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Atmospheric Entry Heat Flux Sensor Calibration and Flight Data Analysis

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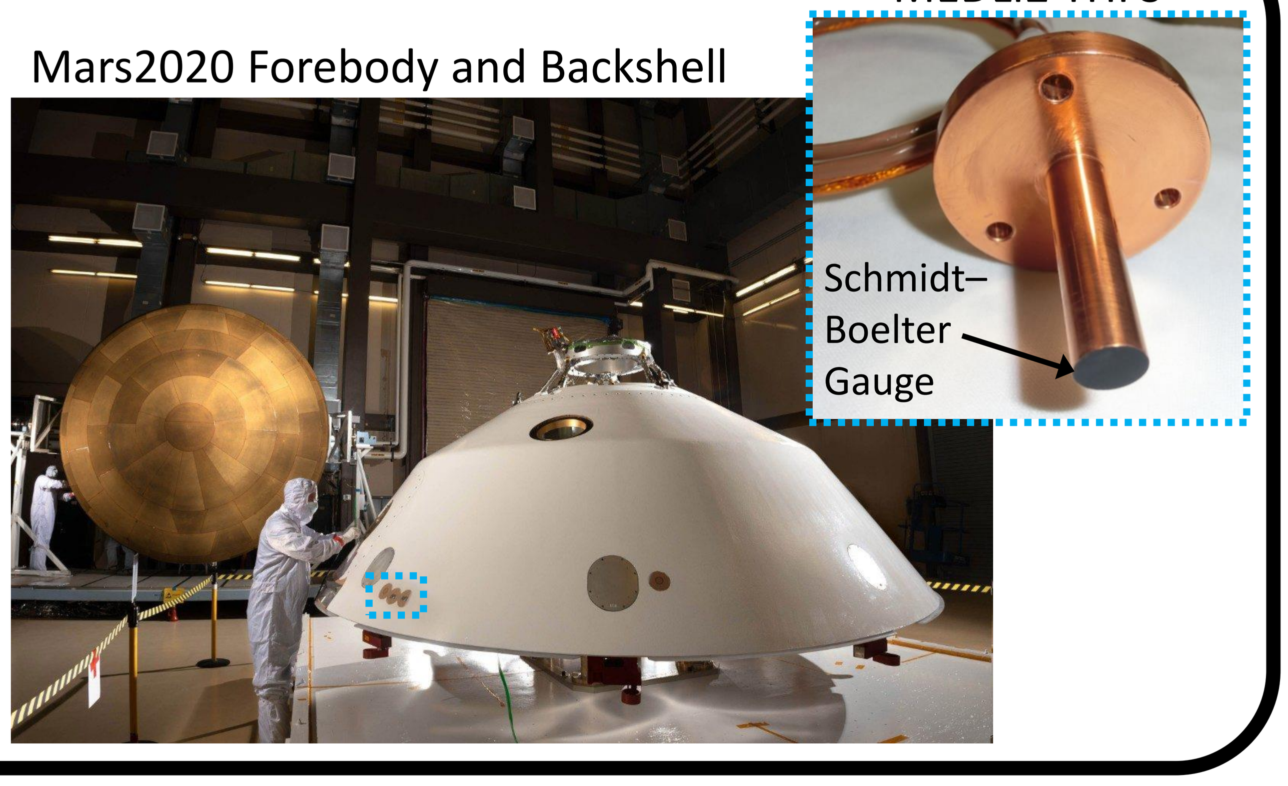
Introduction

- Recent NASA missions have included total heat flux sensors (THFS) embedded in the thermal protection system (TPS) to measure the combined convective and radiative heating during atmospheric entry. These measurements are key to fundamental entry science and mission design.
- The THFSs for the Mars Entry, Descent, and Landing Instrumentation 2 (MEDLI2) sensor suite on the Mars 2020 entry vehicle and the Low-Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID) technology demonstration mission were passively cooled Schmidt–Boelter gauges.
- As presented at IPPW 2021, THFS calibration is notoriously difficult and includes several sources of measurement uncertainty [1].
- Recent work has been conducted to understand and quantify the measurement uncertainty in the MEDLI2 and LOFTID Schmidt-Boelter THFSs.

Mars2020 Forebody and Backshell

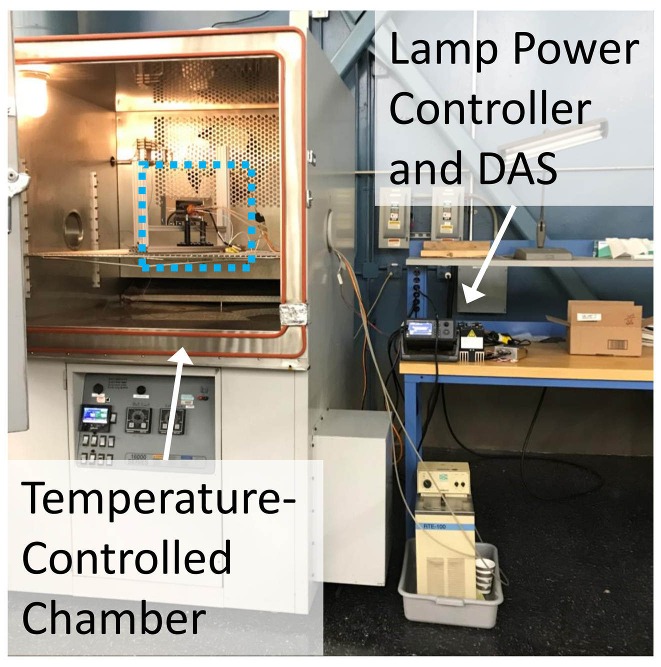
MEDLI2 THFS

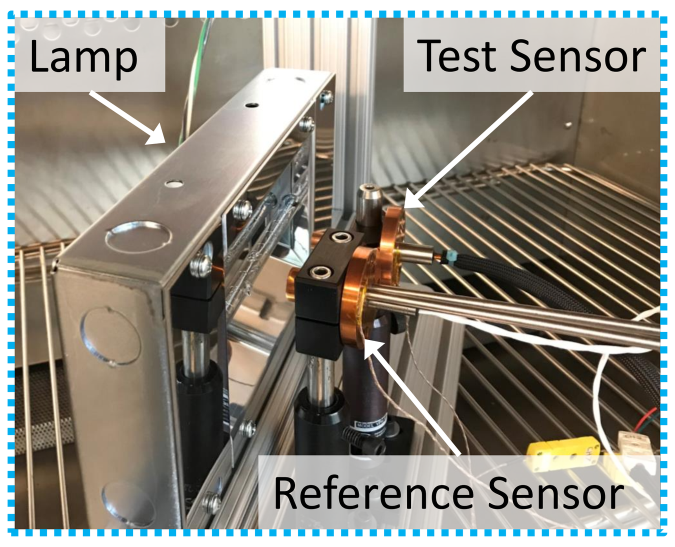


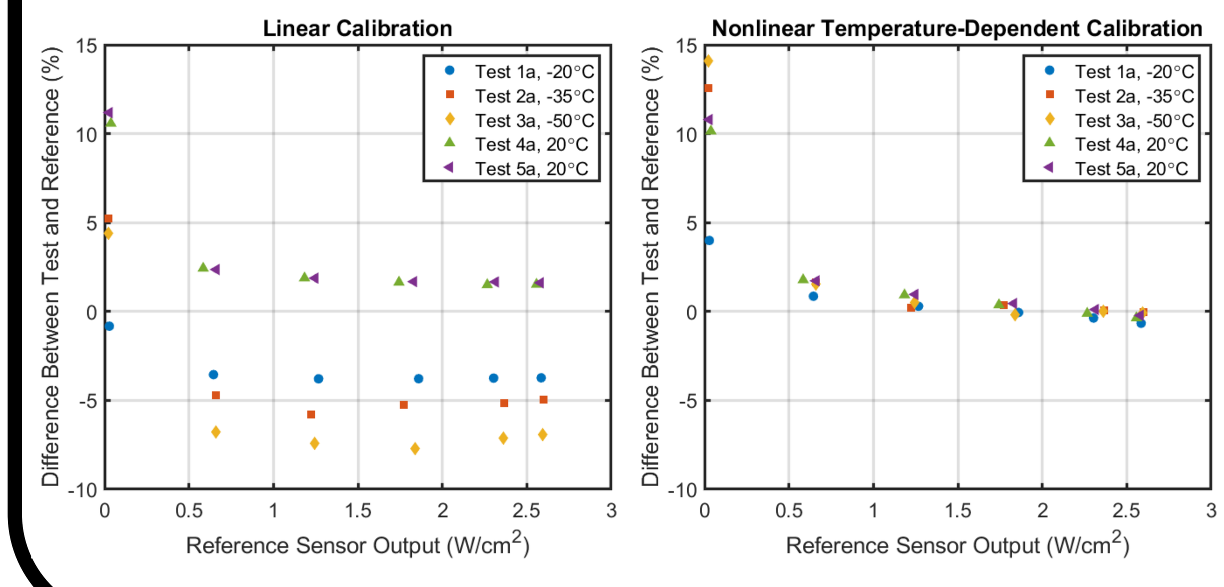
Temperature Dependent Calibration

- The manufacturer provided certificate of calibration reports the calibration as linear.
- Flight spare THFSs were calibrated at flight-relevant temperatures. The THFS output is nonlinearly dependent on the temperature of the sensing element and aligns with a model that assumes a temperature-dependent Seebeck coefficient [2].
- With the linear calibration, the test sensor measurement error is ~7% as -50°C.
- With the nonlinear temperature-dependent calibration, the difference between the test and reference sensor outputs are with ±1%.

As best practice, future missions should individually calibrate each THFS across all applicable use temperatures to account for sensor-to-sensor variations and minimize measurement uncertainty.







Linear Calibration:

$$q = C * V$$

Nonlinear Calibration:

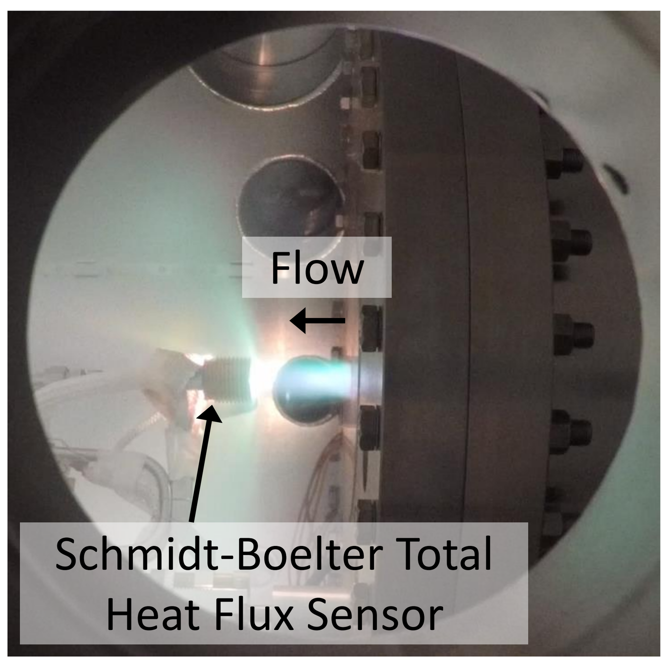
$$q = C\left(\frac{a_1 T_{calibration} + a_0}{a_1 T_{use} + a_0}\right) V$$

a: Seebeck coefficient
C: calibration constant
q: heat flux
T: temperature
V: sensor voltage output

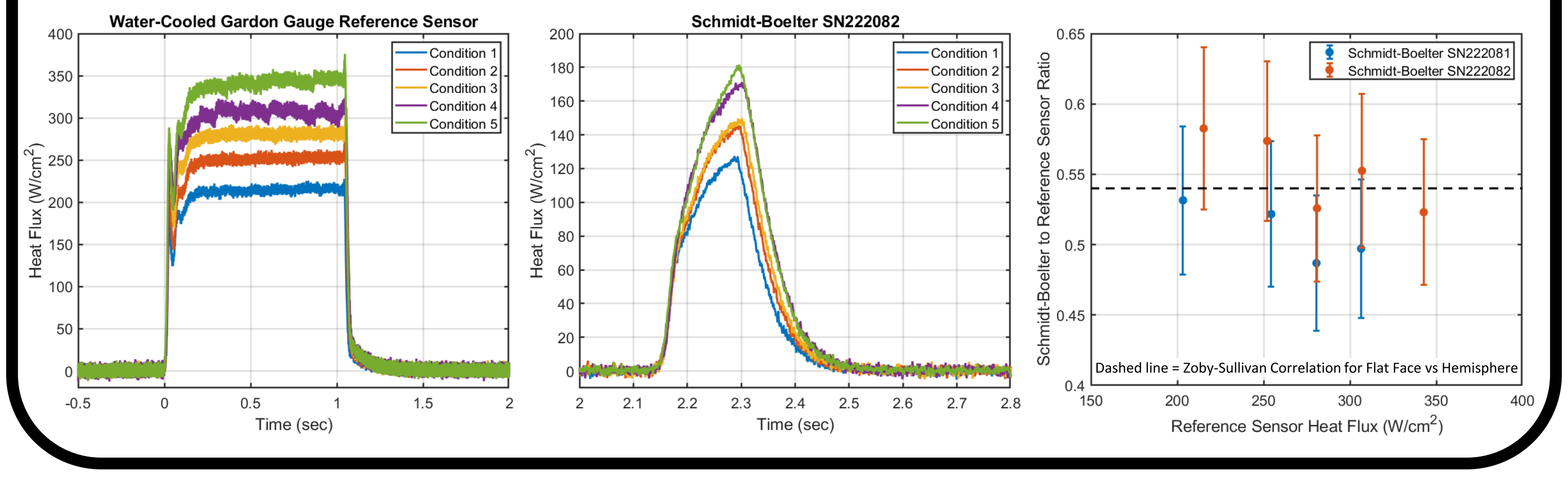
Radiative vs Convective Calibration

- According to ASTM E511-07, there is no standardized method for convective calibration of THFSs [3].
- Following industry standard, MEDLI2 and LOFTID performed pre-flight calibration of their Schmidt-Boelter THFSs using a radiant source.
- NASA Ames' miniature arc jet (mARC) II facility was used to investigate the differences between radiative and convective calibration of Schmidt-Boelter THFSs.
- Five distinct heat fluxes were applied to a flat-faced Schmidt-Boelter THFS as well as a hemispherical, water-cooled Gardon gauge reference THFS.
- The difference in geometry between the Schmidt-Boelter THFS and the reference sensor was accounted for using the Zoby-Sullivan correlation [4].
- The measurement uncertainty was estimated to be ±10%.

THFS in mARC II flow



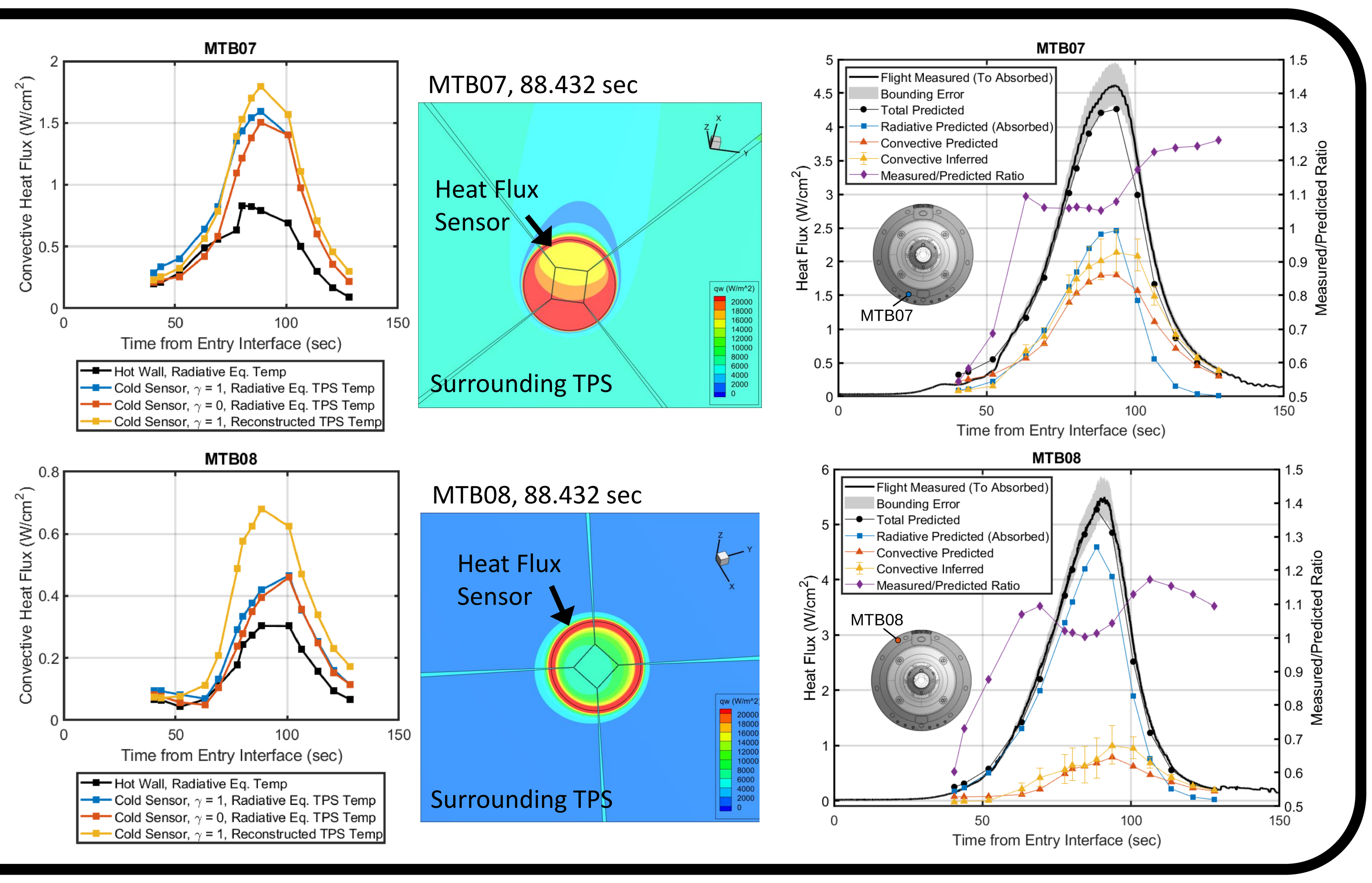
Results from this testing demonstrate that the manufacturer provided absorbed radiative calibration (with temperature correction) match the convective calibration within the measurement uncertainty.



Application Environment

- The MEDLI2 THFSs remained cold (below -24°C) throughout the entry heat pulse while the temperature of the surrounding TPS peaked at ~500-600°C [5-7].
- CFD simulations (DPLR, full 3D, overset grids, best estimated trajectory, and laminar flow) were performed to quantify the effect of a cold sensor embedded in a hot TPS. The transition from a hot-wall to a cold-wall boundary condition results in significant heating augmentation, especially at the hot-wall/cold-wall interface.
- Accounting for sensor and TPS temperatures results in improved agreement between the CFD predictions and the temperature corrected MEDLI2 flight data. Overall, there is excellent agreement (within 8% at peak heating) between the total heat flux sensor flight measurements and the model predictions.

This work highlights the importance of considering the differences between the application environment and the calibration environment when analyzing THFS flight data.



References

[1] Alpert, H., et al., 18th IPPW, 2021. [2] Miller, R.A. and Alpert, H.S. (2023) RSI, 94, 025002. [3] ASTM E511-07, Standard Test Method for Measuring Heat Flux Using a Copper-Constantan Circular Foil, Heat-Flux Transducer. [4] Zoby, E.V., and Sullivan, E.M., NASA TM X-1067, 1966. [5] Miller, R.A., et al., AIAA SciTech, 2022. [6] Miller, R. A., et al., JSR, under review. [7] Alpert, H.S., et al., (2023) JSR.