Comprehensive Sensitivity Analysis and Modeling of Heat Dissipation in High-Power Semiconductor Devices with Microchannel Heat Sinks

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Purpose

- Modern high-performance computer chips dissipate heat at rates that, if left unmanaged, drive temperatures past safe operating limits and degrade performance, reliability, and lifespan. Designing cooling systems that keep chips cool under steady loads and respond quickly to sudden power spikes remains a central challenge in thermal management.
- Our purpose is to investigate a liquid-cooled heat sink consisting of a solid aluminum block in direct thermal contact with a high-power chip. A cylindrical channel runs through the block, carrying water from an inlet to an outlet.
- The exterior surfaces are assumed to be perfectly insulated, so heat enters only from the chip and exits only through the internal fluid channel.

Methods

Three complementary models of the system have been developed:

- Numerical model — CFD-based solution of the conjugate heat transfer problem.
- Experimental model — measurements on a physical test rig for validation.
- Analytical model — closed-form predictions using lumped or reduced-order formulations.

The analytical models support the use of hypercomplex algebra for sensitivity analysis, enabling accurate, derivative-based evaluation of how each design parameter influences performance

Objectives

- Develop and validate a model to predict chip temperature across varying operating conditions.
- Apply hypercomplex sensitivity analysis to quantify the influence of each design parameter on both the steady-state chip temperature and the transient response to power spikes.
- Identify parameter combinations that simultaneously lower steady-state temperature and reduce the thermal time constant.

Numerical Model

- High-fidelity microchannel heat transfer model using ANSYS, a Finite Element Analysis software
- Solve for temperature, pressure, and velocity fields.
- Quantifies the heat extracted from the semiconductor
- Convergence Analysis performed to verify results

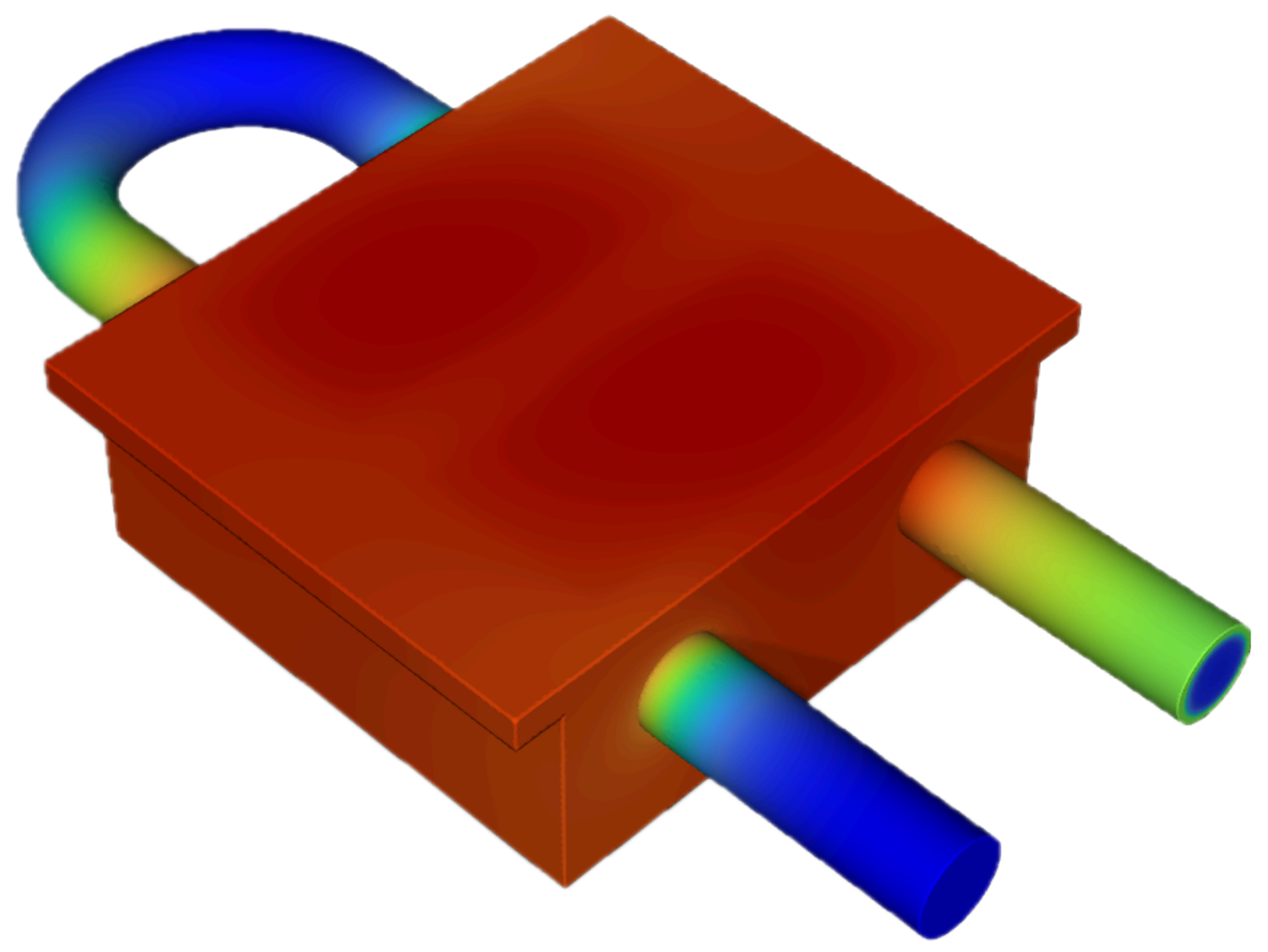

Figure 2: Microchannel model developed in ANSYS

Experimental Model

- A physical microchannel heat exchanger is used to validate the numerical and analytical models.
- Model parameters are tuned, and boundary conditions are adjusted to match experimental results.
- Establishes confidence in the model's accuracy and predictive capability.

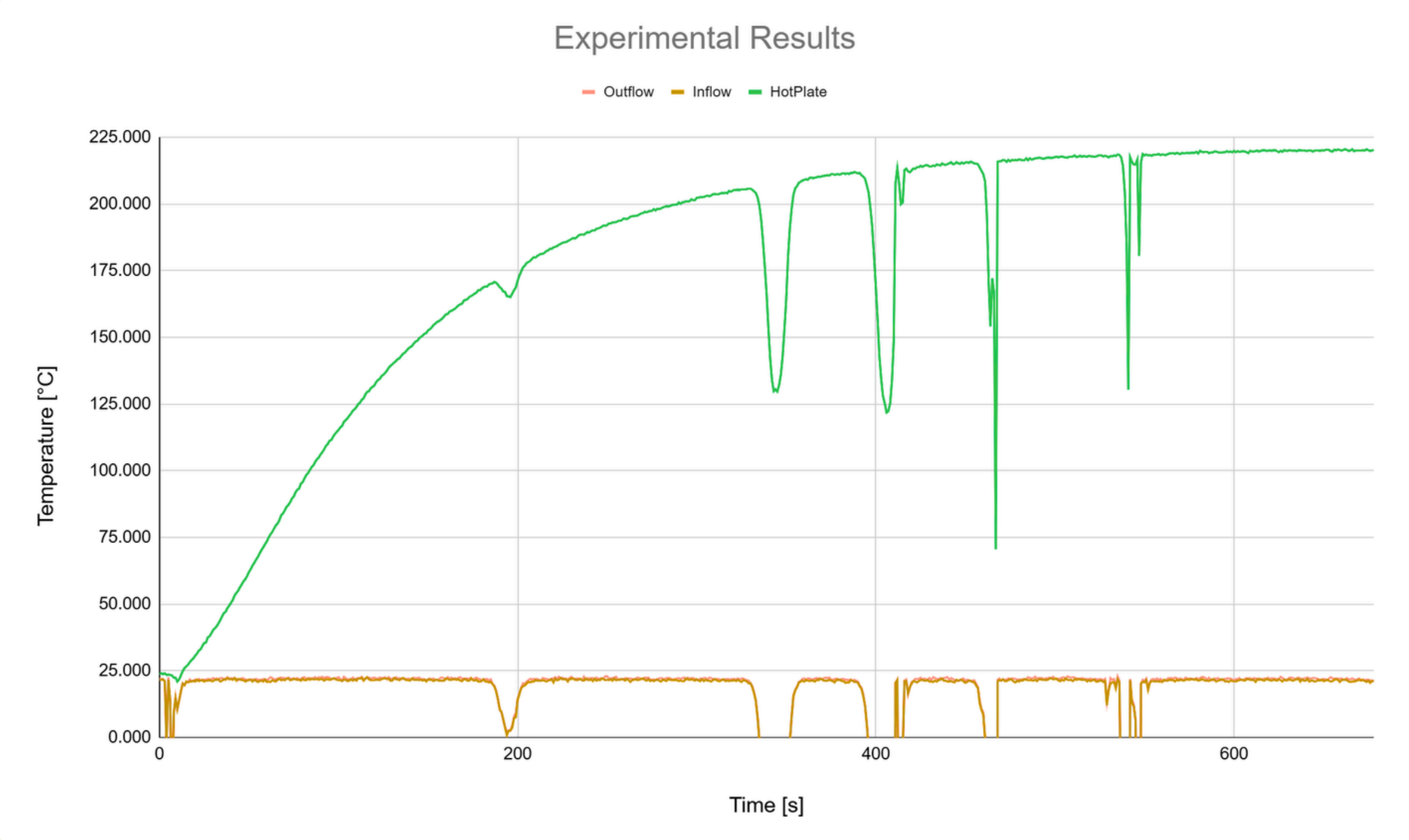

Figure 3: Experimental Results

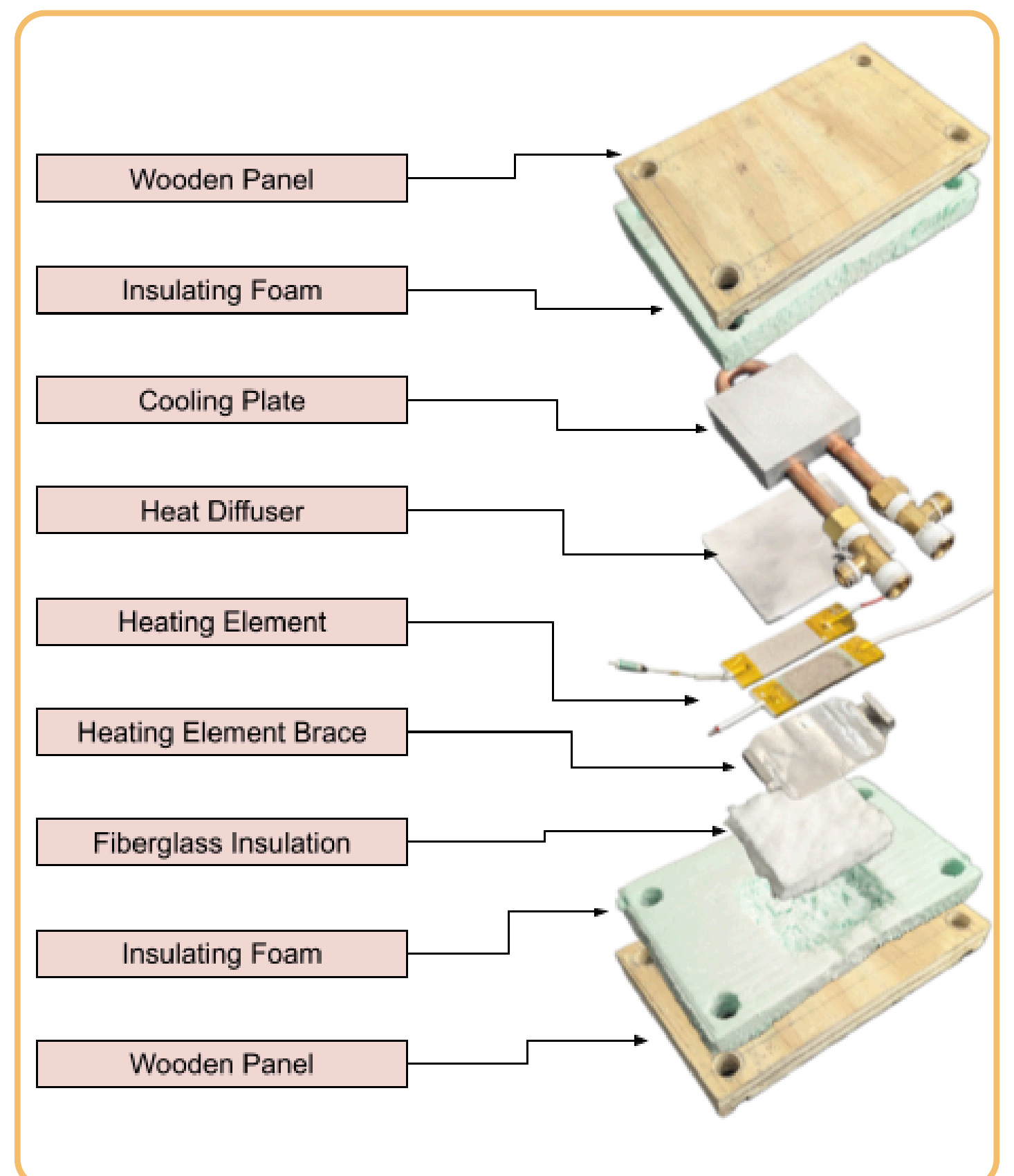

Figure 4: Experimental model diagram

Next Steps

- Complete Experimental Setup and Establish Testing Procedure
- Further training on the sensitivity model
- Continue testing the experimental setup
- Iterate model design until results correlate
- Modify design to improve cooling

Analytical Model

- Uses hypercomplex algebra to compute parameter sensitivities.
- Sensitivity derivation is implemented using OTIlib, an open-source library for Order Truncated Imaginary (OTI) numbers.
- Obtain analytical expressions for parameter sensitivities efficiently.

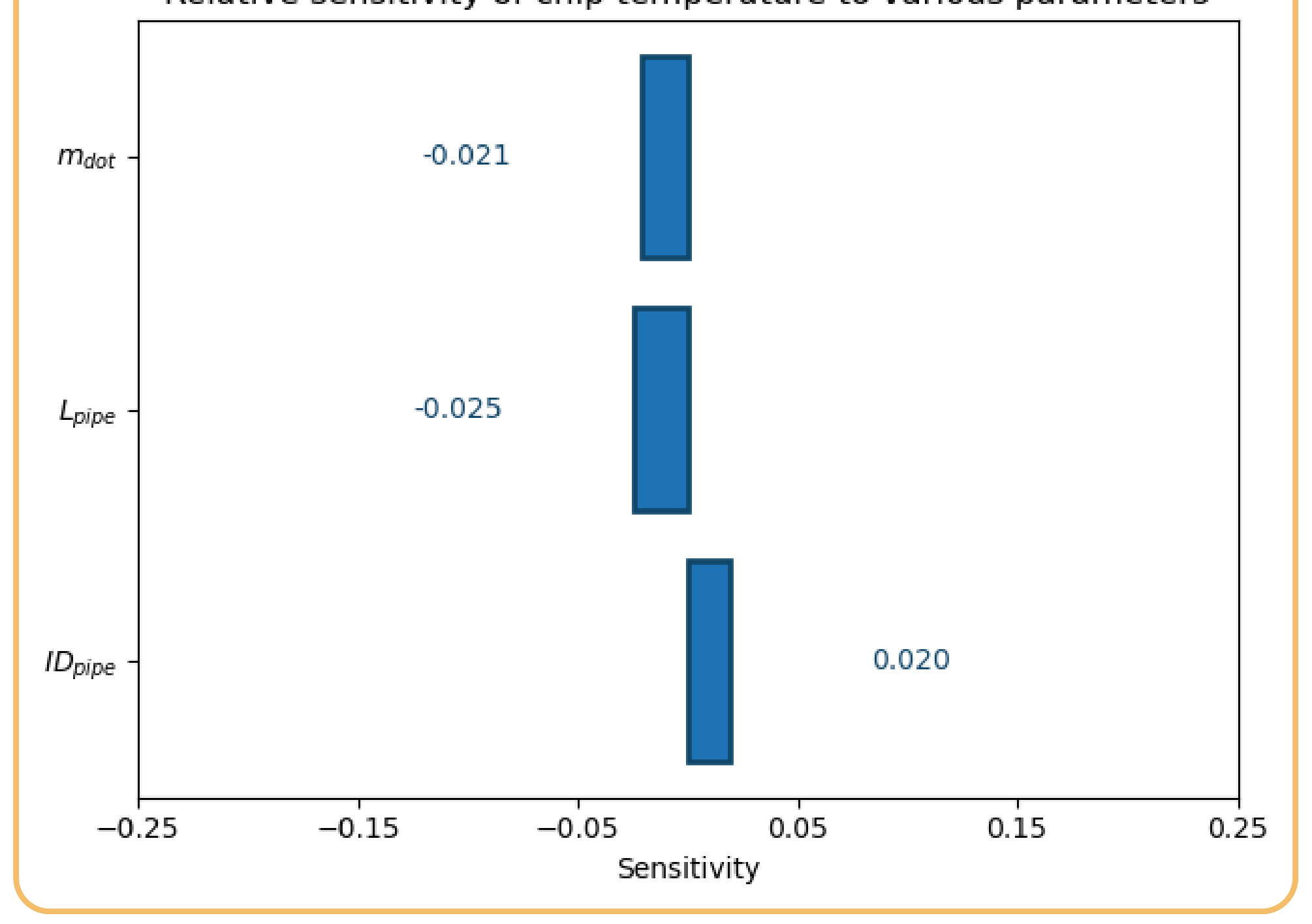

Figure 5: Sensitivity analysis

References

- Theodore L. Bergman, Adrienne S. Lavine, Frank P. Incropera, and David P. DeWitt. Fundamentals of Heat and Mass Transfer. John Wiley & Sons, Hoboken, NJ, 8th edition, 2017. ISBN 978-1-119-32104-4.

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