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INTEGER TECHNOLOGIES

UNIVERSITY OF South Carolina

Real-Time Blockage Detection and Autonomous Recovery in Liquid-Cooled Systems Using Digital Twins

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Overview of Blockage Detection

Objective:

- Detect blockage formation within liquid-cooled power electronic systems.

Importance:

- Vital to maintaining the continued operational capacity of a ship`s systems.

Approach:

- Use Digital Twin (DT) technology.
- Compare thermal data.
- Dissimilarity indicates blockage formation.

DDG 51 Arleigh Burke class destroyer. Military.com. (n.d.).
https://www.military.com/equipment/ddg-51-arleigh-burke-class-destroyer

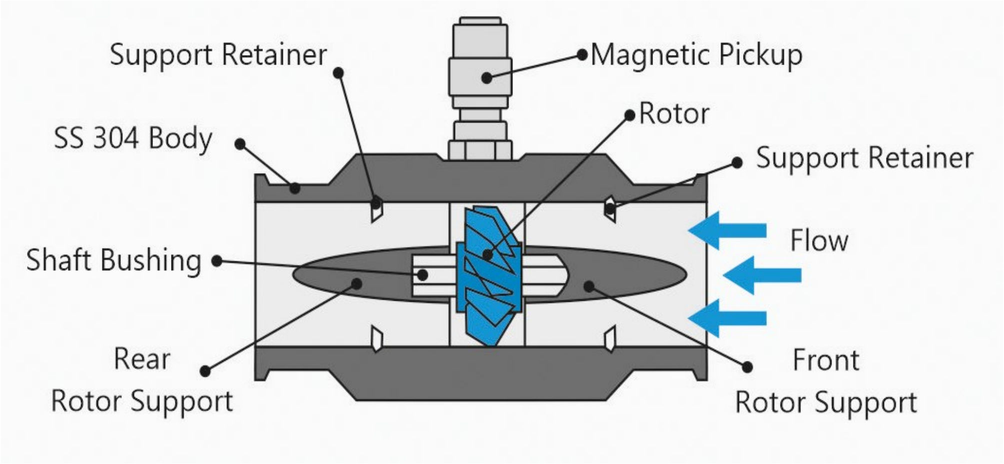
Why not use a flow transmitter?

Drawbacks of Flow Transmitters:

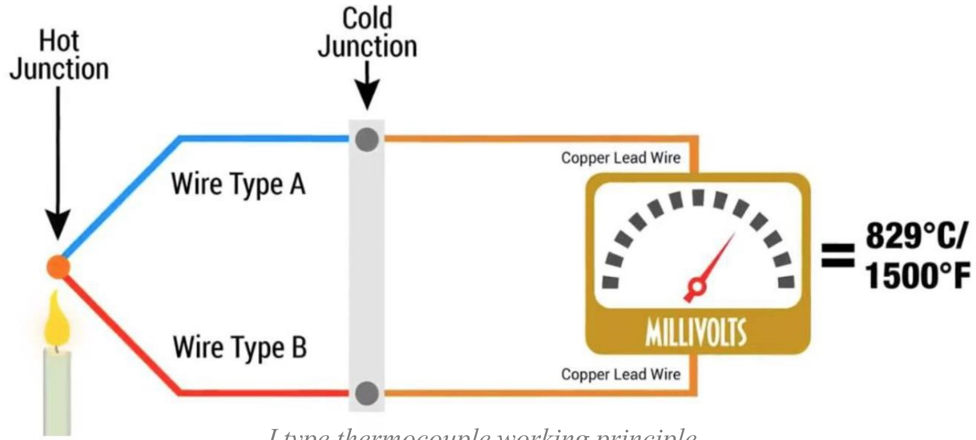
- Maintenance.
- Inline space requirements.
- Turbine models prone to jamming and damage.
- Relatively expensive.

Benefits of Temperature Sensors:

- Relatively inexpensive.
- Smaller inline profile.
- Low maintenance.
- Often preinstalled to liquid cooled power electronics.



Turbine flow transmitter cross section
https://en.enelsan.com/data-base/how-turbine-flow-meter-works



J type thermocouple working principle
MIL-DTL-26482 Series 2 Thermocouple Contacts | MILNEC

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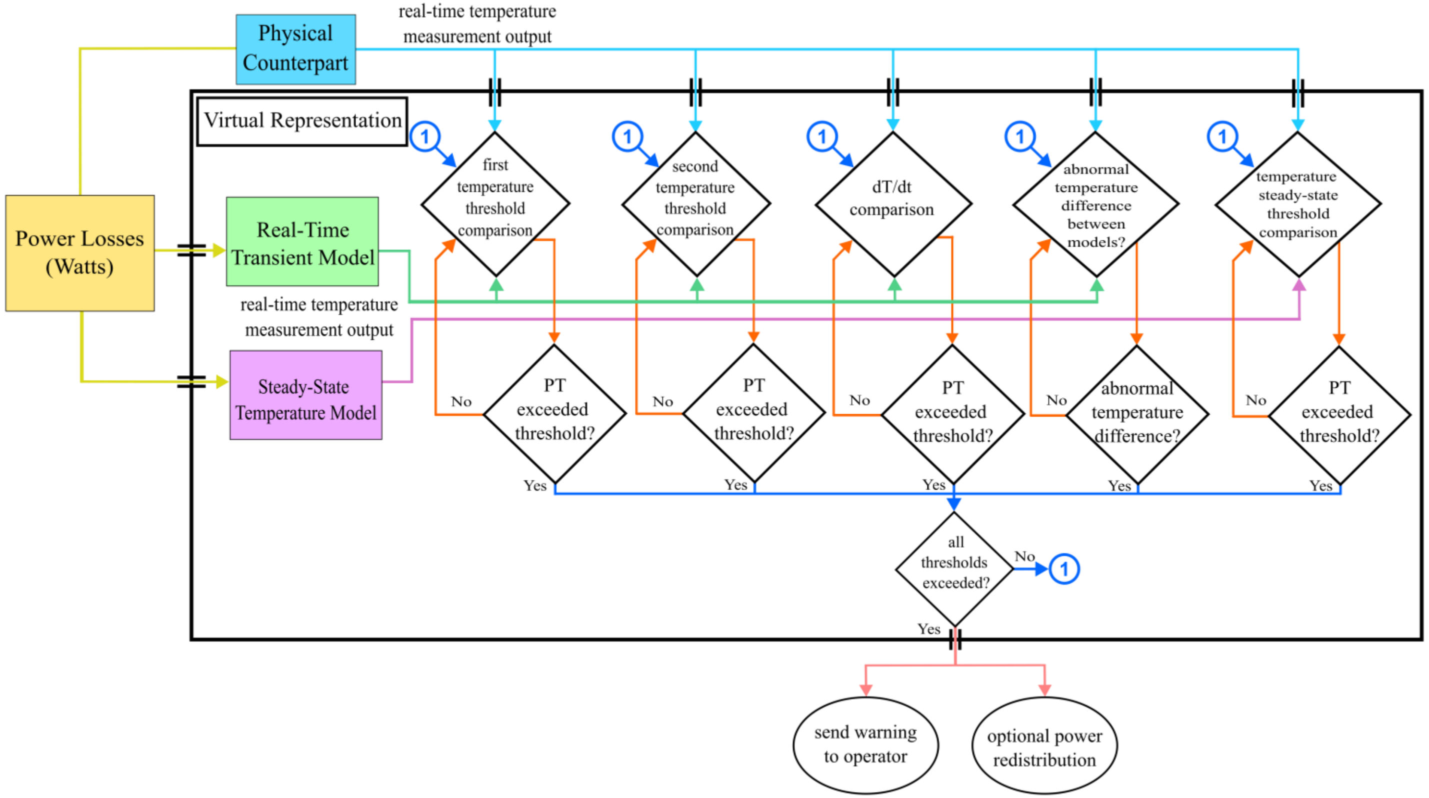
Blockage Detection Approach

- Create a digital model of the physical system.
- Read real-time data from model and physical system.
- Perform checks based on predefined operational thresholds (ϵ):
  - Check 1: $T_{PT} - T_{DT} > \epsilon_{T1}$
  - Check 2: $T_{PT} - T_{DT} > \epsilon_{T2}$
  - Check 3: $|\left(\frac{dT}{dt}\right)_{PT} - \left(\frac{dT}{dt}\right)_{DT}| > \epsilon_{\frac{dT}{dt}}$
  - Check 4: $|(\Delta T_{n-m})_{PT} - (\Delta T_{n-m})_{DT}| > \epsilon_{CL}$
  - Check 5: $T_{PT} - T_{DT_{ss}} > \epsilon_{ss}$



Normal vs Blocked Behavior

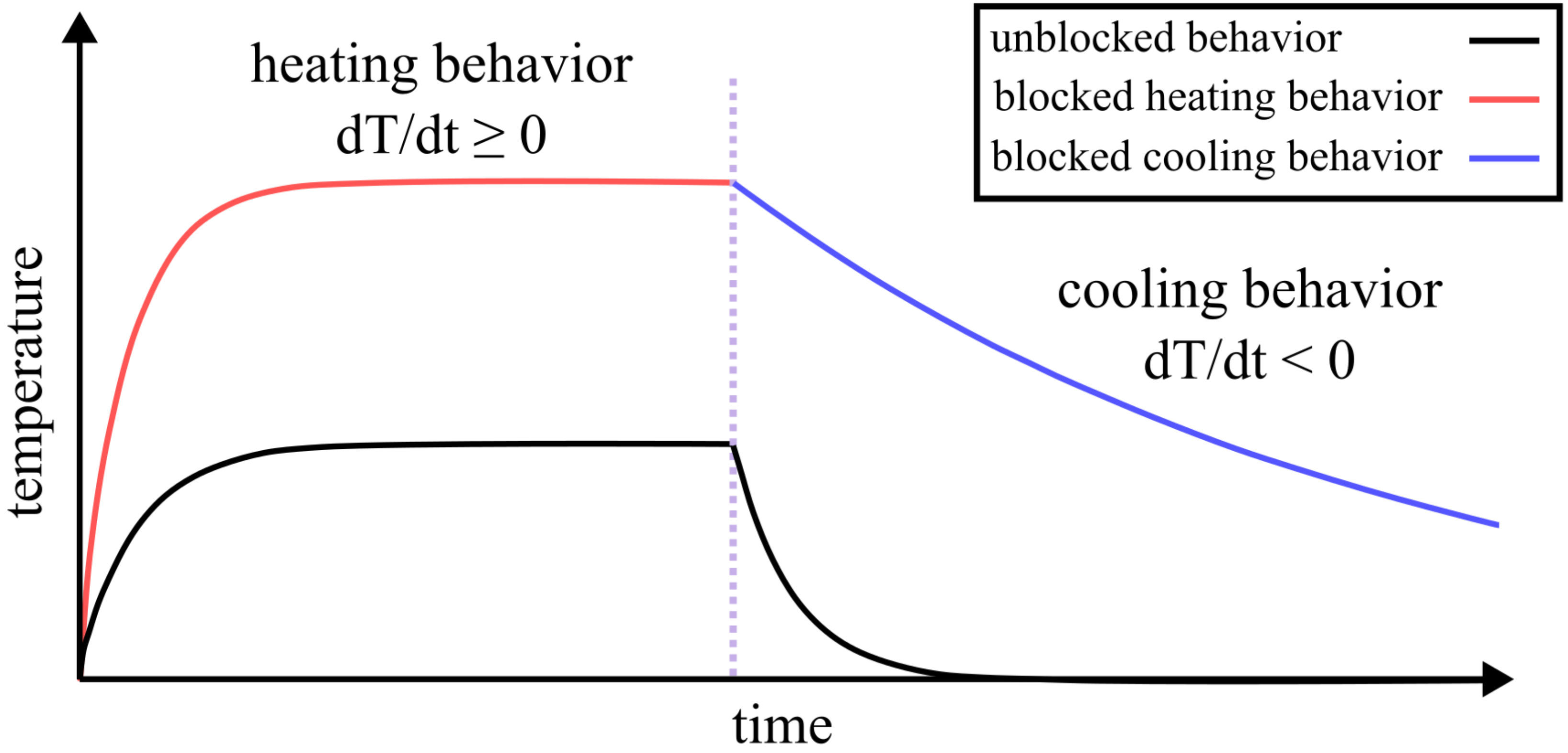
- DT calculates change in temperature over time ($\frac{dT}{dt}$), steady-state, and transient temperatures.

Blocked heating behavior:

- $\left(\frac{dT}{dt}\right)_{PT} > \left(\frac{dT}{dt}\right)_{DT}$
- $T_{PT} > T_{DT}$

Blocked cooling behavior:

- $\left(\frac{dT}{dt}\right)_{PT} < \left(\frac{dT}{dt}\right)_{DT}$
- $T_{PT} > T_{DT}$



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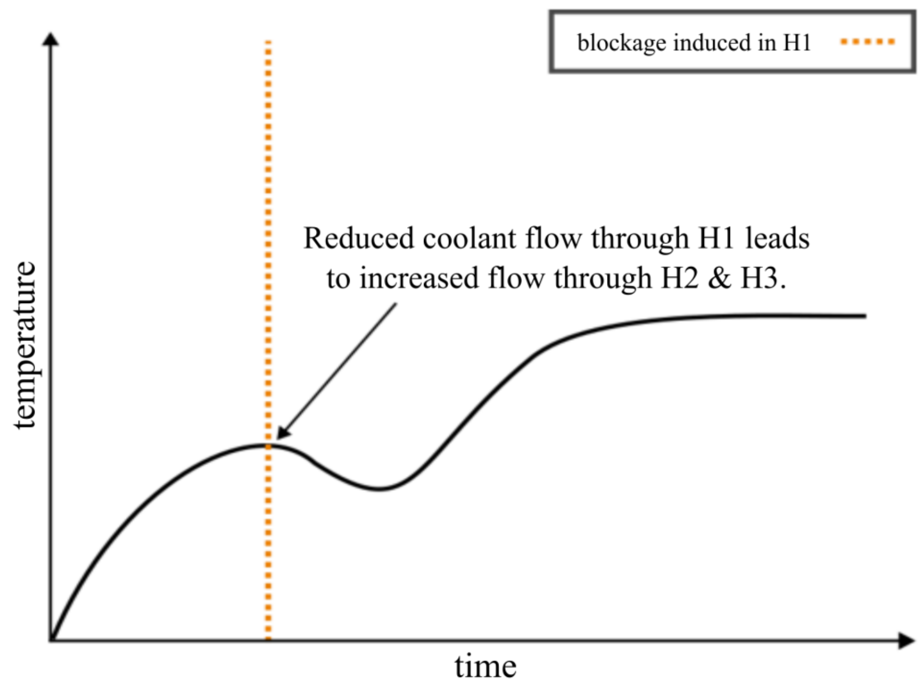
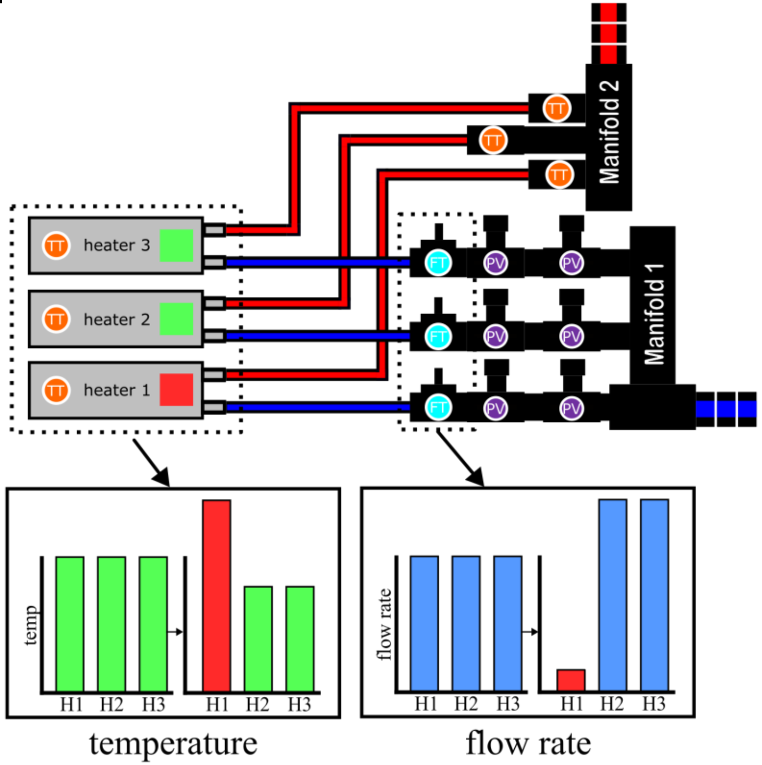
Effect of Blockage on Neighboring Converters

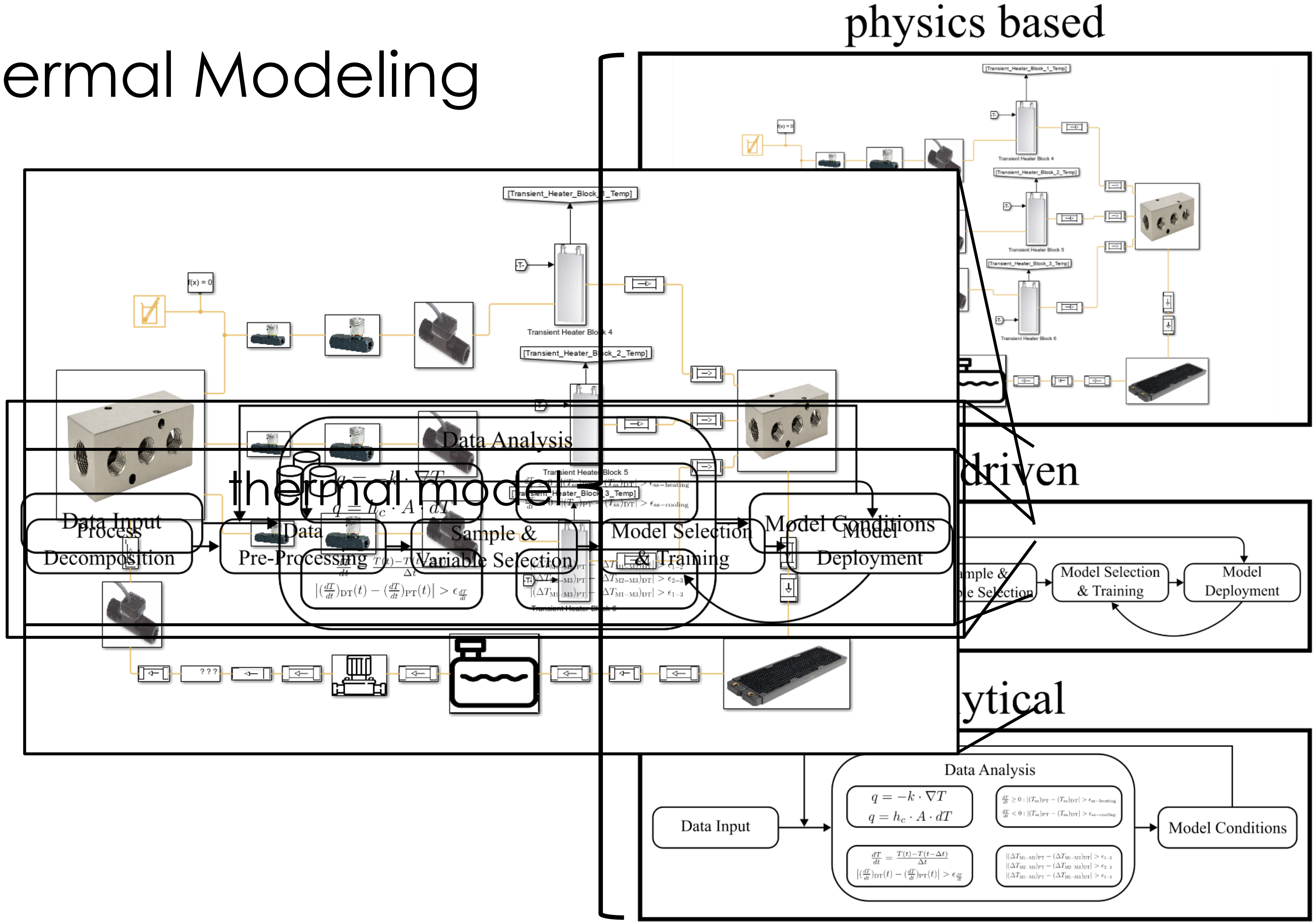
- Coolant flow to neighboring electronic modules increases when a blockage forms in one module.
- Increased coolant flow increases heat transfer in neighboring units.
- Increased heat transfer decreases transient temperature.





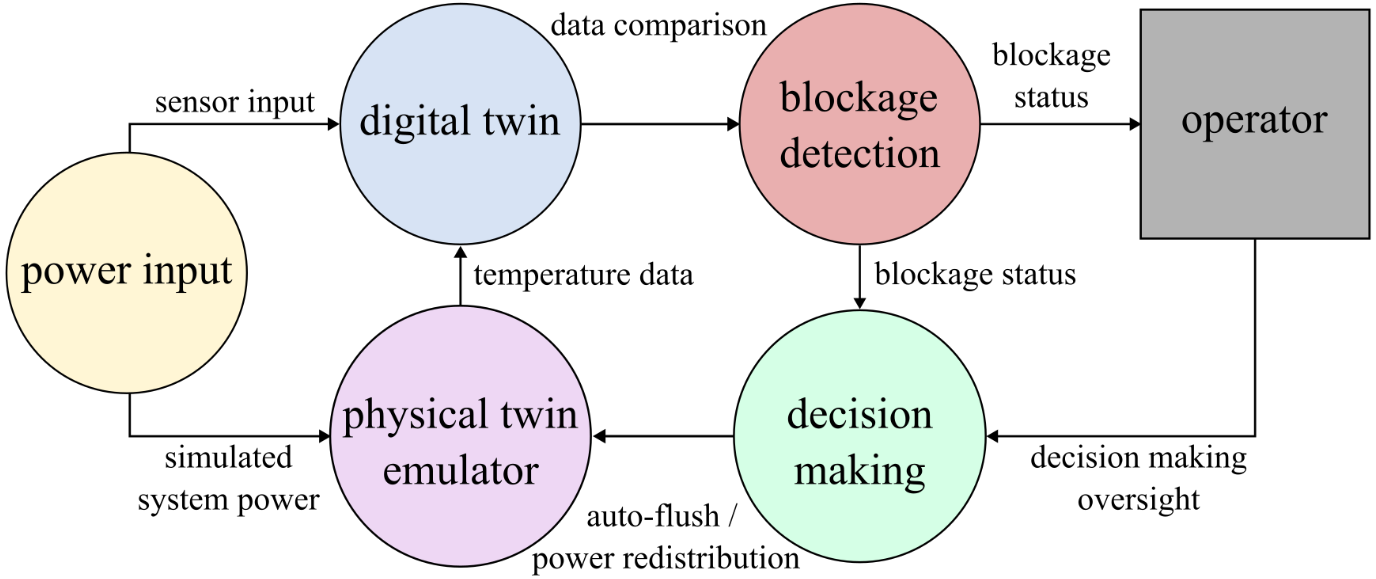
Digital Twin: Thermal Modeling

- Uses physics based, data driven, and analytical models.
  - Physics Based: simulates physical system behavior.
  - Data Driven: utilizes PT data to train and refine physics model.
  - Analytical: performs mathematical calculations to provide instantaneous low-computation results.



Digital Twin: Thermal Modeling

- Encompasses the real-time transient model, and the steady-state temperature calculations.
  - Real-time transient model:
    - Receives power input.
    - No blockage simulation.
    - Provides the normal operation conditions of the PT.
  - Steady-state temperature calculations:
    - Receives power input.
    - Performs thermodynamic calculations.
    - Provides final steady-state temperature of the PT under normal operating conditions.



Digital Twin: Data Analysis and Blockage Detection

- Create a digital model of the physical system.
- Read real-time data from model and physical system.
- Perform checks based on predefined operational thresholds (ϵ):
  - Check 1: $T_{PT} - T_{DT} > \epsilon_{T1}$
  - Check 2: $T_{PT} - T_{DT} > \epsilon_{T2}$
  - Check 3: $|\left(\frac{dT}{dt}\right)_{PT} - \left(\frac{dT}{dt}\right)_{DT}| > \epsilon_{\frac{dT}{dt}}$
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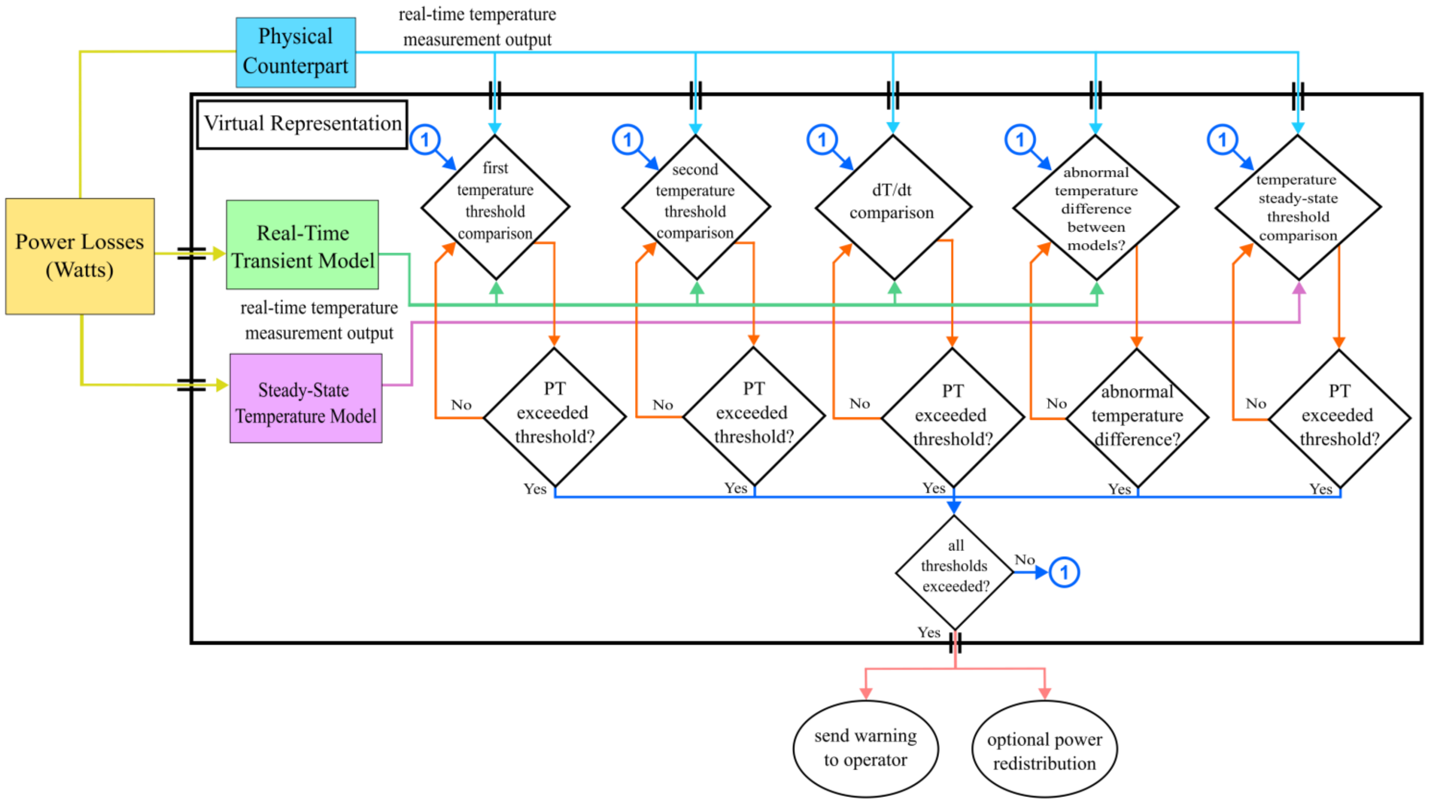
  - Check 5: $T_{PT} - T_{DT_{ss}} > \epsilon_{ss}$



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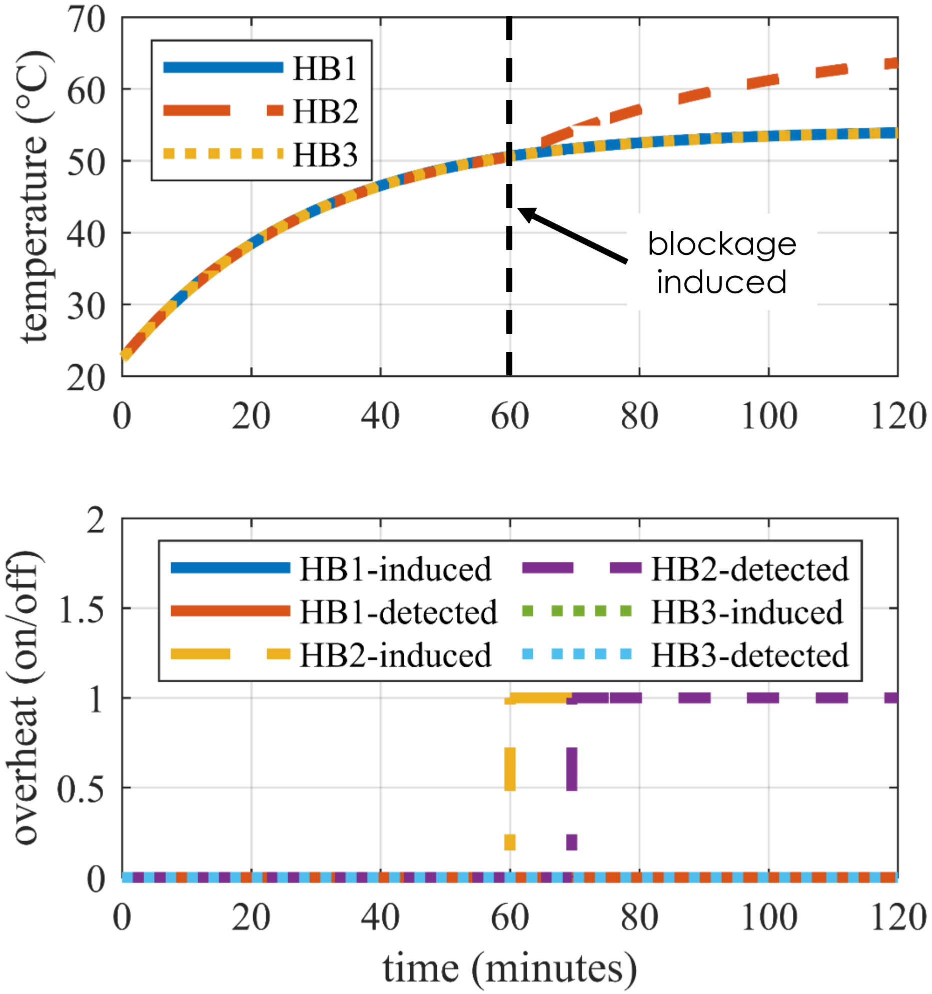
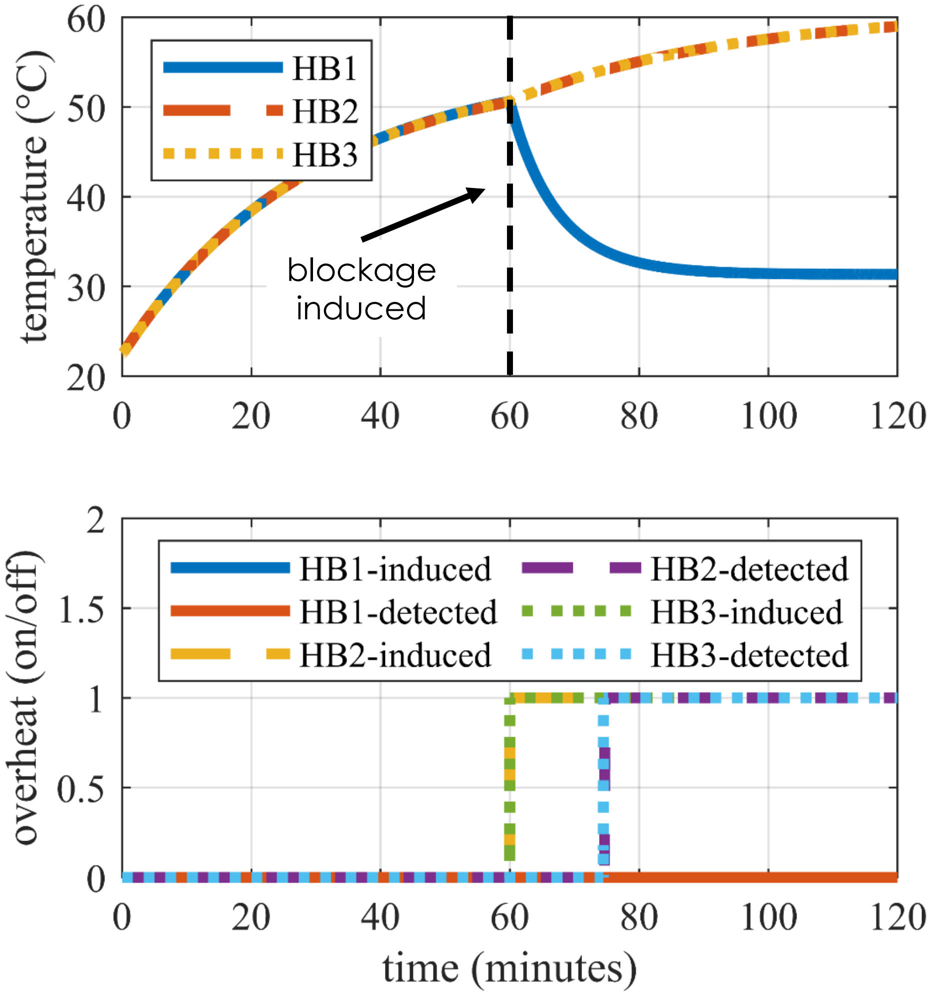
Simulated Testing 1/3

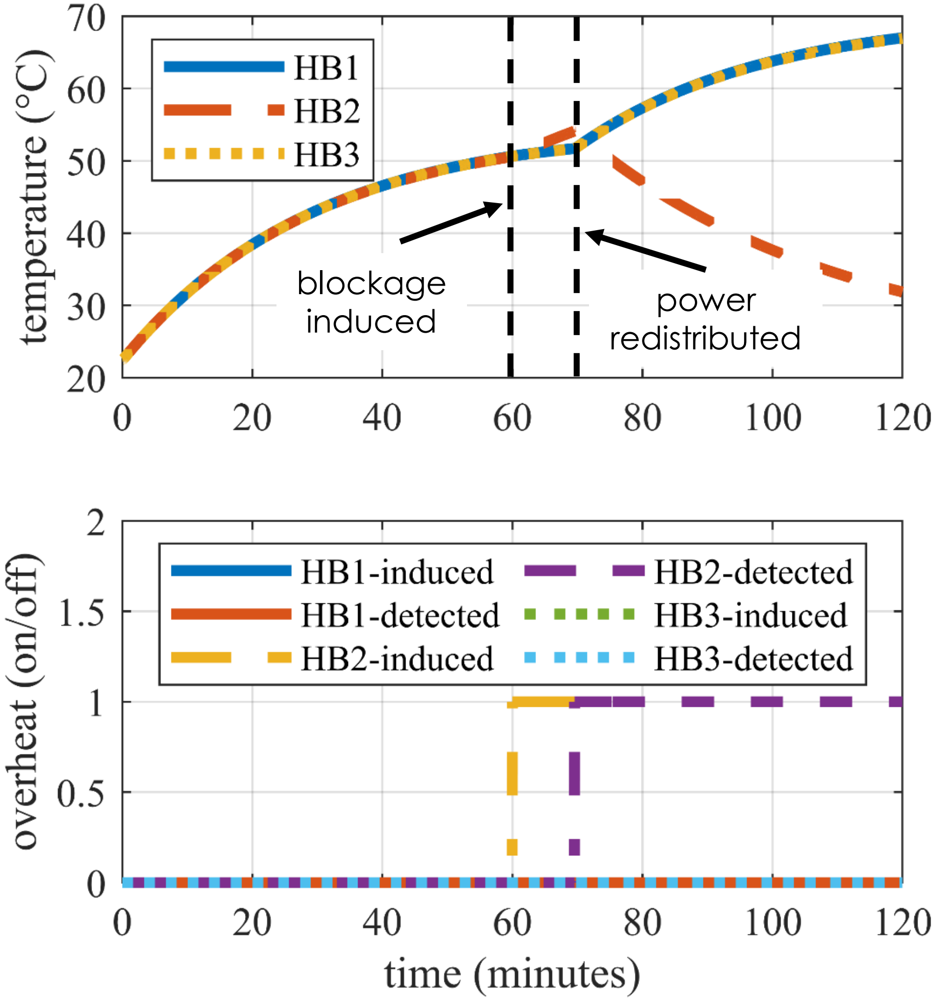


← Test 1a: Single blockage in HB2. Detected 10 minutes post induction.

Test 2a: Dual blockage in HB2 & HB3. Detected 15 minutes post induction. →

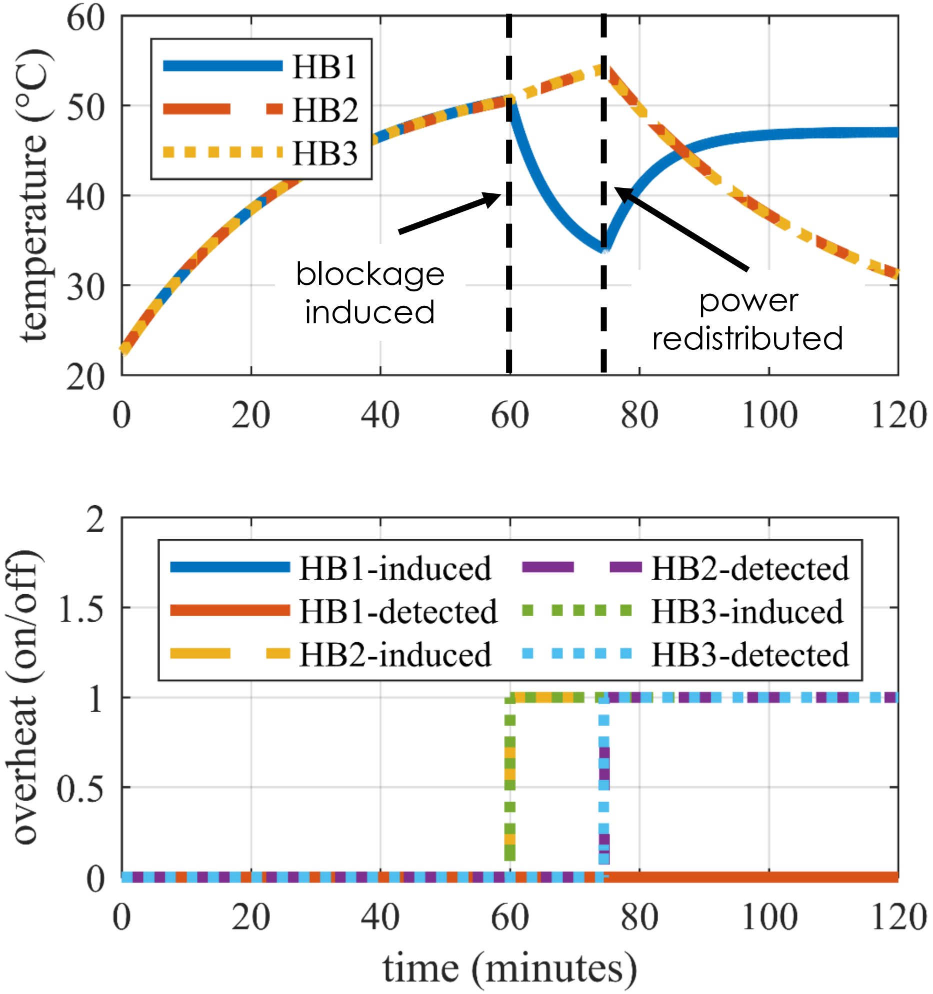


Simulated Testing 2/3



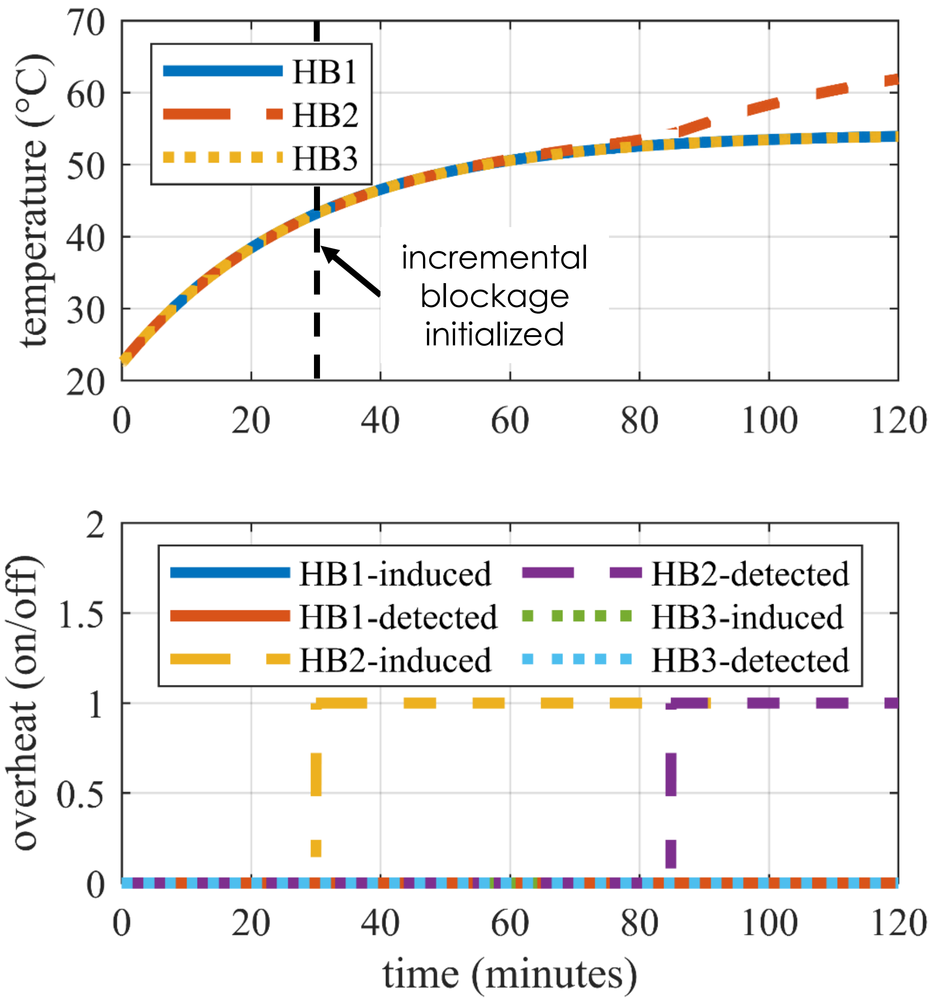
← Test 1b: Single blockage in HB2 with active power redistribution.

Test 2b: Dual blockage in HB2 & HB3 with active power redistribution →



Simulated Testing 3/3

Test 3: Single slow blockage in HB2 detected after 55 minutes. →



Data Metrics For Simulated Testing

	Test 1a	Test 2a	Test 1b	Test 2b	Test 3
Approximate time to detect blockage (min)	10	15	10	15	55
Temp at blockage induction (°C)	51	51	51	51	44
Max temp at blockage detection (°C)	55	54	52	53	53
Max system temp (°C)	63	59	52	53	61
Max temp increase (ΔT) from blockage induction to detection (°C)	4	3	1	2	9

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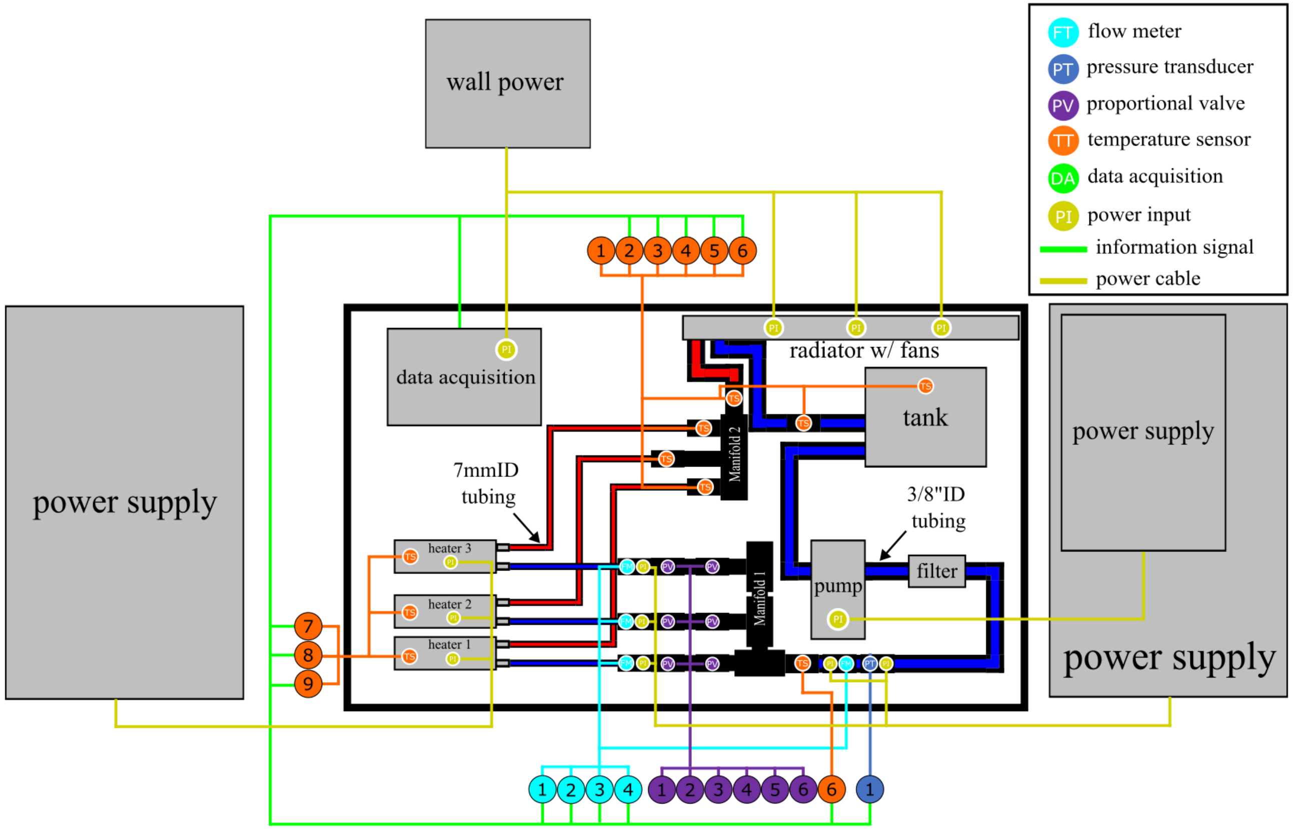
Conclusion

- Anomaly detection and rectification framework based on digital twin technology was presented.
- The digital twin was validated for further thermal anomaly detection research using simulated testing and results.
  - Real-time blockages were detected in simulated water-cooled system.
- DT informed operator of blockage formation, giving time for protective actions to be taken, and optionally performed automatic power redistribution.

Next Steps

- Utilize a physical testbed to allow for validation of the simulated findings.
- Physical testbed has already been constructed.
- Various tests will be performed to ensure that DT methodology produces similarly effective results in experimental scenarios.



Acknowledgement

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Thank You!

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