Nonlinear Model Predictive Control of a Latent Thermal Energy Storage Device for Electronics Cooling Applications

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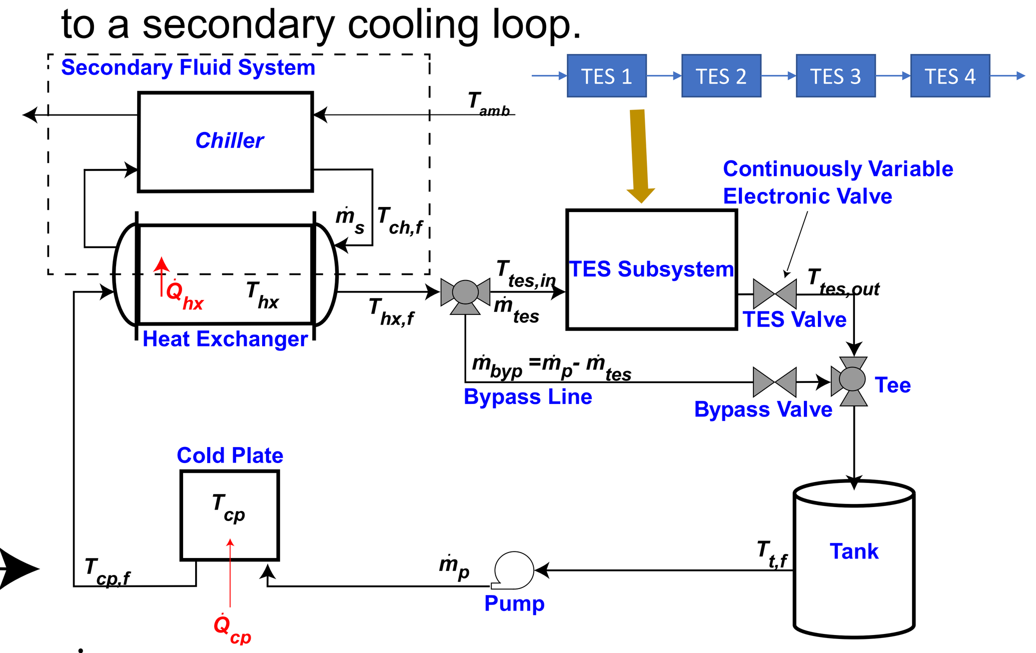
Motivation

- **Thermal management systems** (TMSs) integrated with phase-change **thermal energy storage** (TES) devices, to provide robustness against highly transient heat loads produced by electrical systems, are called **hybrid TMSs.**
- The TES is designed to provide additional heat rejection via **latent heat capacity with a phase change material** (PCM) only when needed, so its operation must be **actively controlled.**
- To fully utilize the benefits of hybrid TMS, **a nonlinear finite-horizon model predictive controller** (NMPC) may be synthesized..
- To accurately predict TES state of charge (SOC) during transient operation, a fine discretization of the PCM melt front is needed.

Approach and Methodology

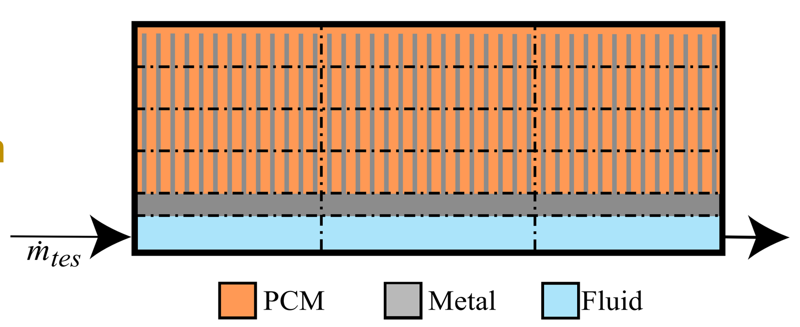
The **single-phase cooling loop** considered in this work is shown on the right. The cold plate and heat exchanger solid and liquid masses are each modeled as a **lumped parameter system**. In addition, the tank is modeled as a single state, assuming total mixing.

$\dot{Q}_{HX}$: State-dependent heat transfer to a secondary cooling loop.



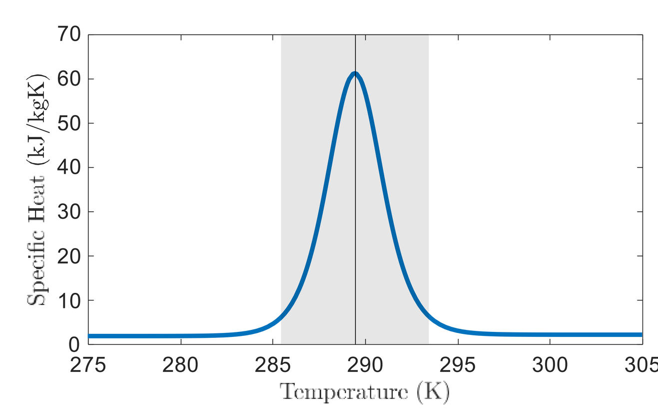
$\dot{Q}_{CP}$: Unknown heat generation into the cold plate solid mass

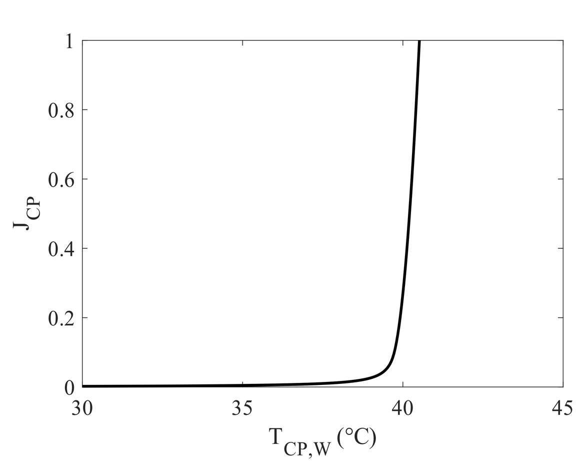
Right: The spatial domain of each TES device is discretized to **transform the PDE into a system of ODEs**. The PCM and fins are tightly packed, such that they can be modeled as a composite.



The hybrid TMS may be **modeled as a graph**, where the temperature of each control volume corresponds to a node in the associated graph. This allows for flexible and computationally efficient modeling of the hybrid system.

Right: The latent melting zone of the PCM is modeled as a **continuous, sharp increase in the specific heat** around the melting point of the PCM.





Above: pseudo barrier function

A **non-linear model predictive controller** (NMPC) is synthesized to control the hybrid TMS.

- Prediction model: **77 states, 2 control actions** (primary and TES branch mass flow rates).
- The multi-objective function J is comprised of 3 objectives.

$$J[n] = \sum_{k=n}^{N+n} \left(J_{CP}[k] + J_{TES}[k] + J_u[k]\right)$$

- J_{CP}: **Cold Plate temperature** is to be regulated below some threshold $T_{cp,max}$ if it is possible to do so within the horizon of the NMPC. This is achieved using a **pseudo barrier function**. While a true barrier function is asymptotic at the threshold, this function is not, allowing the cost function to be defined above the soft constraint.
- J_{TES}: **TES device temperature** is penalized by a quadratic function to compensate for the **limited time horizon**.
- J_u: **Mass flow rate** is penalized to ensure **power efficient solutions**, and the change in mass flow rate is also penalized to **minimize actuator wear**.

- The system dynamics may be written as in Eq. 1.

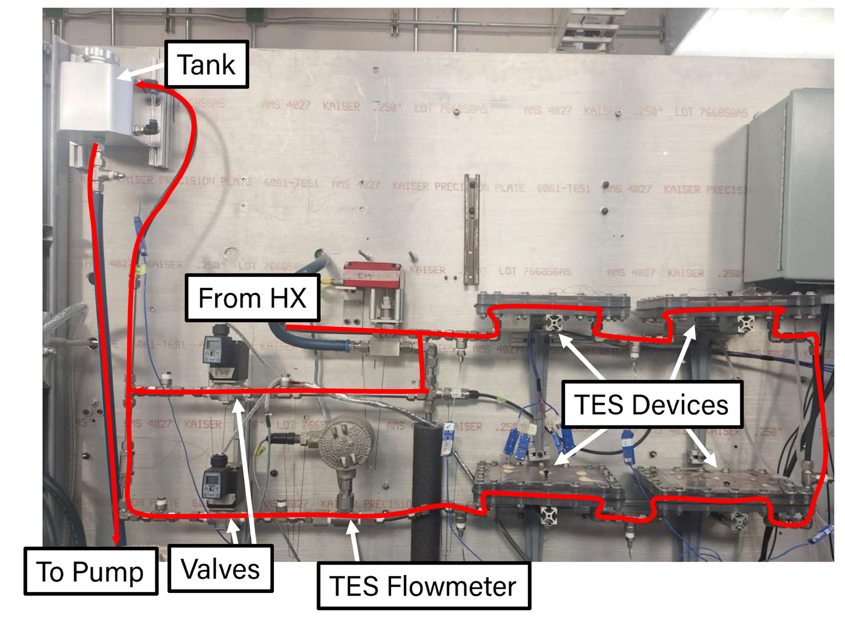
$$M(x)\dot{x} = C(x,u,d)x + Bd \qquad (1)$$

- To implement the predictive step in the NMPC, the system dynamics are linearized at each point in the finite horizon and integrated using the implicit trapezoidal integration rule.
- Linearization is done by assuming M and C are constant over one step in the NMPC horizon.
- Approximate gradients are obtained for the linearized system to accelerate computation time.

NMPC parameters

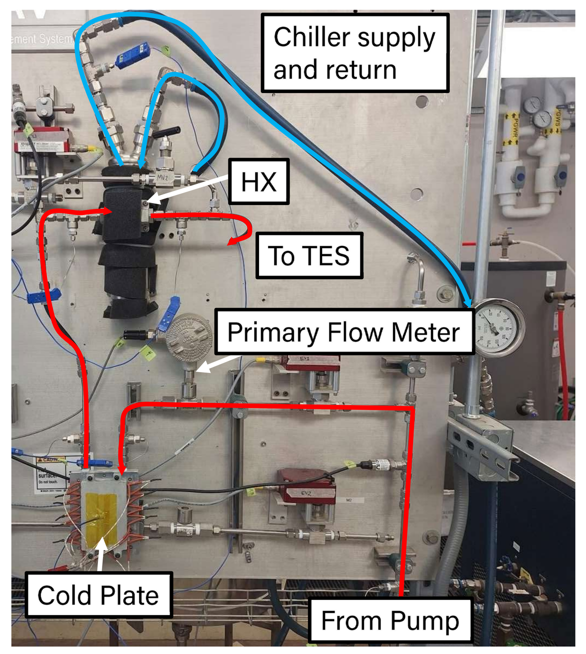
Parameter	Selected Value	Unit	Description
N	25	steps	Steps in NMPC Horizon
Δt	1	s	Control action update rate
u_{min}	0.0005	$kg \cdot s^{-1}$	Min allowed flow rate
u_{max}	0.1	$kg \cdot s^{-1}$	Max allowed flow data
Δu_{max}	0.02	$kg \cdot s^{-1}$	Max allowed change in flow rate
$T_{CP,W,max}$	45	°C	Soft constraint max cold plate temperature
$T_{CH,F}$	8	°C	Chiller inlet temperature

Experimental System



Left: Front side of hybrid TMS experimental system

Right: Rear side of hybrid TMS experimental system



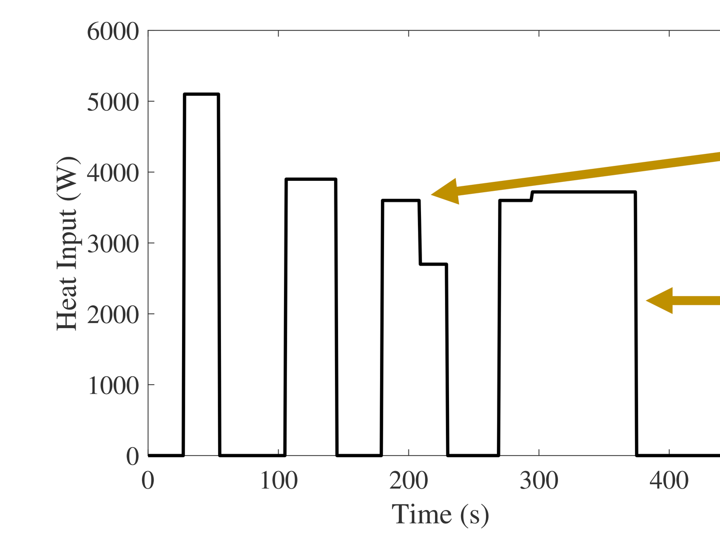
- The proposed NMPC was implemented on an experimental test system. Type-T thermocouples are used to measure twelve of the total seventy-two states. An observer is used to estimate the remaining states.
- NMPC determines mass flow rate setpoints, and individual lower-level controllers are used to track these setpoints.

Results

- Simulated and experimental data was collected using the disturbance profile on the right, for the proposed closed loop system both with and without a TES.

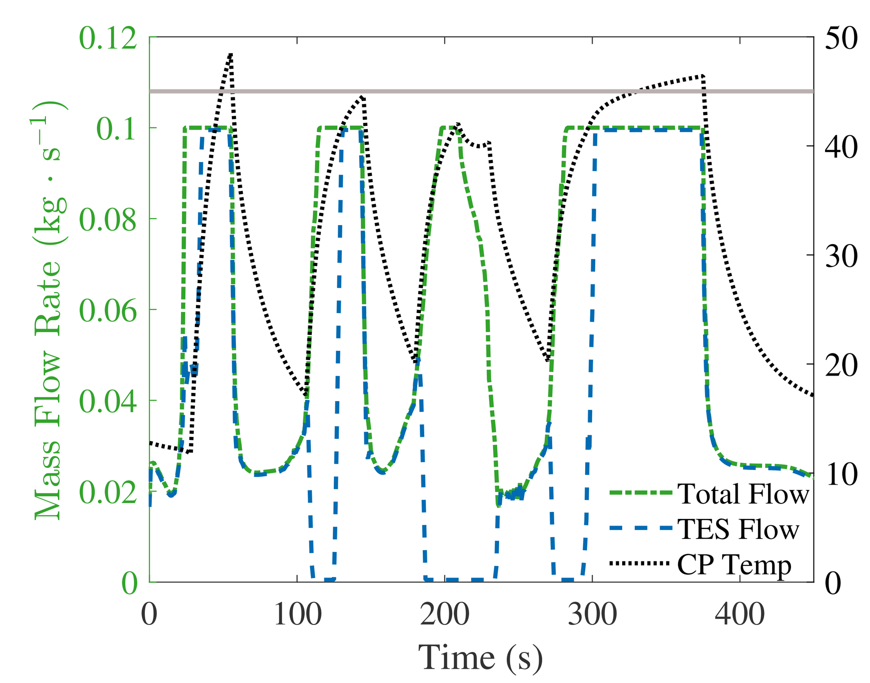
Main Takeaways:

- The NMPC is effectively able to coordinate TES usage
- Experimental results match well with simulated results
- Controller update rate: 1s
  Maximum controller execution time: 0.4s

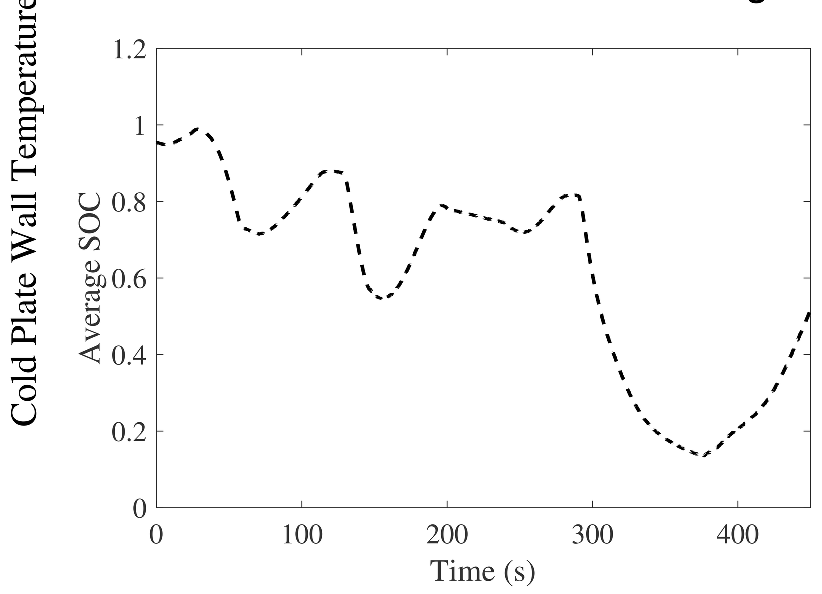


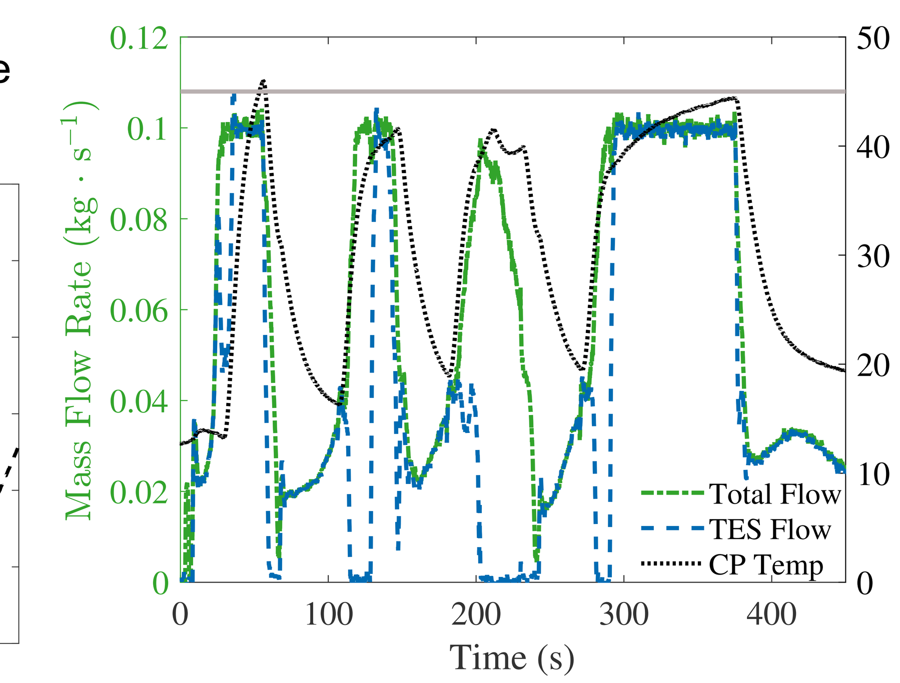
Left: Cold plate disturbance profile

- Decreasing load to demonstrate NMPC solution near soft constraint boundary
- Sustained loading to show significant TES usage.



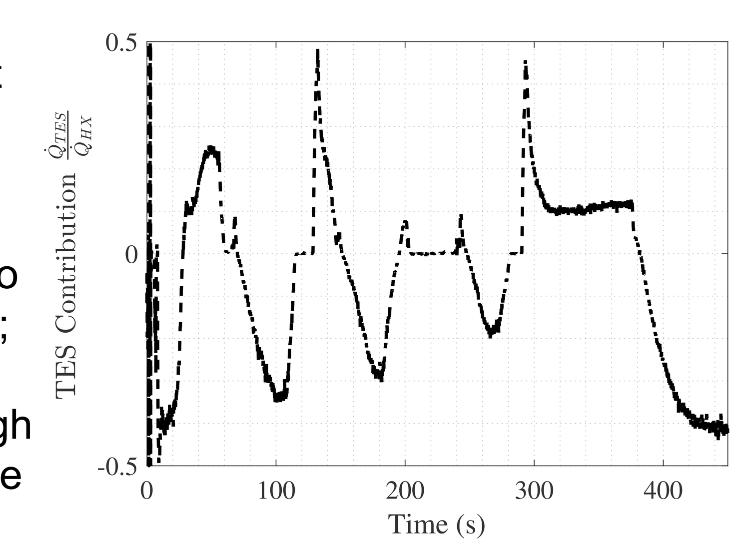
Left: Simulated closed loop response
Right: Measured closed loop response
Below: Measured TES state of charge

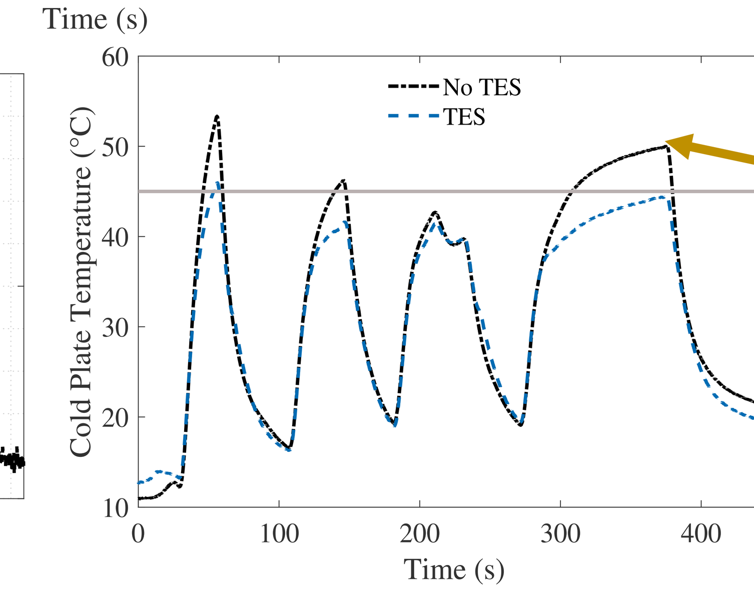




Right: Ratio between heat transfer to TES and heat transfer through HX.

- TES is placed downstream of the HX to maximize heat rejection; This results in relatively less heat transfer through the TES compared to the HX.





Left: Cold plate temperature with and without TES

- TES can keep the cold plate 7°C cooler during peak loads
- Despite NMPC, the system without the TES is unable to keep the temperature below the barrier temperature.

Summary & Future Work

Key Contributions

- Real-time control with a nonlinear model predictive controller of a hybrid TES system.

Future Work

- Improve low level controllers.
- Utilize a more sophisticated power consumption cost function.
- Use control co-design approaches to fully optimize the system.

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