Real-Time Control of a Transient Thermal Management System with Integrated Latent Thermal Energy Storage

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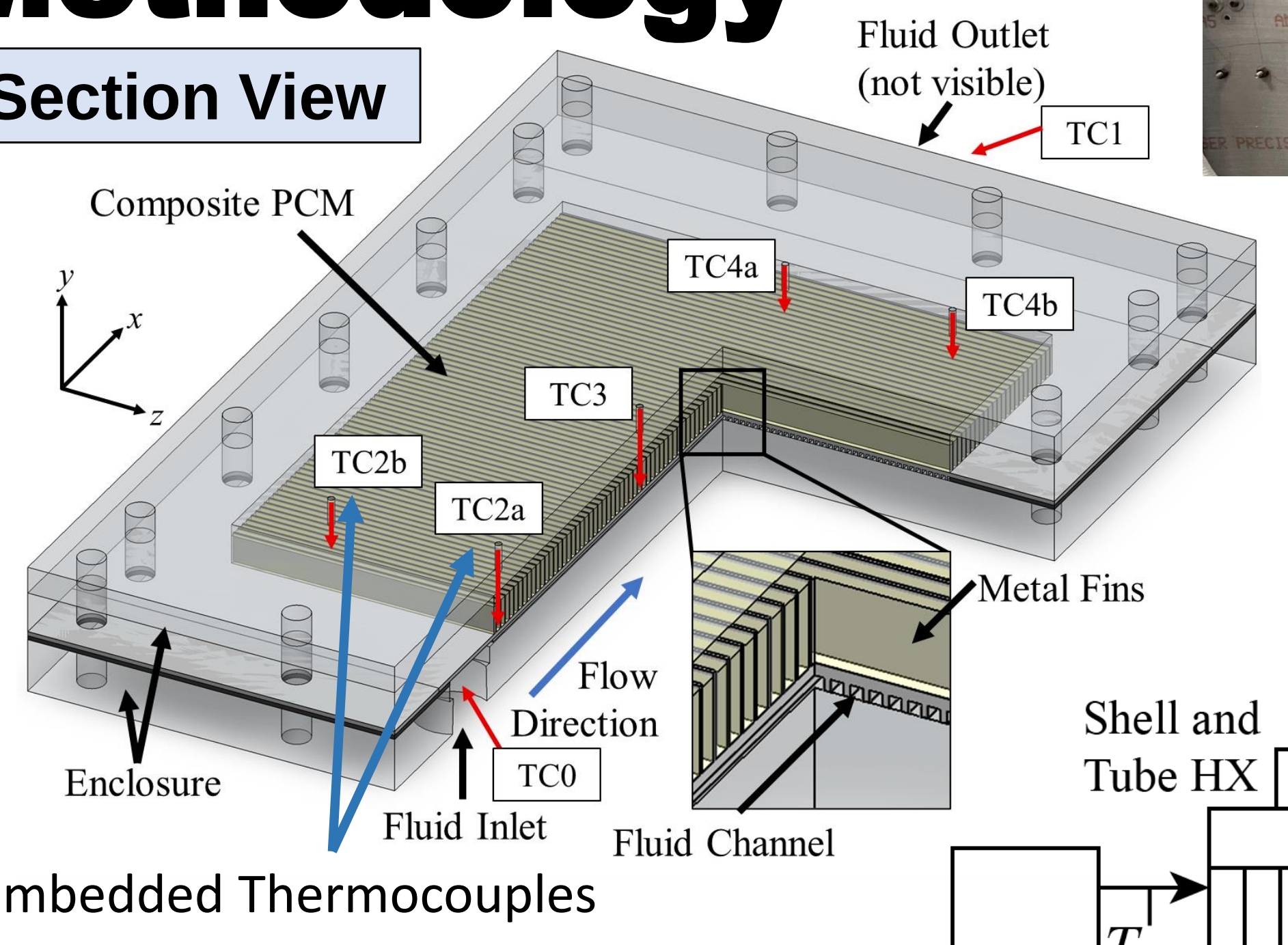
Problem Statement

- Phase-change **thermal energy storage** (TES) devices integrated into **thermal management systems** (TMSs) provide robustness against highly transient heat loads produced by electrical systems
- TES is designed to provide additional heat rejection capacity only when needed, so its operation must be **actively controlled**
- Control strategies for such systems have been developed and tested in simulation; **experimental testing and validation is limited** because of the large computational cost of optimal control strategies and **need for online state of charge estimation**
- In this work, we implement and test a logic-based controller that was previously developed in [1] on an **experimental hybrid TMS testbed** along with a state of charge estimator and low-level PID controllers

Approach and Methodology

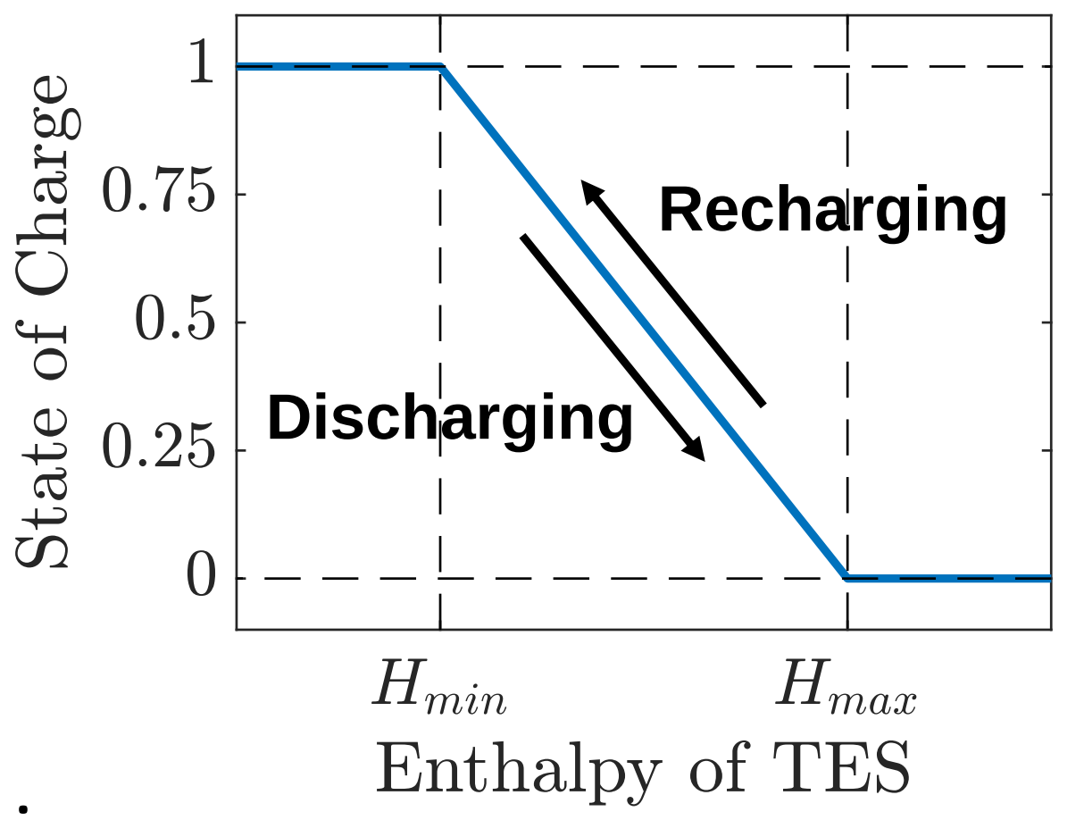
SOC Estimation

TES Section View



Embedded Thermocouples

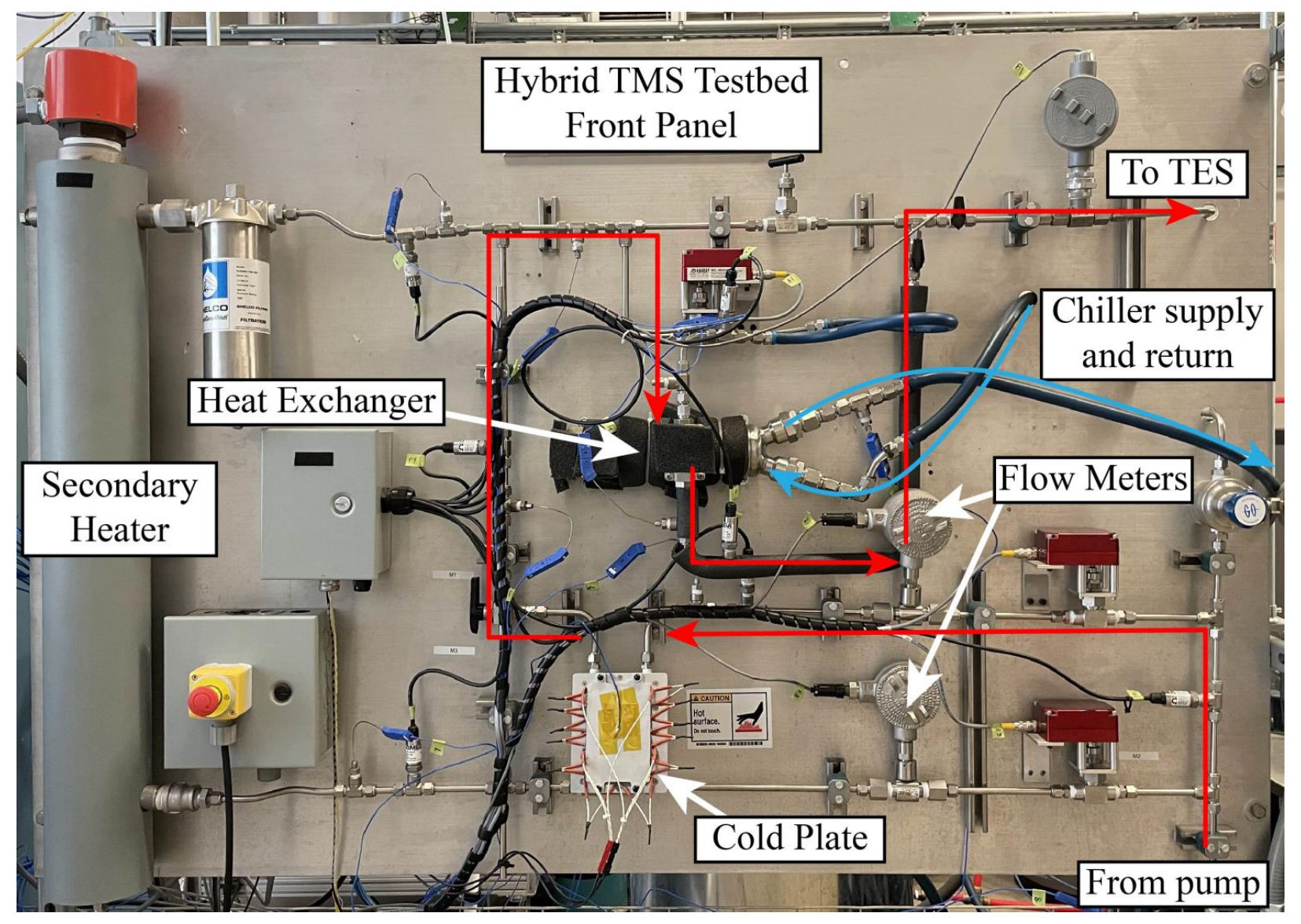
- The **state of charge** (SOC) quantifies the remaining energy storage capacity of the TES. When SOC drops to zero, the TES is no longer capable of rapidly absorbing heat and must be **recharged**
- SOC is estimated by a **model-based state estimator** using a reduced-order finite volume heat transfer model and measurements of the internal temperature state of the TES
- With the **State Dependent Riccati Equation Filter** (SDRE Filter), convergence and boundedness of the state estimates can be guaranteed [2]

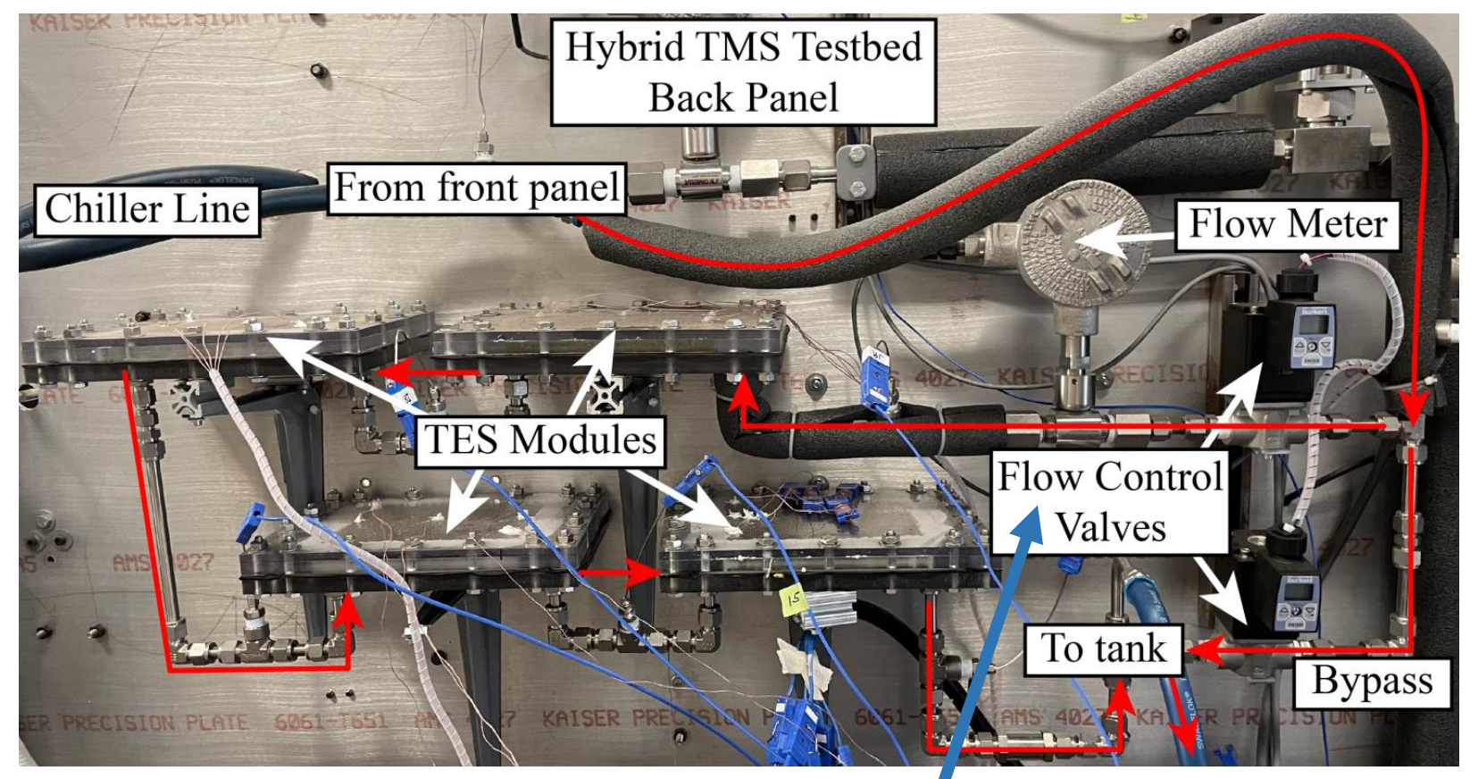


Controller Logic

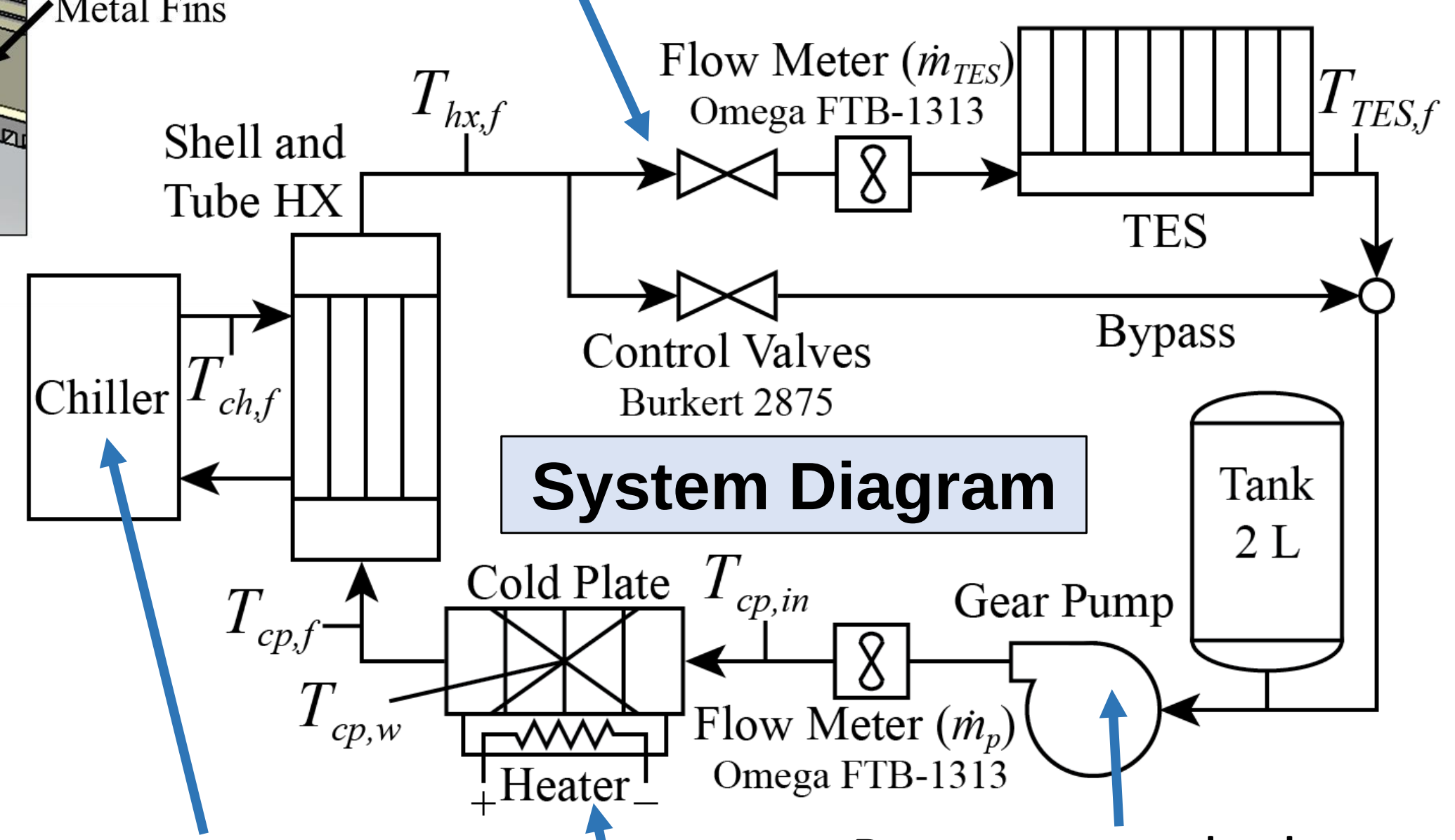
- The controller must balance two objectives:
  1. Recharge the TES whenever possible, when $T_{TES,f} > T_{hx,f}$
  2. Maintain the temperature of the cold plate surface, $T_{cp,w}$
- Control logic chooses one of **four operation modes** to determine the mass flow rates (control actions)
- PID controllers regulate the pump speed and valve positions to achieve the specified flow rates

Mode	Control Action
Recharge	Maximum primary flow rate Maximum TES flow rate
Discharge	Maximum primary flow rate TES flow rate proportional to cold plate temperature
Bypass	Maximum primary flow rate Zero flow through TES
Idle	Reduce primary flow rate to 10% of maximum Zero flow through TES





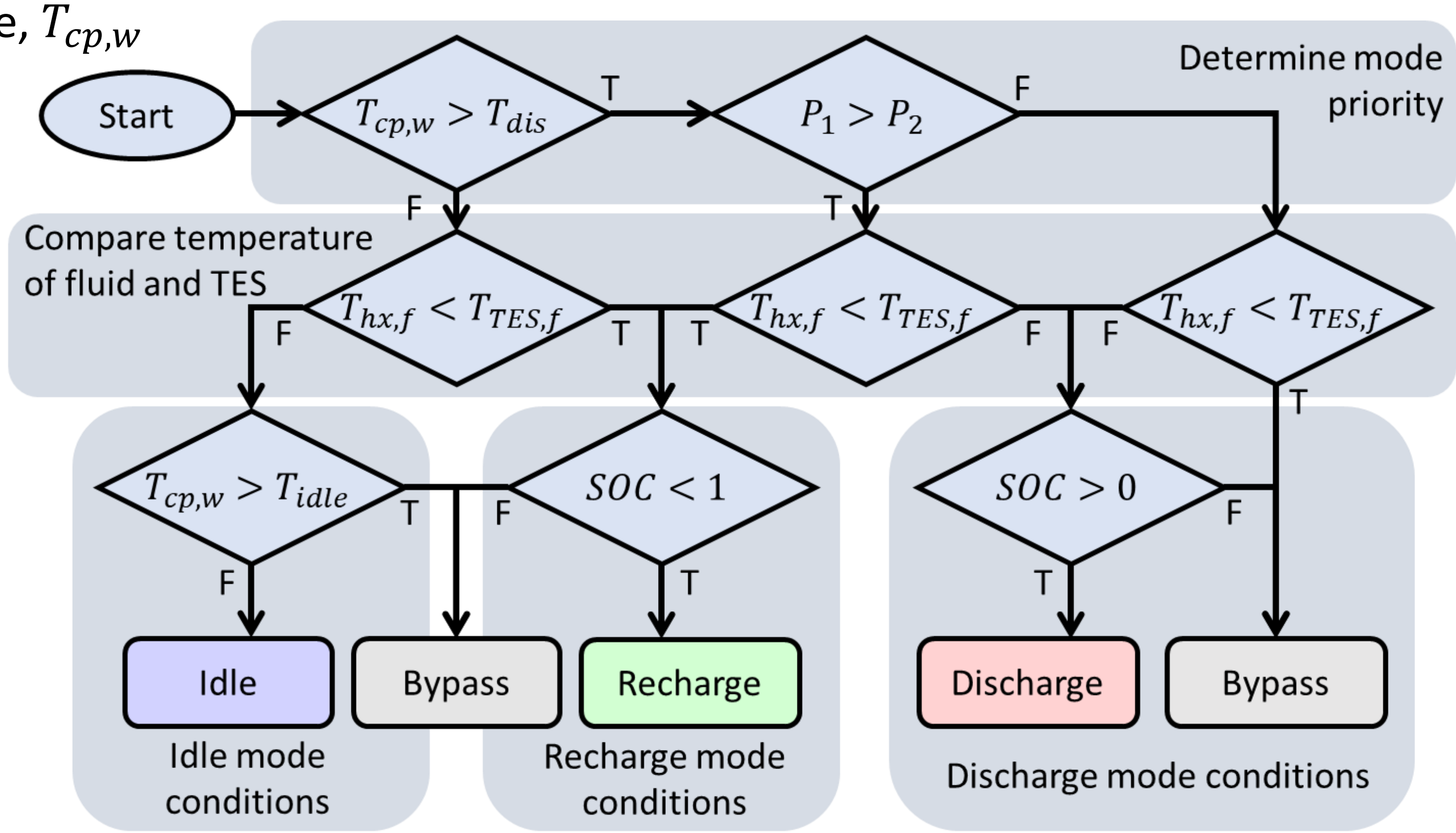
Variable position valves control the flow rate through the TES, $\dot{m}_{TES}$



Chiller operation is uncontrollable

Pump controls the primary flow rate, $\dot{m}_p$

Unpredictable transient heat pulses are applied through the cold plate

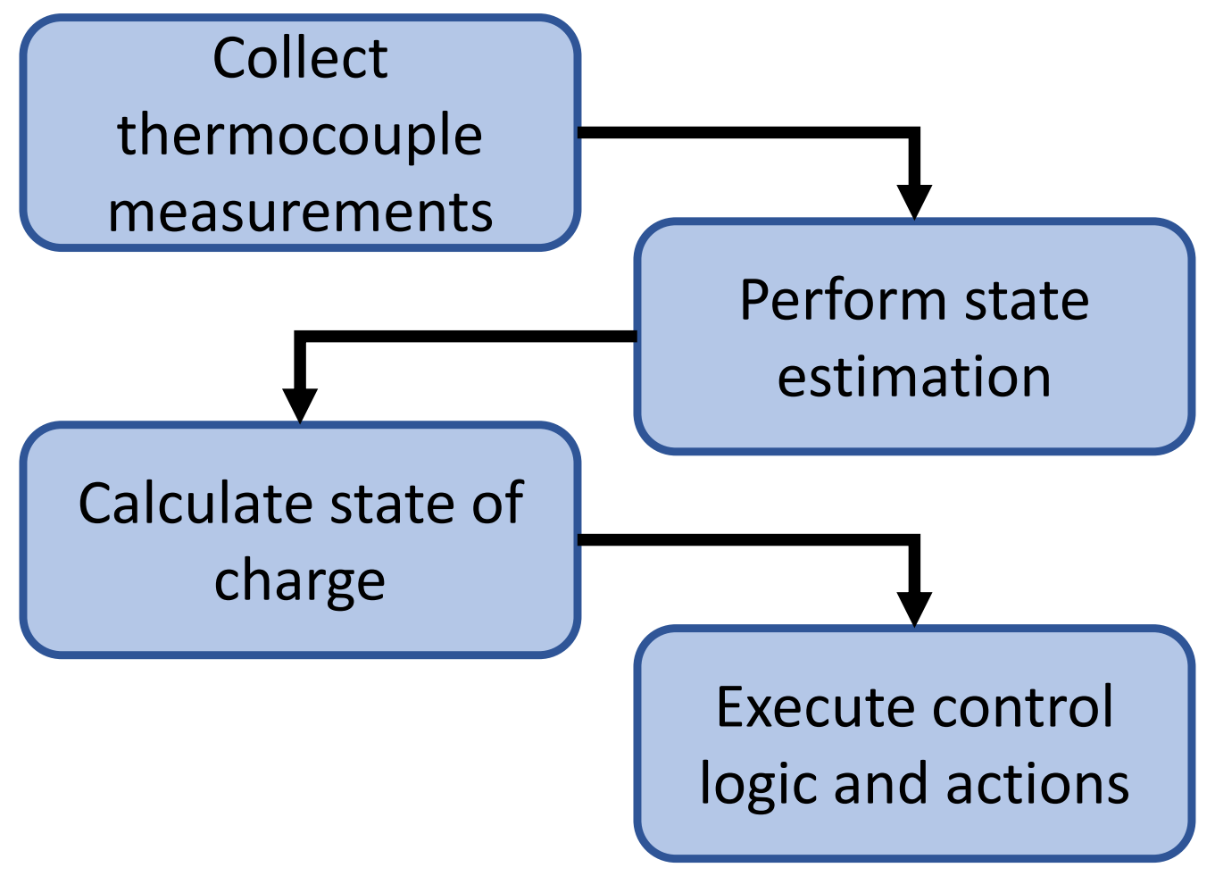


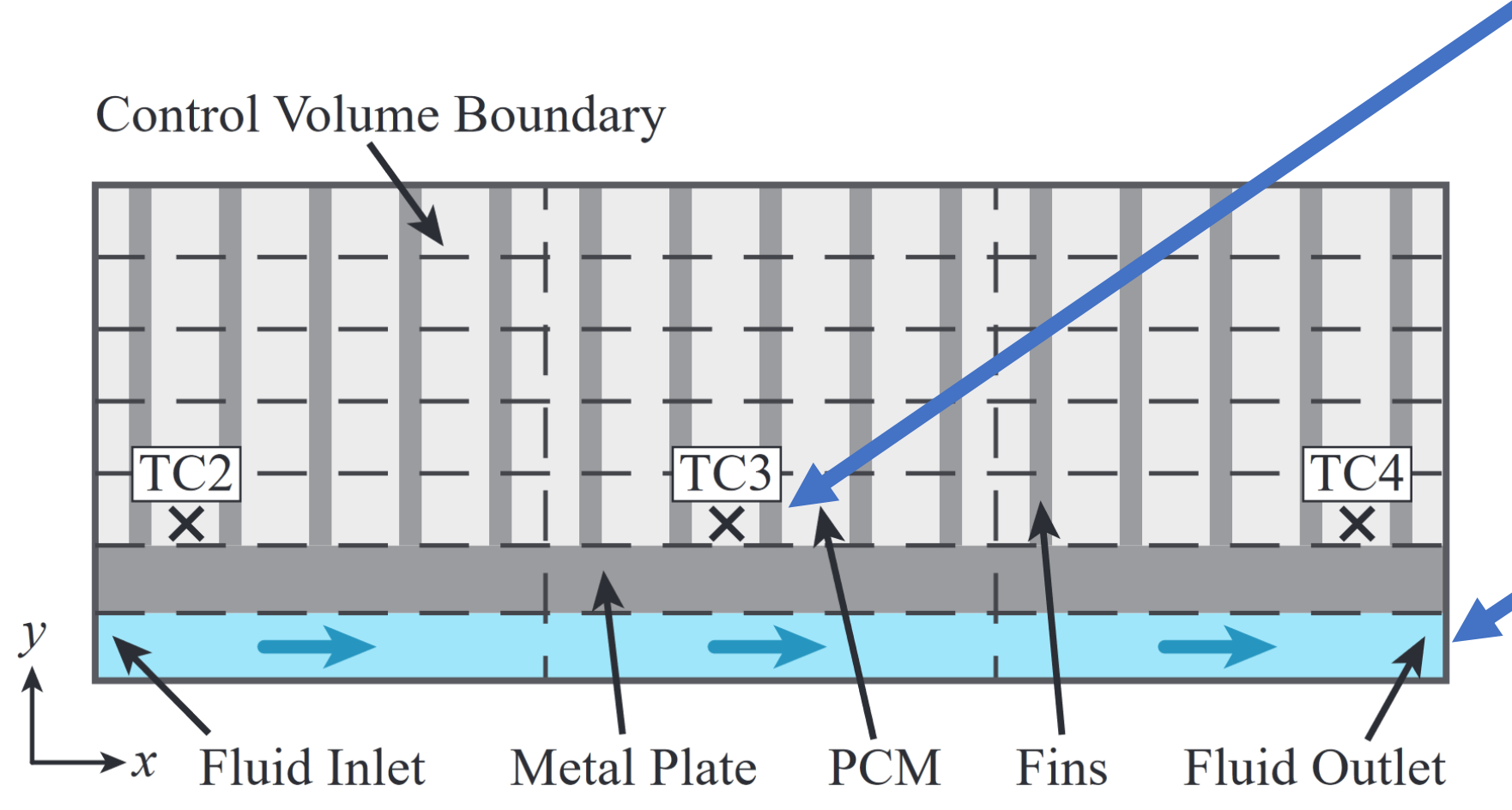
[1] M. Shanks and N. Jain, in *2022 21st IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (iTherm),* May 2022.
[2] M. Shanks, U. Inyang-Udoh, and N. Jain, submitted to *ASME Journal of Dynamic Systems, Measurements, and Controls,* under review, 2023.

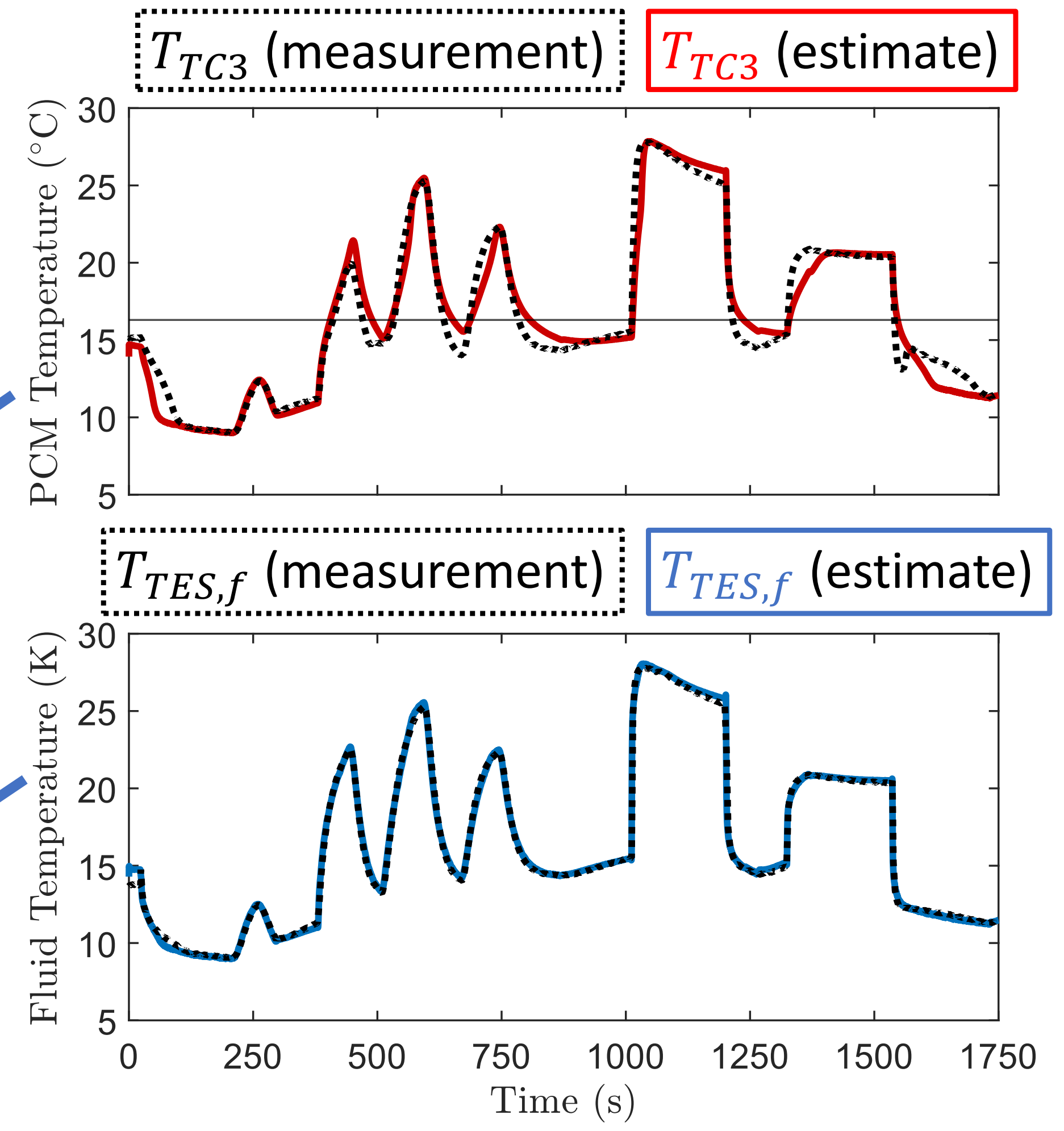
Controller Implementation

Estimator Validation

The following case study demonstrates the state estimator in an experimental environment. Estimates for internal temperature states are compared to corresponding thermocouple measurements. The SOC cannot be validated experimentally because it is not possible to determine the SOC without the state estimator.

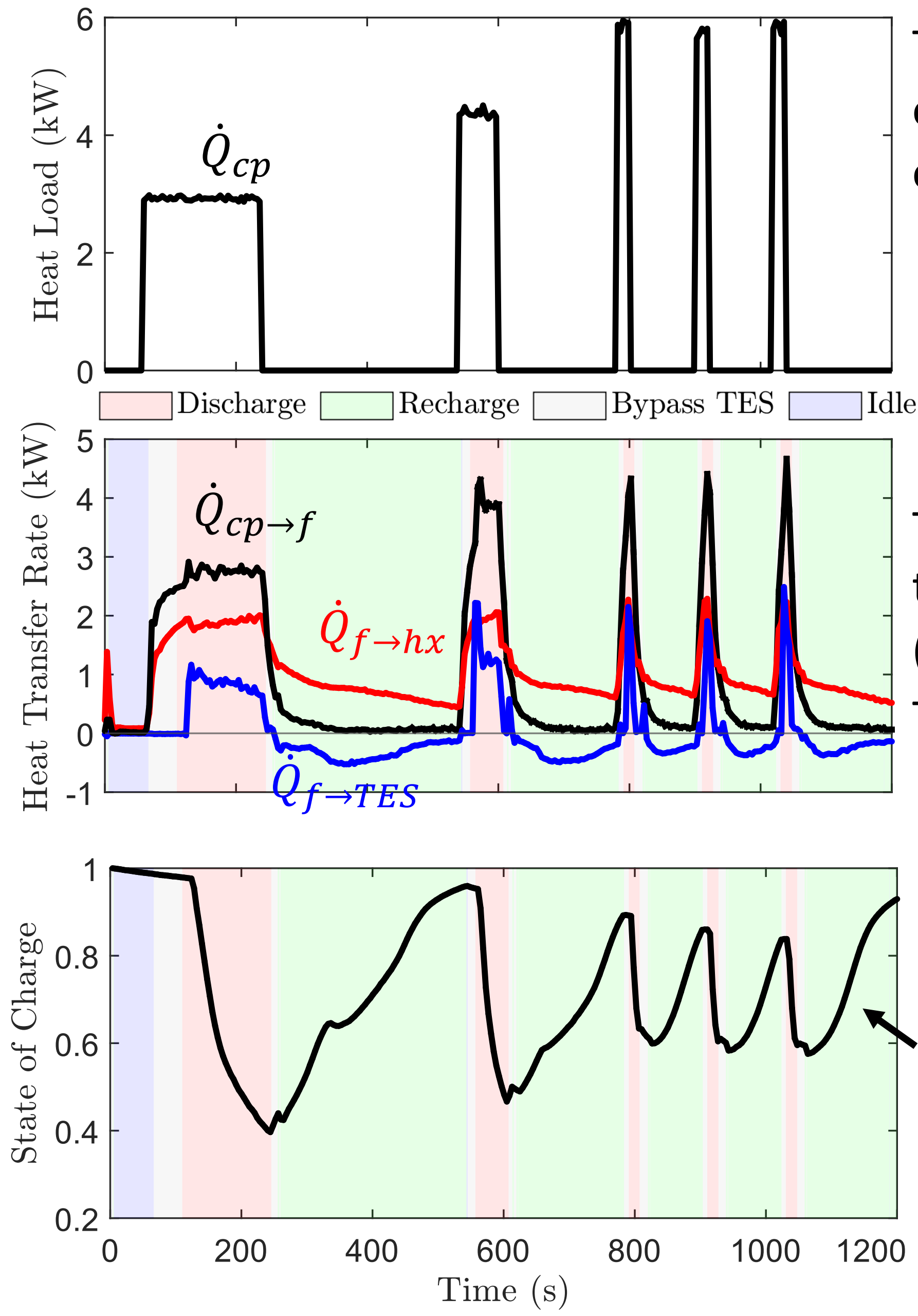






Controller Testing

The following case study demonstrates the proposed heuristic controller for the hybrid TMS and compares it to a benchmark conventional TMS without thermal storage. The heat load $\dot{Q}_{cp}$ notionally represents a load produced by an intermittently-used electrical system.



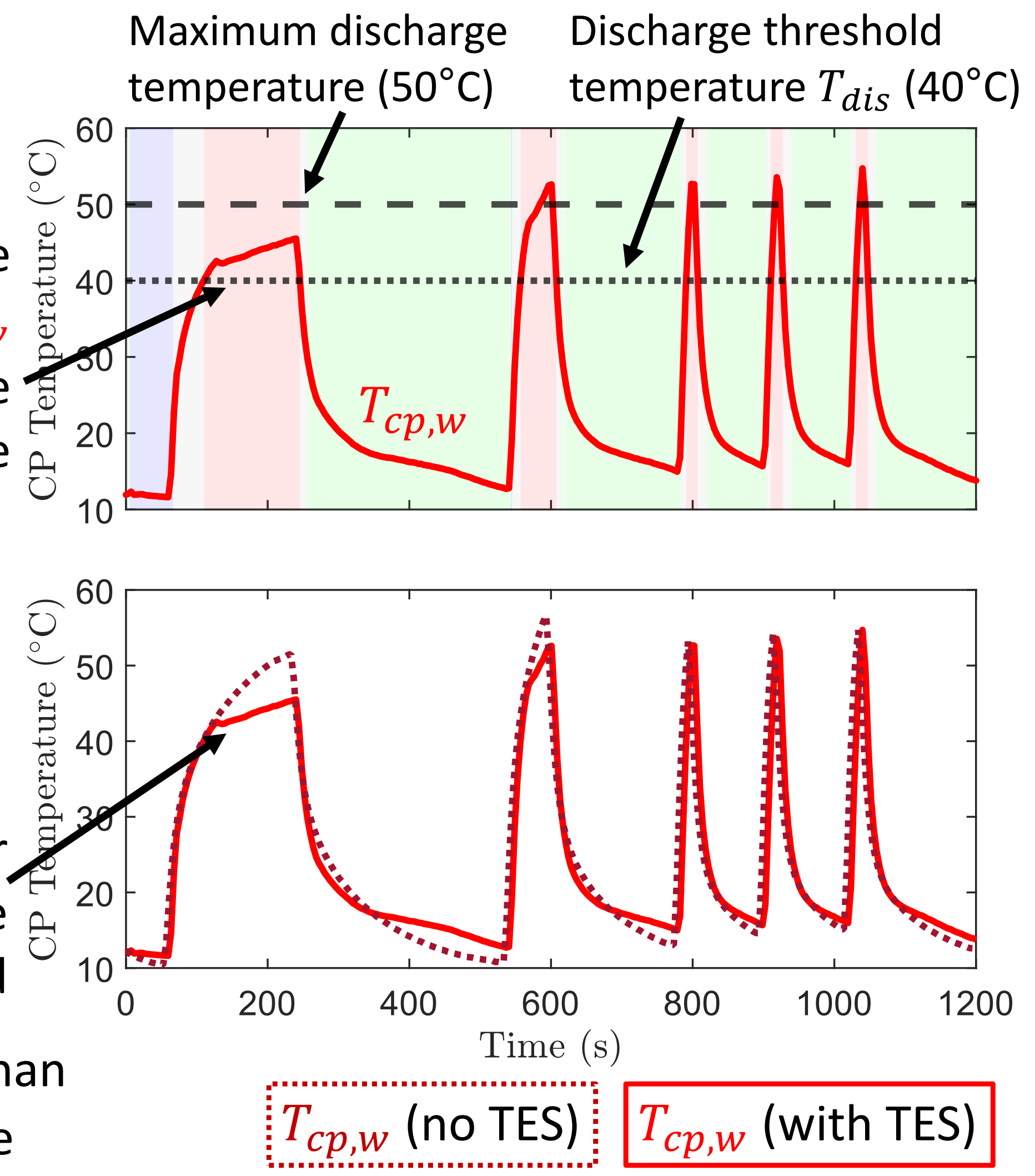
The cold plate applies a series of transient heat pulses ($\dot{Q}_{cp}$) of magnitude up to 6 kW

The controller discharges the TES (red shading) when $T_{cp,w}$ exceeds the discharge threshold temperature

The heat load is both rejected through the heat exchanger ($\dot{Q}_{f\rightarrow hx}$) and absorbed by the TES ($\dot{Q}_{f\rightarrow TES}$) when discharging

Cold plate reaches a lower maximum temperature when the TES is used

$T_{hx,f}$ tends to be only slightly less than T_{melt} during recharging, slowing the process. When the TES is discharging, $T_{hx,f}$ is much higher than the temperature of the PCM, accelerating the discharge.



In the above figure, an identical experiment is run without enabling the controller or TES

Summary & Future Work

Key Contributions

- State of charge of TES can be estimated online with limited temperature measurements
- Heuristic logic-based control strategy performs well experimentally even when the upcoming heat loads are unknown

Future Work

- Design advanced control strategies (e.g. model predictive control) and benchmark performance against heuristic methods

Acknowledgements

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