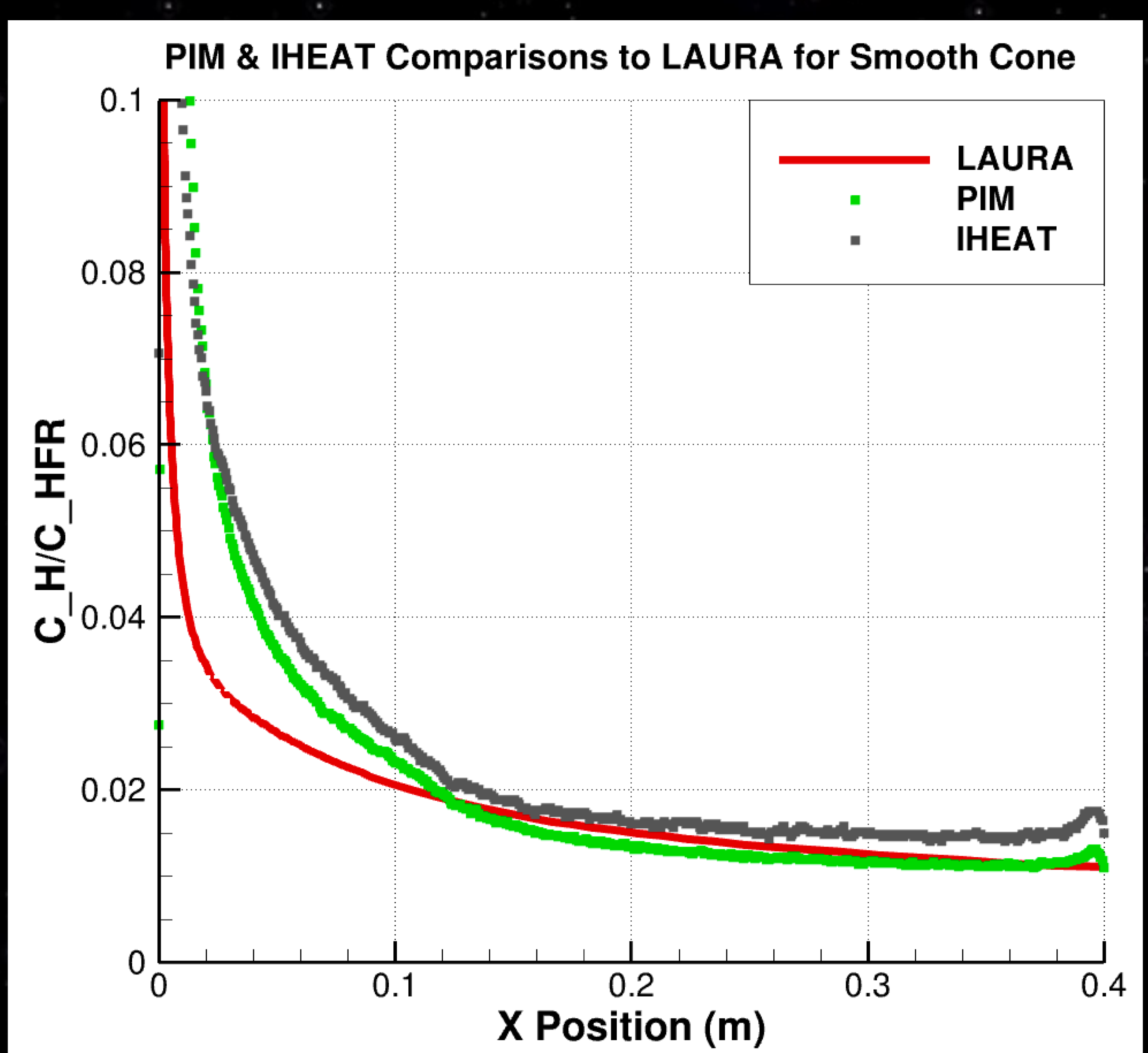

Figure 4: Comparison of PIM and IHEAT solutions to LAURA CFD solutions for a simple, smooth cone run. Disparities near the tip of the cone are due to multidimensional internal heating effects.

Results and Future Work

- A comparison of method collapse for a smooth hemisphere can be seen in Fig 3. PIM collapses much more quickly than IHEAT, as it takes within a second after centerline to collapse while the step approximation method takes multiple seconds seconds to fully collapse.
- PIM’s centerline heating line cut is conventionally presented as a time-averaged curve in order to eliminate nonphysical, temporal noise from the phosphor thermography system, and thus more accurately represent the steady-state solution.
- In Fig 4, a comparison of the two methods to the Langley Aerothermodynamic Upwind Relaxation Algorithm (LAURA) CFD code can be seen. For a smooth cone run, PIM agrees more with CFD prediction than IHEAT, showing an improvement in modeling the physics.
- 1-Dimensional finite-difference is sufficient for most planetary applications; however, for high-gradient regions of heating, multidimensional internal heating effects need to be accounted for. Future work will add multidimensional capabilities to PIM, such as the alternating direction implicit method (ADI).
- Overall, PIM offers a more robust and more accurate heat transfer analysis method for data reduction of tests in the Mach 6 and Mach 10 wind tunnels at NASA Langley and will be incorporated into the current data reduction code, IHEAT