Control Co-Design of a Thermal Management System with Integrated Latent Thermal Energy Storage and a Logic-based Controller

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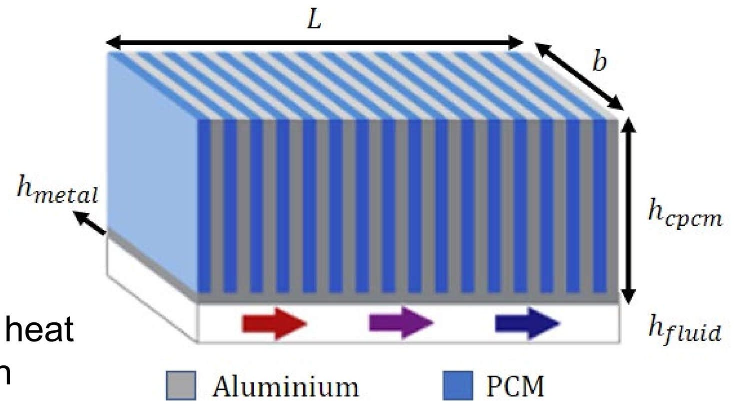
Motivation

- **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**
- Typically, the TES device and its controller are designed independently of one another in a sequential design process
- TES devices designed independently may not satisfy system level requirements
- **Designing the TES device and its controller simultaneously using control co-design is needed to ensure consideration of system requirements**

Above: NASA's X-57 Electric Aircraft *(source: www.nasa.gov)*

Below: a rectangular plate-fin TES



Approach and Methodology

Pictured to the right is a schematic of the single-phase cooling loop model used in this work. The simulation of the TMS uses low-order models for the heat exchanger, the cold plate, and the tank and a high-order model for the TES device. The combine metal and PCM layer is referred to as composite PCM (CPCM) layer.

The controller directs the flow of fluid through the TES according to two conditions: discharging (C_D) and recharging (C_R).

- **Discharging** takes place when the temperature of the tank fluid (T_{tf}) is greater than the controller discharge temperature and there is PCM available in the TES to absorb the heat.
- **Recharging** takes place when the temperature of the TES device is greater than the fluid existing the heat exchanger.

$$C_D \coloneqq \{(T_{tf} > \bar{T}_{tf}) \wedge (SOC > 0)\}$$
$$C_R \coloneqq \{T_{hx} < T_{TES}\}$$

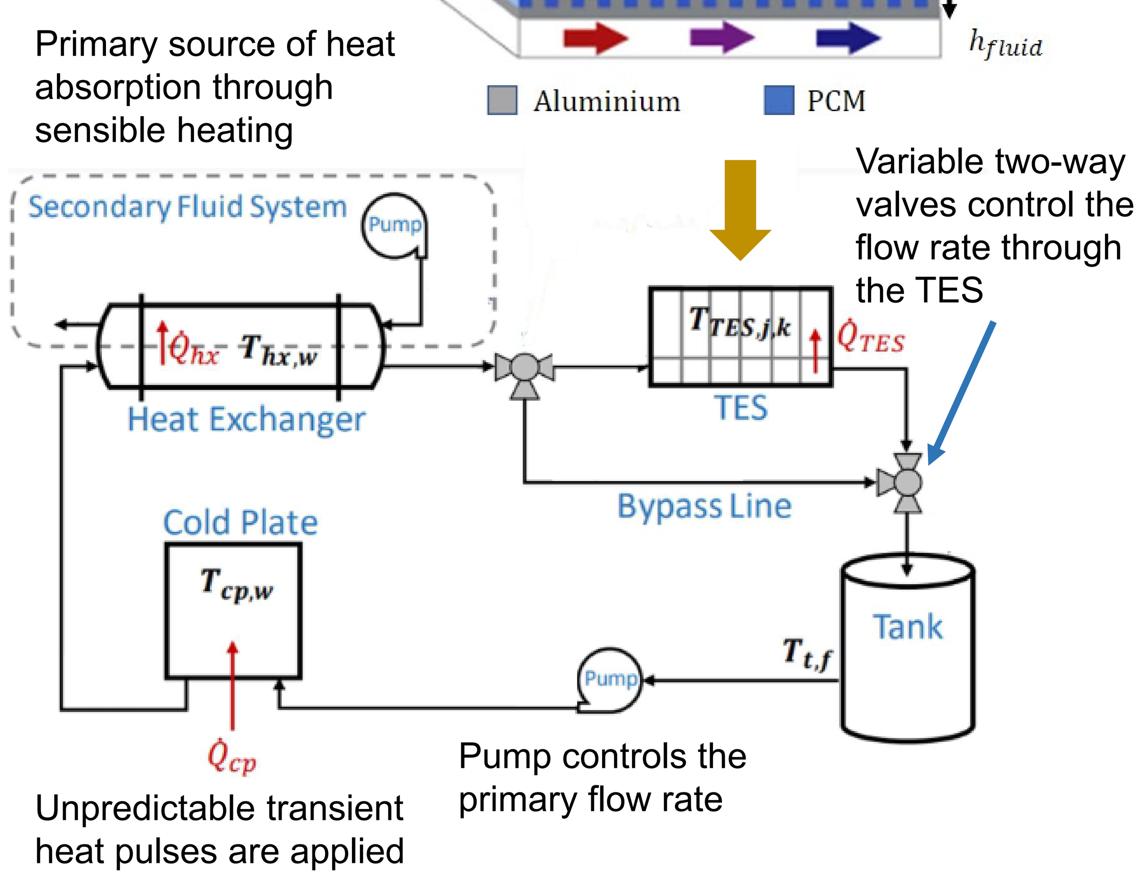


Table: controller logic table

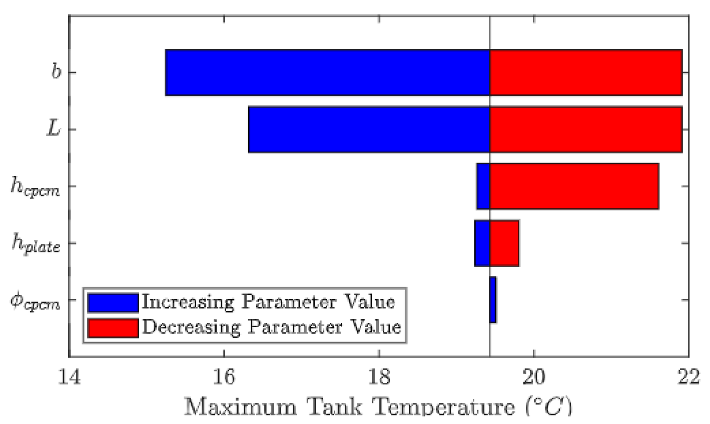
C_D	C_R	Controller Mode	Control Action
False	True	Recharge	Maximum TES flow rate
True	False	Discharge	Maximum TES flow rate
True	True	Bypass TES	Zero flow through TES
False	False	Bypass TES	Zero flow through TES

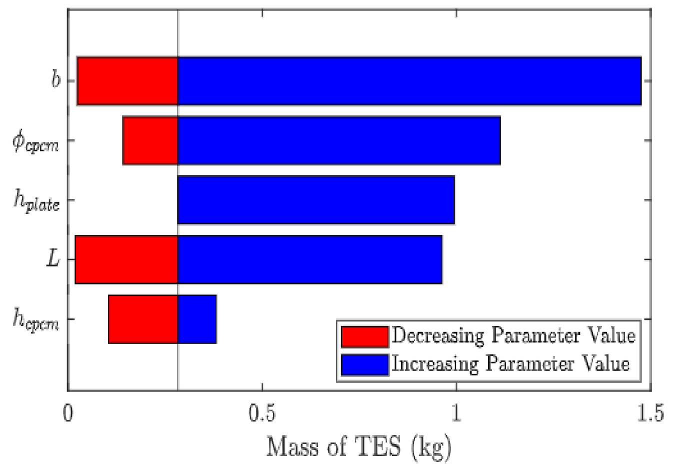
State of charge (SOC) is a measure of the remaining energy storage capacity of the TES.

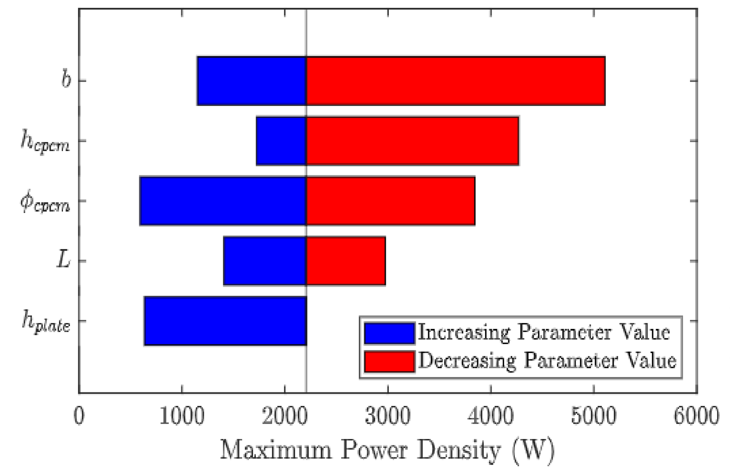
- A value of 1 means the PCM is at its minimum temperature and is fully liquid.
- A value of 0 means the PCM is at its maximum temperature and is fully liquid.

Sensitivity analysis of TES design parameters that affect system level objectives:

- Maximum tank temperature
- Maximum power density
- Mass of TES device



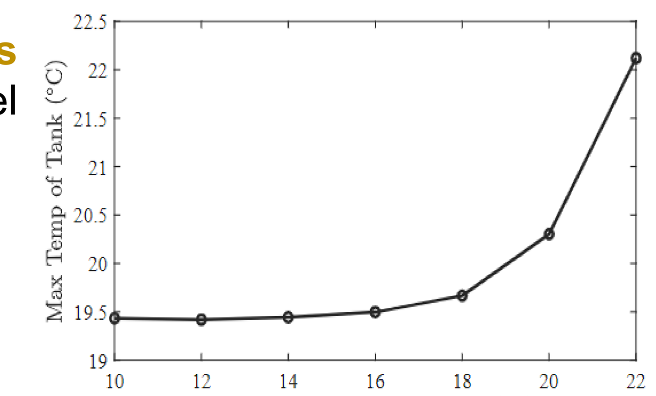


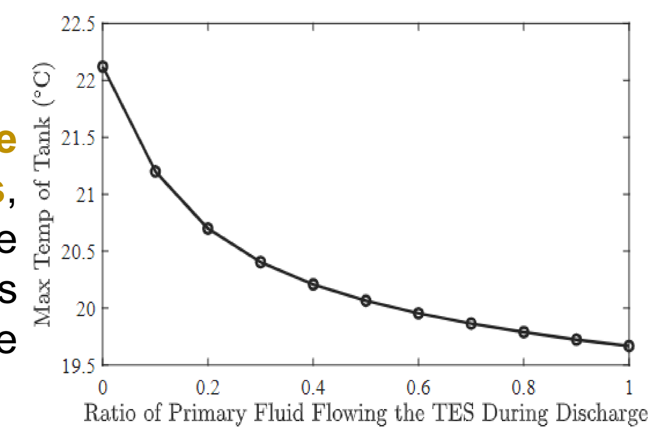


Four TES parameters effect all system-level objectives significantly:

- Length (L)
- Width (b)
- Height of CPCM (h_{cpcm})
- Metal fraction of CPCM (ϕ_{cpcm})

Increase of **one of the controller parameters**, the TES discharge temperature, increases the tank temperature and must be optimized.





Above: controller parameters do not have affect TES requirements, only tank fluid temperature.

Case Study

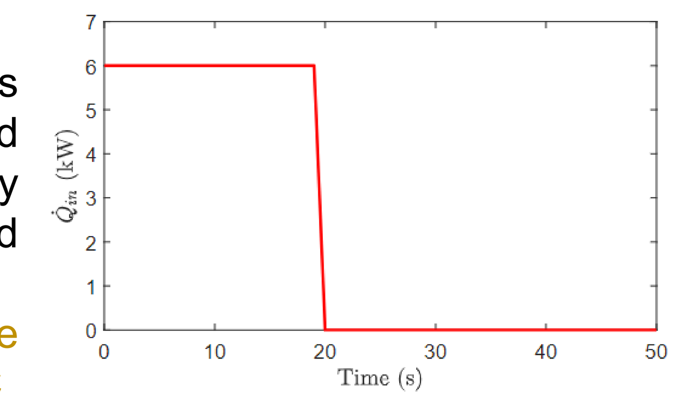
The following case study demonstrates that the TES design is sensitive to the heat load it will be used to absorb. The TES and controller were designed using the control co-design strategy for two different heat loads: A (a fairly constant heat load), and B (a more transient heat load).

Goal: minimize tank temperature for a TES device no more than 1 kg that can keep the cold plate temperature under 50 °C

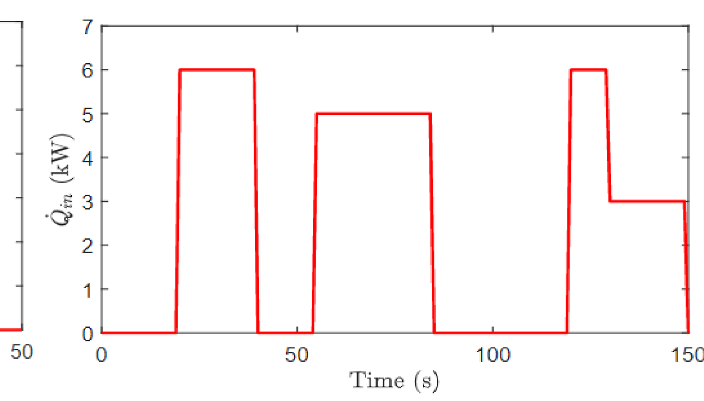
Benchmark System

- Hybrid TMS designed in a sequential manner.
- TES device was optimized to maximize power density independent of controller and incoming heat load.
- Optimized TES design simulated with the controller parameters from CCD B

Below: heat load A



Below: heat load B



CCD A: TES and controller device optimized for heat load A
CCD B: TES and controller device optimized for heat load B
CLO: Component level optimization of benchmark system

Variable	CCD A	CCD B	CLO
V_{cpcm}	240.46 cm^3	352.28 cm^3	167.94 cm^3
$\bar{T}_{tf}$	13.17 C	16.06 C	16.06 C
T_{tf}^{max}	14.34 C	16.64 C	17.38 C
P_{TES}^{avg}	2.3 kW	2.2 kW	2.3 kW

Table: comparison of optimized design results

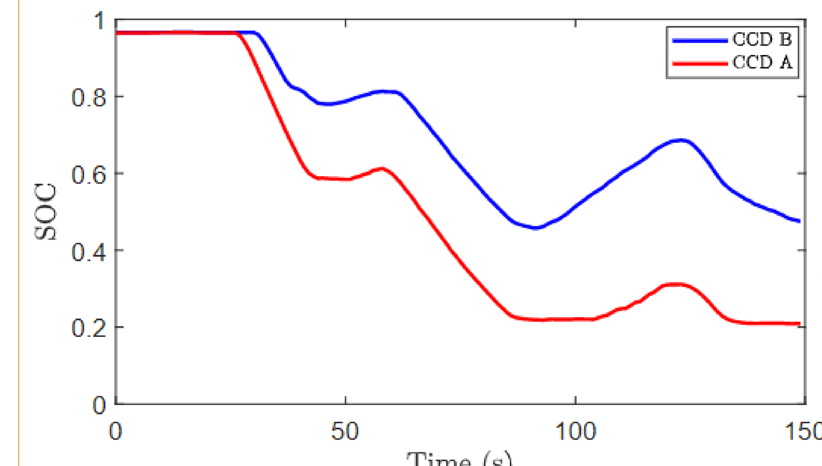
The most significant difference amongst the three designs is the **volume of the CPCM layer**:

- TES device from CCD B has ~32 % more PCM by volume than TES device from CCD A
- TES device from CCD B has ~52 % more than the benchmark CLO TES device.

This is because TES device from CCD B was **designed for a transient heat load** and thus was optimized to have more PCM by volume for future unexpected heat loads and controller parameters chosen to conserve SOC.

CCD A v/s CCD B: TES device from CCD B outperforms TES device from CCD A when simulated against heat load B:

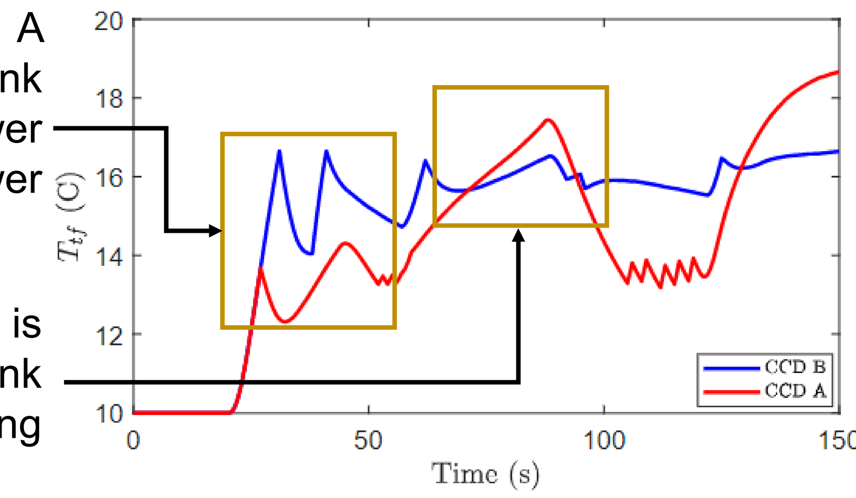
- **More PCM by volume** demands less recharging of TES.
- **Higher discharge temperature** conserves SOC while achieving system objectives



Higher SOC remaining at the end of the simulation makes TES device from CCD B more robust to transient heat load without requiring much recharging.

TES device from CCD A maintains the tank temperature at a lower value due to lower discharge temperature.

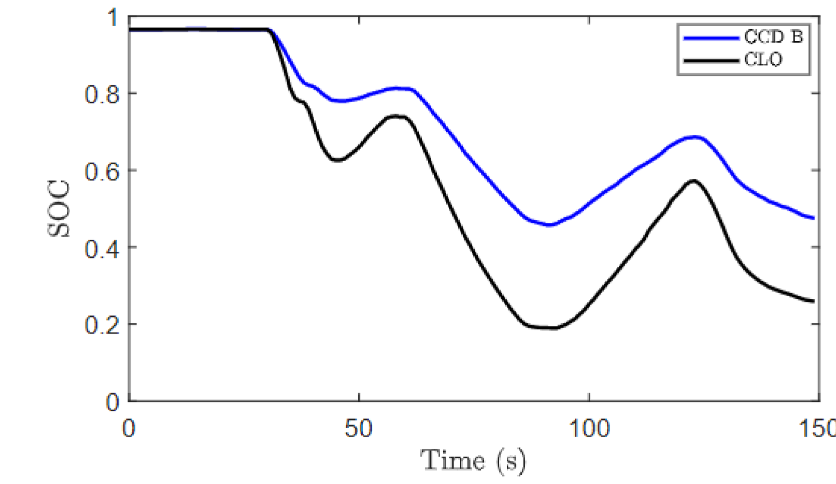
TES device from CCD A is unable to sustain the tank fluid temperature for long heat pulses.



CCD B v/s CLO : Simulating the two TMSs against heat load B at the same discharge temperature obtained from CCD B as the CLO designed TES does not have a controller of its own.

TES from CCD B outperforms the TES from CLO against a transient heat load:

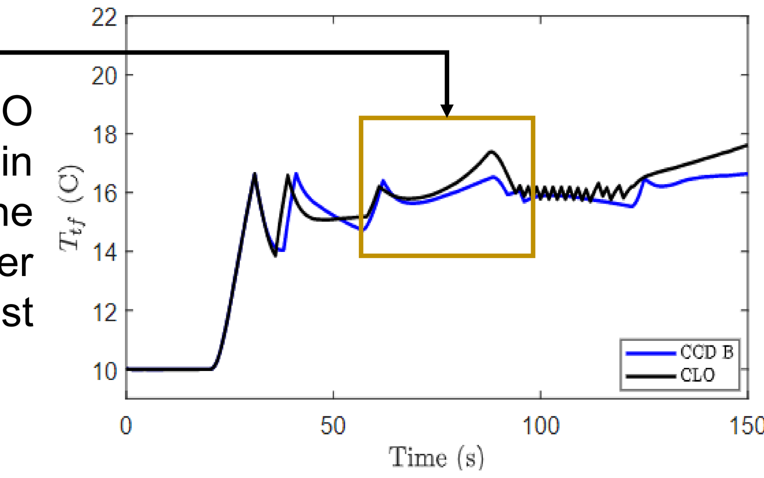
- It requires less recharging and has more SOC remaining due to **higher PCM by volume.**
- TES device from CLO relies on recharging as it maximizes for power density **at the cost of the volume of the PCM.**



TES from CLO uses more SOC and relies heavily on recharging to mitigate future heat loads.

The performance of the CLO optimized TES device changes with the controller conditions.

TES device from CLO is unable to maintain the temperature of the tank fluid for longer heat pulses due to fast SOC consumption.



Summary & Future Work

Key Contributions

- CCD solutions proposed TES devices with higher PCM by volume than CLO optimized TES due to consideration of heat loads, making them more robust to future unexpected heat loads.
- CCD solutions are sensitive to expected heat loads considered in optimization.

Future Work

- Development of more advanced CCD algorithms to account for sets of possible heat loads.

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