Closed-Loop Analysis of Thermal Energy Storage Device Arrangement in a Thermal Management System

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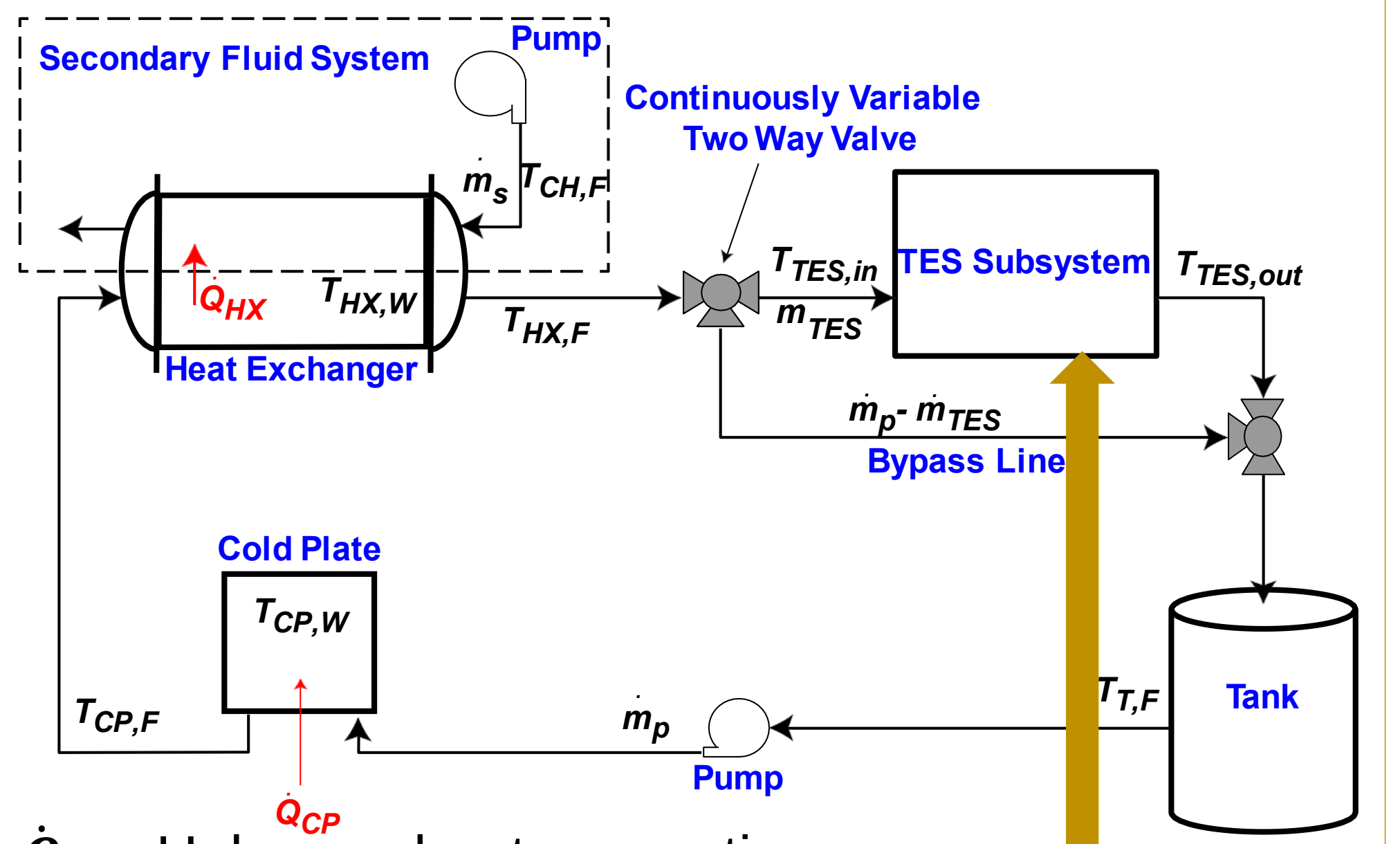
Motivation

- **Thermal management systems** (TMSs) integrated with phase-change **thermal energy storage** (TES) devices provide robustness against highly transient heat loads produced by electrical systems are called **hybrid TMSs**
- TES is designed to provide additional heat rejection capacity only when needed, so its operation must be **actively controlled**
- In the design of a particular hybrid TMS, **footprint and volumetric constraints** may play a decisive role in forming the feasible design space
- Geometric constraints may be alleviated by the arrangement of **multiple, smaller TES devices**
- **Closed-loop evaluation of hybrid TMS system performance is needed to characterize different TES arrangements**

Approach and Methodology

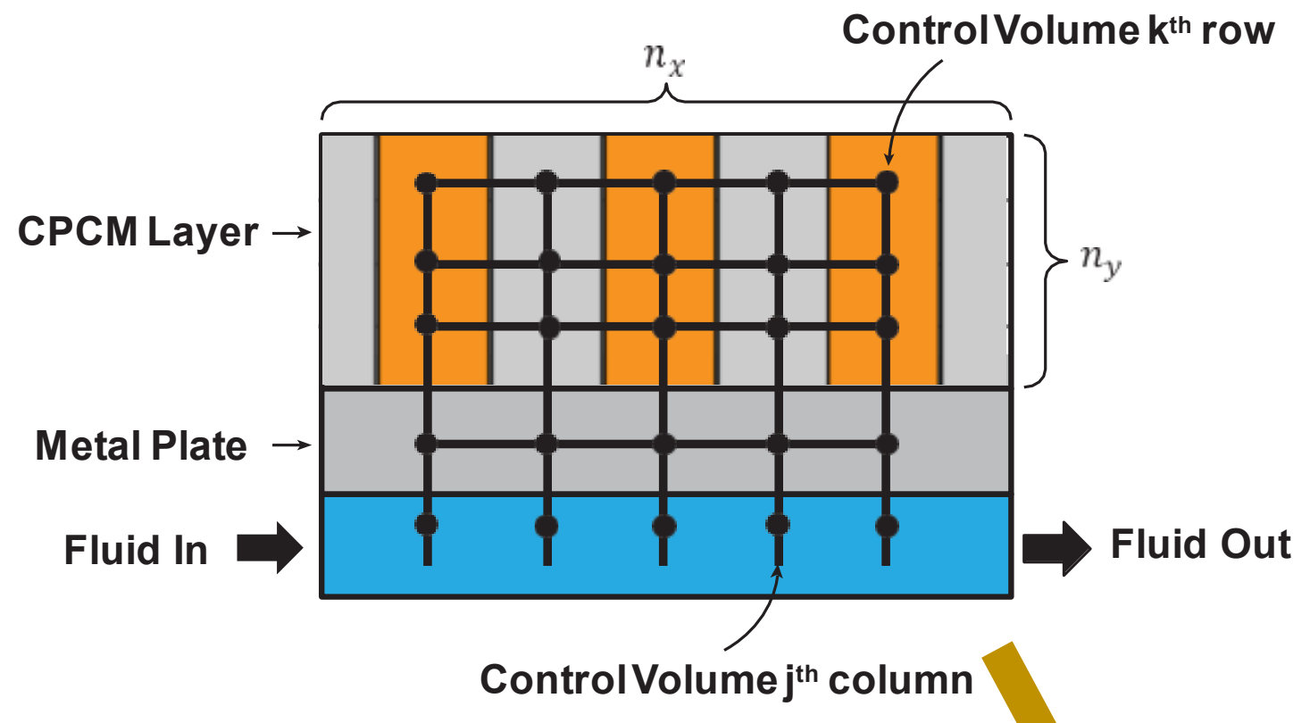
The **single-phase cooling loop** considered in this work is shown on the right. The cold plate and heat exchanger solid and liquid masses are each modeled as a **lumped parameter system**. In addition, the tank is modeled as a single state, assuming perfect mixing.

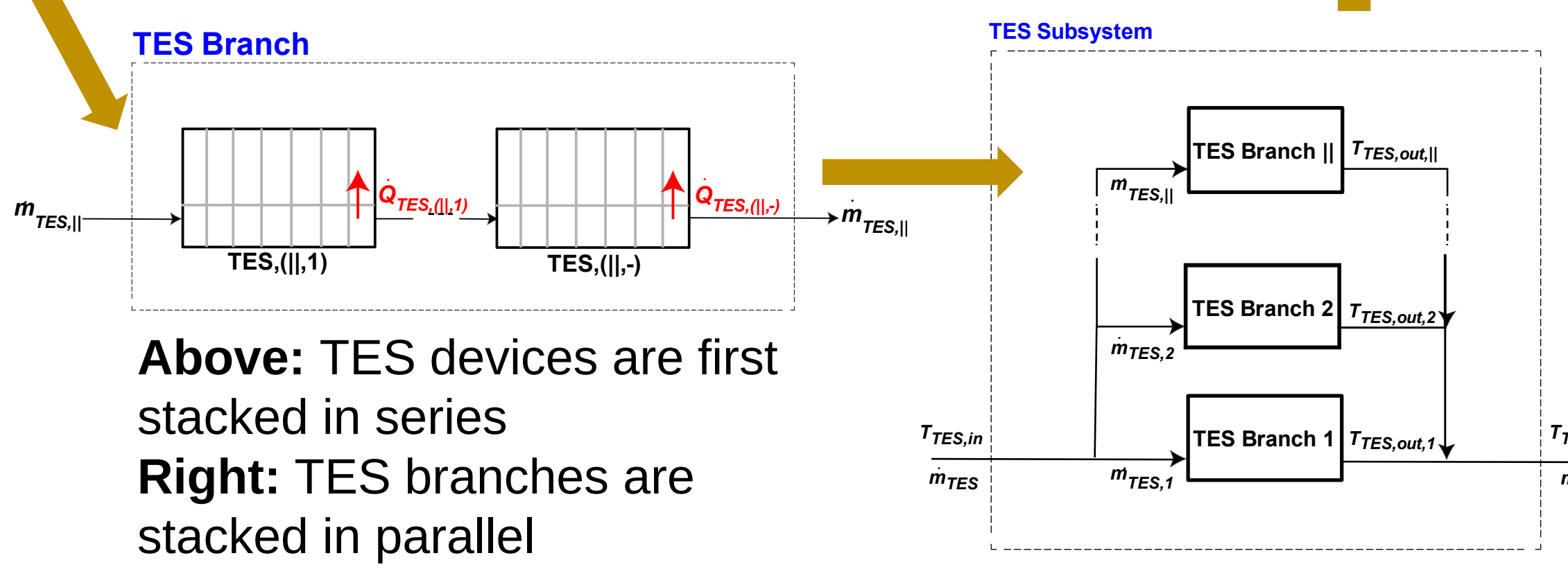
$\dot{Q}_{HX}$: State dependent heat transfer to a secondary cooling loop.



$\dot{Q}_{CP}$: 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**. Within the TES subsystem, the TES devices are allowed to be arranged in **arbitrary $n_{||}$ by n_{-} rectangular configurations**. The PCM and fins are tightly packed, such that they can be modeled as a composite.





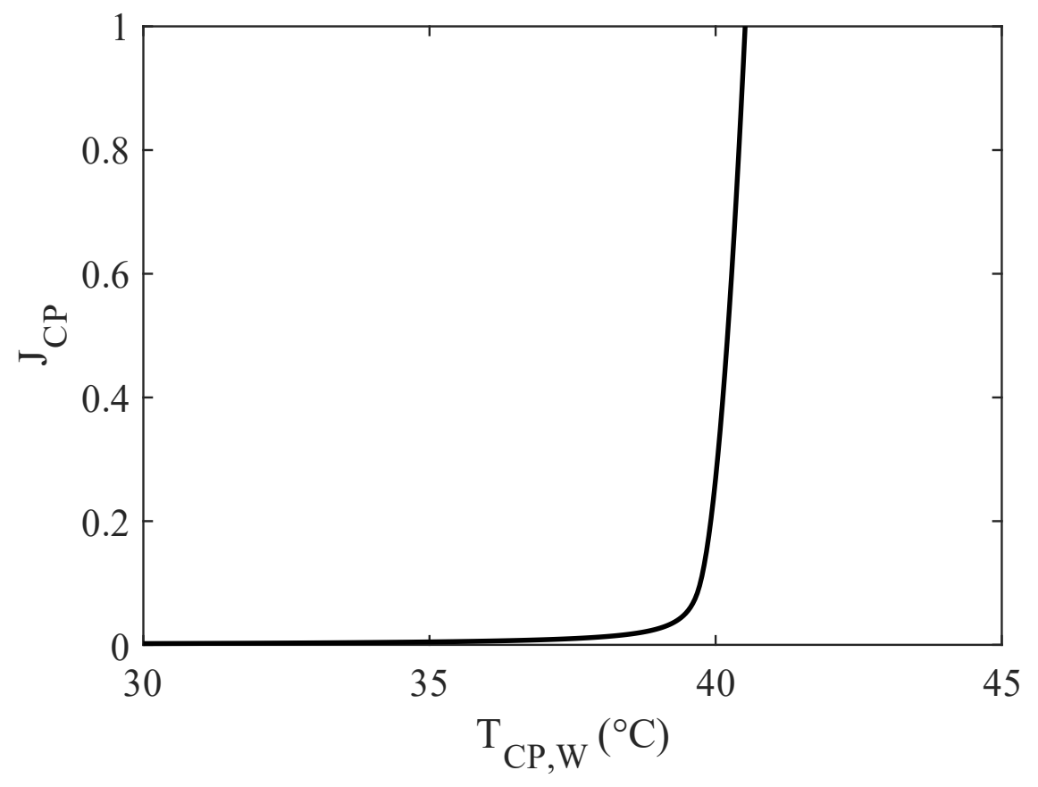
Above: TES devices are first stacked in series
Right: TES branches are stacked in parallel

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 modeling of arbitrary TES device configurations.

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

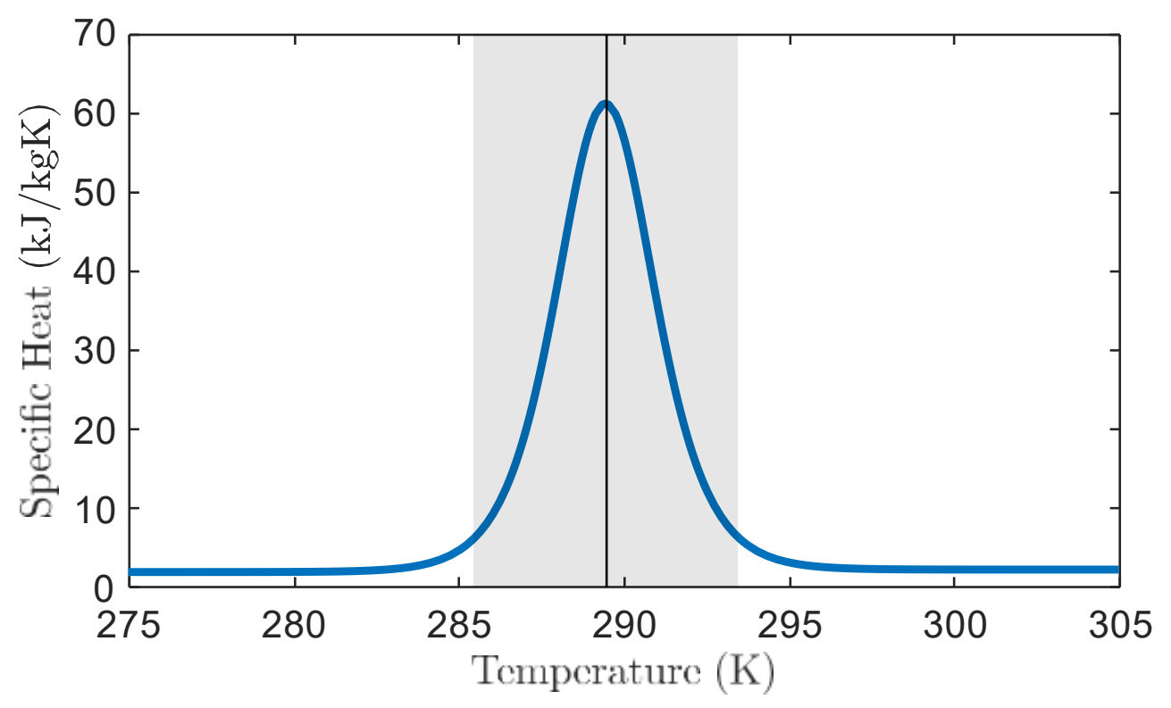
- Prediction model: **77 states, 2 control actions** (primary and TES branch mass flow rates).
- The multi-objective function J is comprised of 3 objectives.

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



Above: pseudo barrier function

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.



- **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 is mass flow rate is also penalized to **minimize actuator wear**.

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
$T_{CP,W,max}$	40	$°C$	Soft constraint max cold plate temperature
$T_{CH,F}$	8	$°C$	Chiller inlet temperature

Above: Table of important NMPC parameters

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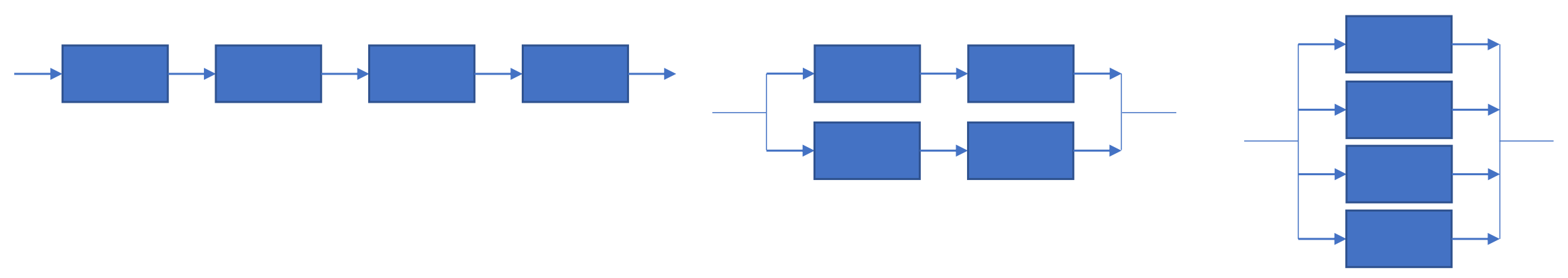
Case Study 1: Different Device Arrangements

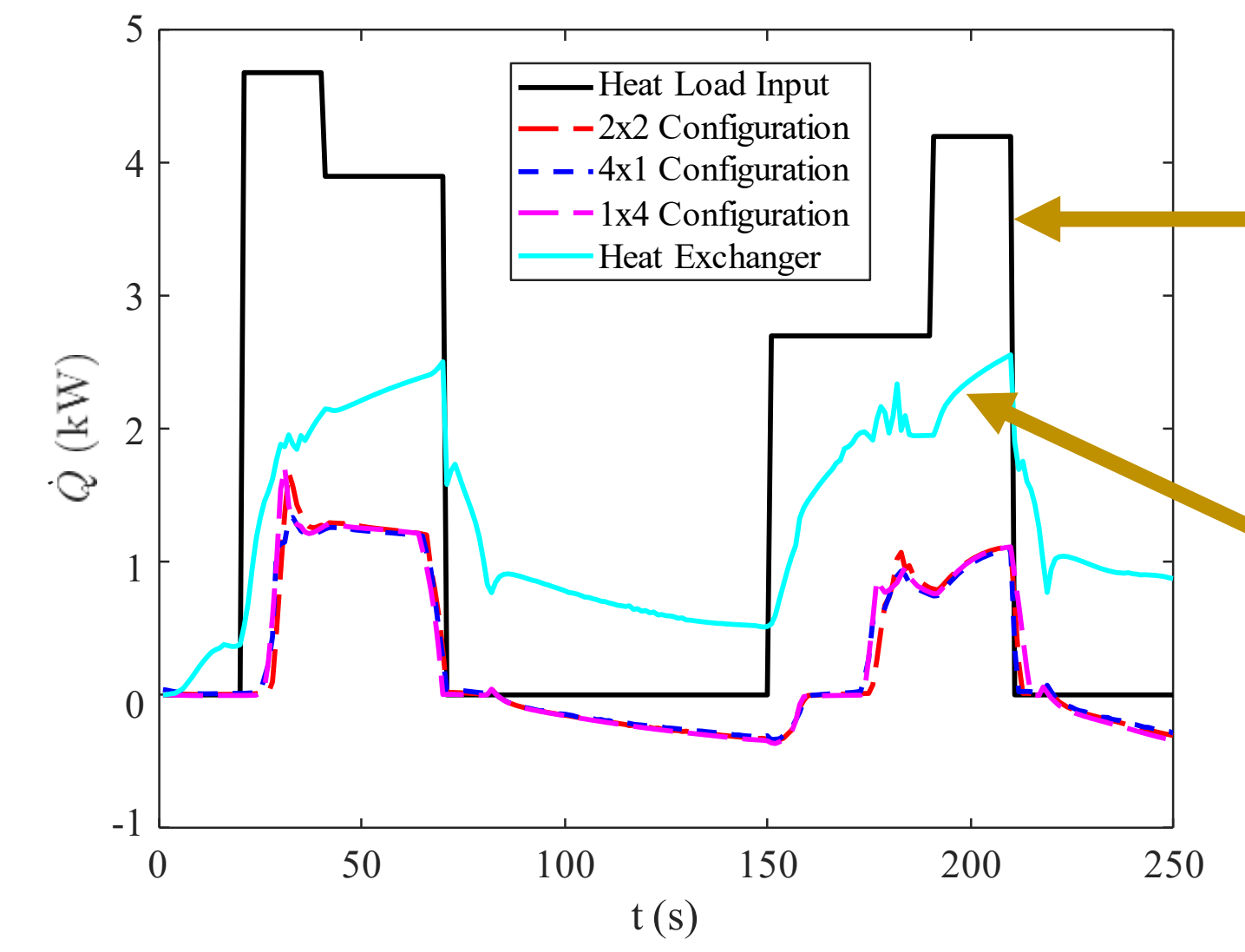
- 3 arrangements:
  - 1 x 4
  - 2 x 2
  - 4 x 1



- The initial temperature of the PCM composite is 10℃, and the initial temperature of all other states is 15℃.

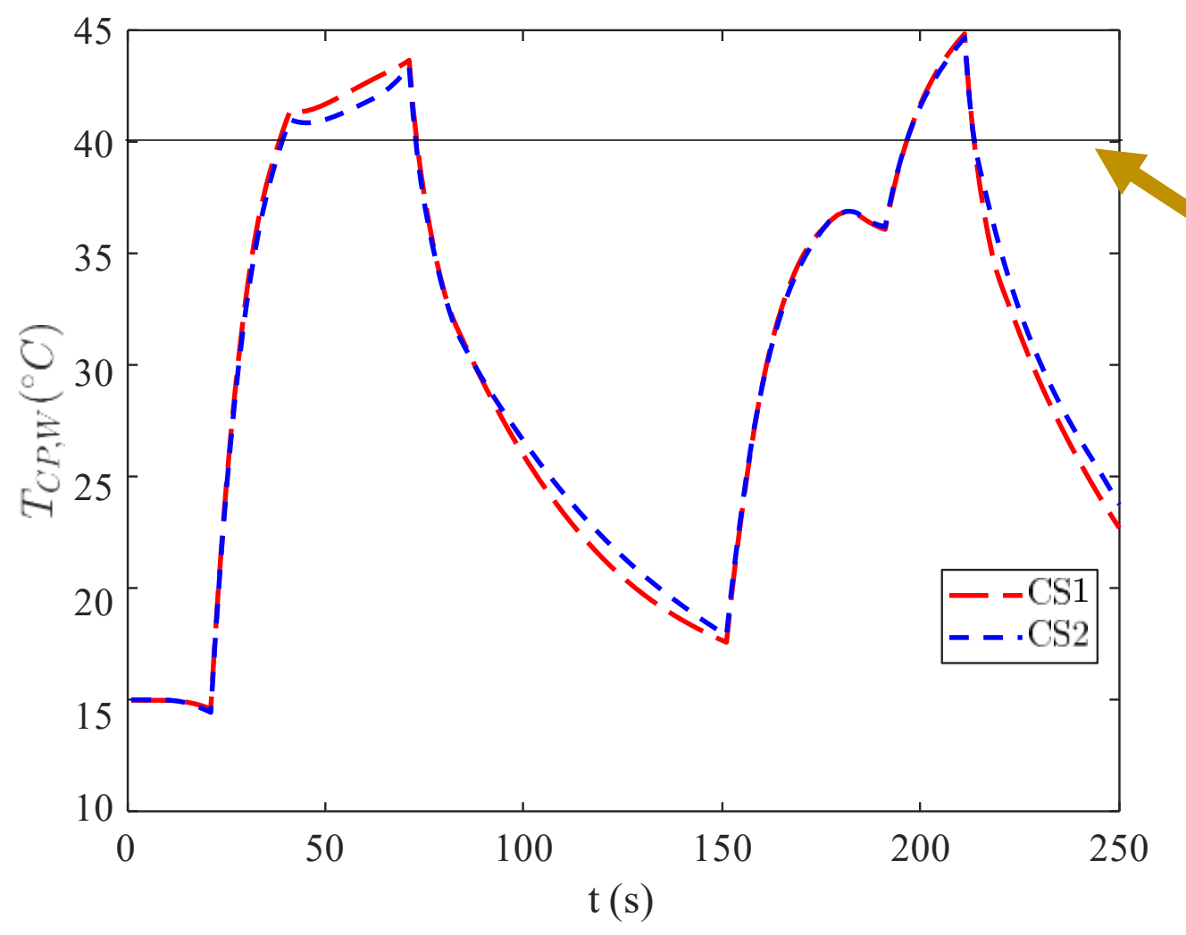
Main Takeaway:

- The **OCP for the parallel configuration is more complex** because each parallel branch has its own control action.
- The system curves for each configuration indicate that **series (1x4) is the least power efficient**.



Left: Heat load profile and heat rate for case study 1

- Significant heat load to test response when cold plate exceeds soft constraint temperature
- Most heat through HX because it is placed before the TES

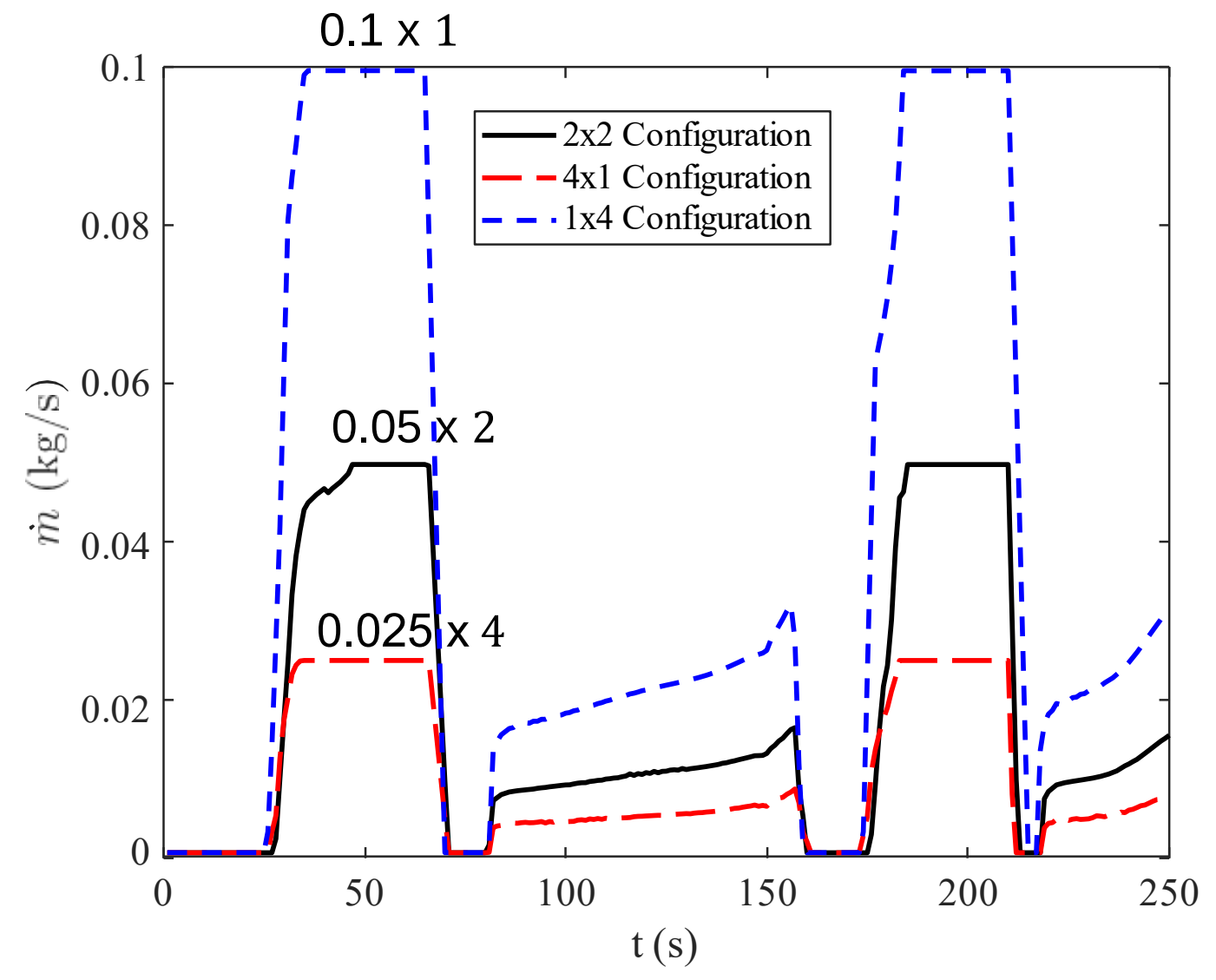


Left: CP temperature between case studies

- CP temperature exceeds the soft constraint in both case studies.

Right: Closed Loop Control Action for case study 1

- Total TES mass flow rate is the same for each configuration
- Mass flow rate through each branch is split evenly, though different mass flow rates were allowed

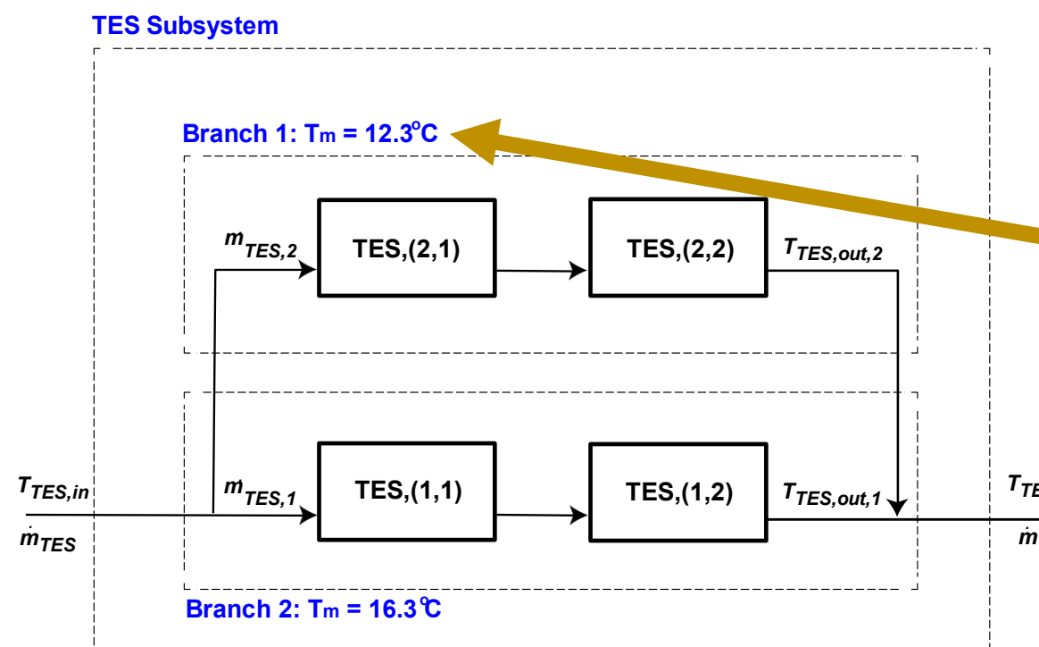


Case Study 2: Different Melting Temperatures

- The focus is on the 2x2 configuration
- Same heat load & initial conditions as case study 1

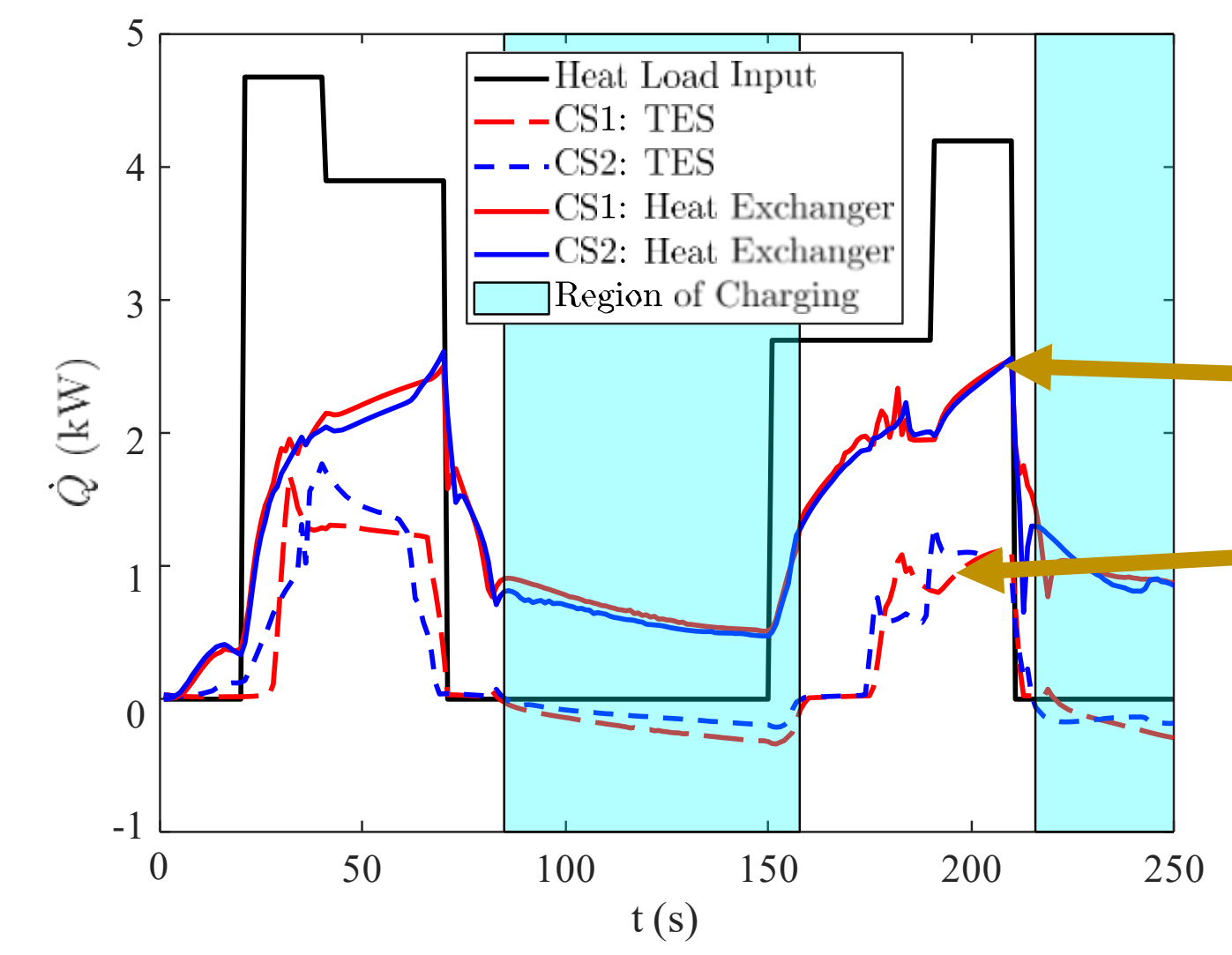
Main Takeaway:

- In fluctuating ambient conditions, different melting temperatures may **absorb less total energy from the environment** than equal
- Control actions change more often, leading to **more actuator wear**



Left: TES subsystem configuration for case study 2

- Branch one melting point is reduced
- All other material properties the same

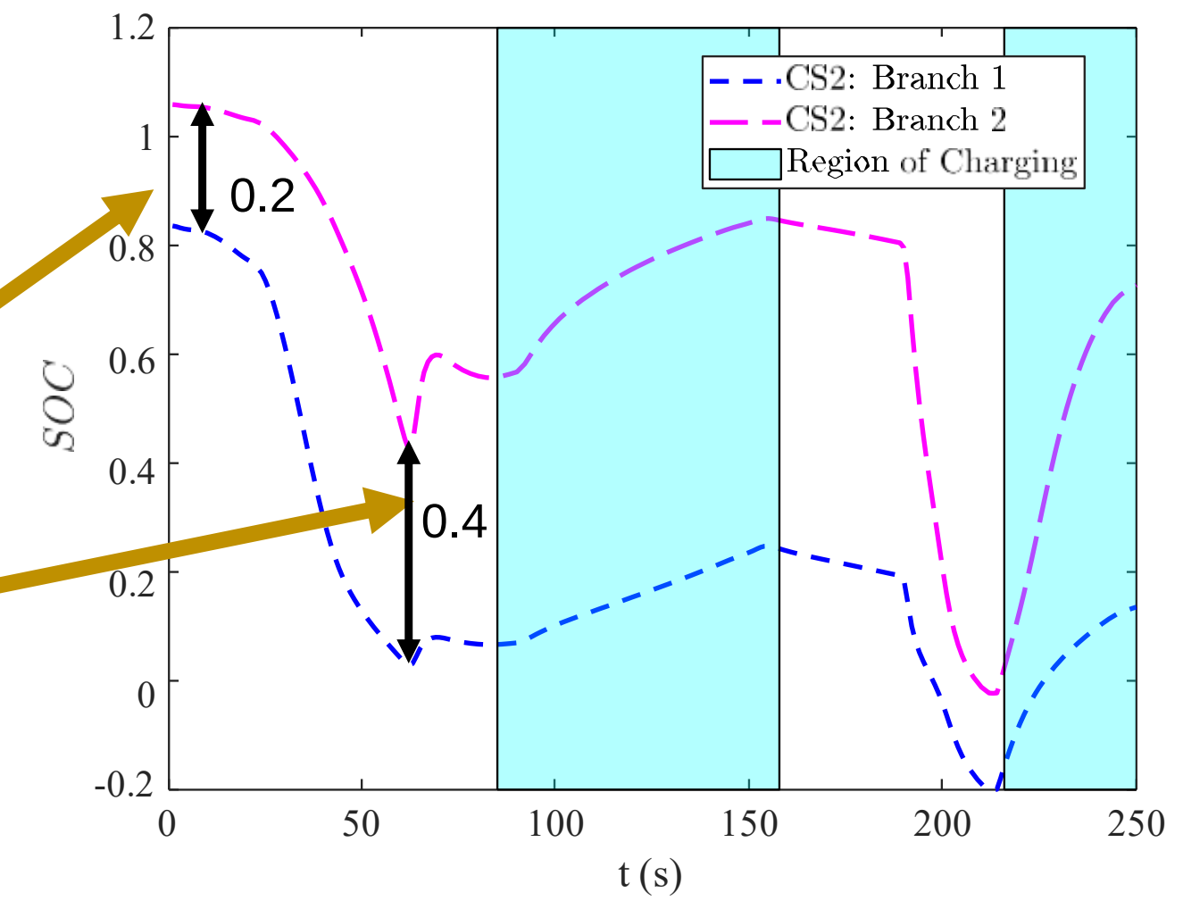


Left: Heat Load Profile and heat rate comparison between case studies

- HX energy rate remains the same
- TES energy rate is different

Right: SOC for case study 2

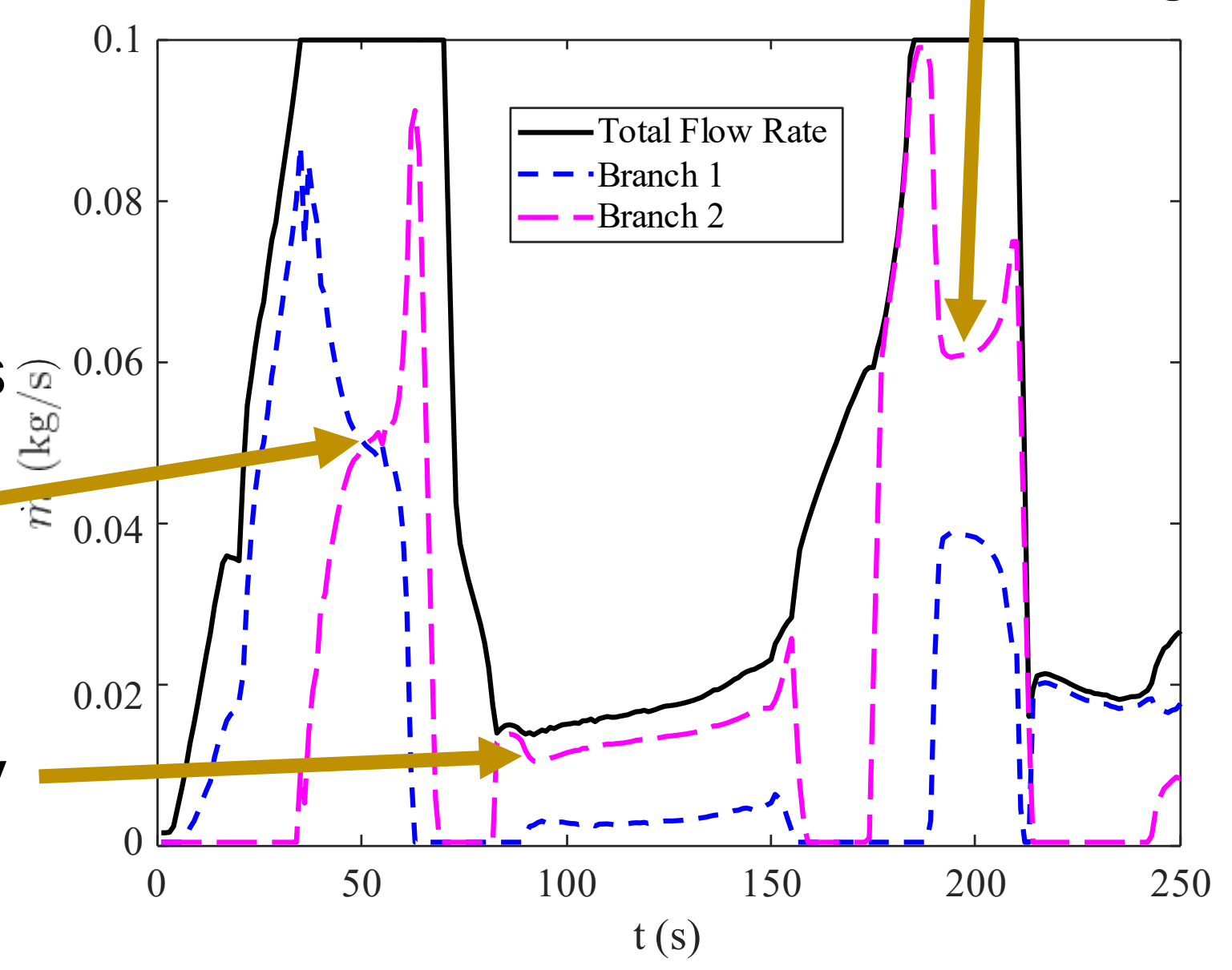
- Lower melting point reduces initial SOC
- Difference is SOC increases during discharge



After mostly melting branch 2, both branches are used for cooling

Right: Closed Loop Control Action for case study 2

- mass flow rate switches to branch 2 after discharging branch 1
- When recharging, the higher melting point TES is preferred initially



Summary & Future Work

Key Contributions

- Related TES subsystem configuration and PCM phase change properties to transient performance evaluation via scalable modeling.

Future Work

- Explore how **different ambient environments** affect TES devices with different melting points.
- Investigate how **different disturbance profiles** impact results
- Experimentally **validate expected system curves** for each TES subsystem configuration

Acknowledgements

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