Integrating Digital Twin Technology for Real Time Blockage Detection in Water Cooled Electronics

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Abstract

This paper presents a culmination of research into integrating Digital Twin (DT) technology in water-cooled electronic systems to improve system reliability by detecting faults in the cooling system that maintains the proper operation of heat-producing electronic components and systems. A DT is a virtual representation of a physical twin (PT). This PT can represent real-world systems, individual components, or processes. Using the DT, operators can gain insight into the behavior and characteristics of the PT, thereby facilitating informed decisions to improve its health and optimize processes. The DT system is designed to detect obstructions forming in the waste heat-producing components within a liquid-based cooling system. The DT accomplishes this by emulating the thermal behavior of the system and its response to blockage formations. Detecting these formations is critical to the system's health, as blockages can lead to loss of coolant flow and subsequent overheating of the affected component. This leads to performance degradation and damage to the affected component(s). A temperature-based detection method, using thermocouples, is used as it offers a cost-effective and more straightforward alternative to detecting coolant loss compared to flow devices like flow meters. This is due to the relatively simple operating principle and low average unit cost of thermocouples compared to most flow meters. By comparing the thermal behavior to the PT, the DT enables real-time monitoring and detection of blockage formations, thus allowing corrective actions to be quickly implemented. The DT automatically diagnoses blockages in the cooling channels using a series of abnormal thermal behavior triggers and alerts operators or controllers. A simulated Physical Twin Emulator (PTE) and real-world testbed

cooling systems were created to evaluate the developed DT's effectiveness. The DT was calibrated through thermal characterization experiments, and its blockage detection capabilities were tested in the emulator and the physical testbed. During PTE testing at near-total (98.5%) blockage conditions, the DT detected the formation of blockages in the affected component in 1.33 minutes during a heating profile of 125W (overtemperature reached >80 °C five minutes after blockage introduction) and 1.58 minutes during a cooling profile (225W initial, lowering to 25W). When under multiple 80% blockages (125 watts), detection required 5.66 minutes, as activation of all abnormal thermal triggers required additional time. In real-world testing using a prototype liquid cooled testbed, the DT successfully alerted the operator to a near-total blockage 1.27 minutes after introducing a near-total (90%) blockage (200-watt input). Overall, this research demonstrates the potential use of DTs for blockage detection in water-cooled electronic systems.

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Chapter 1

Introduction

1.1 What is a Digital Twin

A Digital Twin (DT) is a virtual representation, or "living model," of a physical object, system, or process that mimics the aspects and operations of the real-world Physical Twin (PT). It provides operators with insights into the operational status, process outcomes, and other aspects related to the proper functioning of the PT system [1]. A DT continually adapts to operational changes and maintains calibration by exchanging information between the physical and virtual systems via real-time sensory data gathered from the PT counterpart throughout its operational or "Product lifecycle" [1, 2]. DTs are increasingly used to enable the proactive identification of potential issues within, as well as to monitor and predict conditions in, the PT. This includes determining the remaining useful life (RUL) of components, predictive maintenance, and optimizing processes within the PT [3]. The DT mainly consists of three components: A physical reality (PT), a virtual representation (DT), and the connection through which information between the PT and DT flows. This connection is called the "Digital Thread" and allows data from the PT to update the models in the digital twin [4, 5]. See Figure 1.1 to represent this connection and operational flow between a PT and its DT.

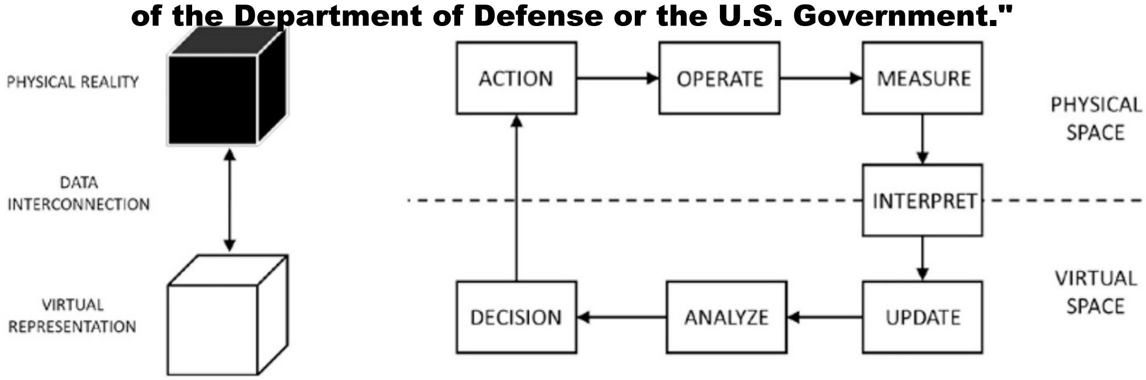

Figure 1.1 Components and Interconnection between Physical space (PT) and Virtual Space (DT) [4]

In addition to Digital Twins, various other methods exist for creating virtual representations of physical systems, such as the Digital Model (DM) and Digital Shadow (DS). Each of these representations features different levels of interconnection with its physical counterpart and is suited to specific situations and applications (1.2)

1.2 Digital Model (DM) vs. Digital Shadow (DS) vs. Digital Twin (DT)

A Digital Model (DM) is primarily used in the design phase of a physical system, offering a virtual representation of the asset that is less costly and faster to produce. However, it lacks real-time interaction with the physical counterpart, as it does not exchange data continuously or automatically with the real-world asset. Instead, the DM requires manual updates based on changes or conditions in the physical system and limits its ability to reflect real-time operational changes, long-term wear, or evolving behaviors. While the DM is helpful for initial simulations and testing, it cannot adapt to dynamic conditions in the way that more advanced digital systems can [2, 4].

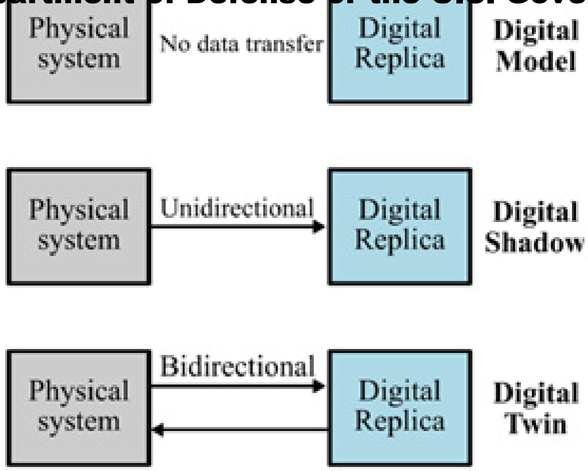

Figure 1.2 Comparison of data transfer between a Physical Model/Replica and an accompanying Digital Model, Digital Shadow, or Digital Twin system [2].

In a DS-PT system, the DS transmits real-time data from the physical asset to its digital counterpart, thus providing a passive mirror of its status [2]. In doing so, the DS may continuously reflect the performance and behavior of the physical system but cannot influence or interact with it directly. While the DS can provide insights into the asset's operation, i.e., detecting issues or identifying inefficiencies, it cannot take corrective action or initiate adjustments automatically. The data gathered by the DS may be interpreted by human operators, who then make decisions and adjustments based on the insights provided. This limitation may result in slower response times, as manual intervention is needed to act on the data, potentially delaying corrective actions if required.

While this aspect is somewhat debated among authors, for a DT – especially an automated DT – to be created, it must enable bidirectional data transfer, allowing continuous interaction between the physical and digital counterparts [2, 3]. This connection allows both twins to communicate and collaborate in maintaining and optimizing conditions within the physical system. Real-time data gathered from the PT via sensors and other instruments is used by the DT to simulate the physical system's current state. The DT compares this data with the conditions of the PT and can then adjust parameters within the physical system to optimize or steer operations toward a desired outcome. Unlike a DS, which only reflects the physical system's behavior, a DT can influence the physical system directly through adjustments based on its analysis and simulation of real-time data. This dynamic interaction enables the DT to continuously optimize performance and autonomously respond to changes in the operational status of the PT [1, 2, 3].

1.3 Benefits of Digital Twins

Due to its nature as a virtual–simulated – model, the DT can be easily manipulated, and potential changes to the DT and their results are analyzed in a controlled-simulated environment. This aspect provides a more cost-effective method of analyzing a system's behaviors and potential responses because of malfunctions or unexpected disruptions to system functions. This information and the use of the DT can give operators more insight into the operational health and status of the PT system, allowing for preventive measures to be taken to improve the operation of the PT [5].

1.4 Applications of DTs in Water Cooled Electronics

This paper focuses on one application of DT technology: its use in water-cooled electronics. The research involves developing a DT capable of monitoring the conditions within a water-cooled electronics system, with an emphasis on maintaining the quality and integrity of the water coolant and how a loss of this integrity affects the operation of these electronic systems. It also explores the potential advantages and benefits of using a DT for this application.

While several factors contribute to the failure of electronic components, the most common causes are temperature, vibration, and humidity [6, 7], as shown in Figure 1.3. Vibration-related failure accounts for an estimated 20% of failure instances and often results from operating in vibration-intensive environments. A constant applied vibration on the electronics' components can result in fatigue damage, potentially leading to performance degradation, component failure, or, under specific conditions, the catastrophic disassembly of electronic components [8]. However, while vibration is an important factor to consider in electronic design, the most significant source of failures in electronics is temperature, specifically waste heat production, accounting for an estimated 55% of recorded failure methods [6, 7].

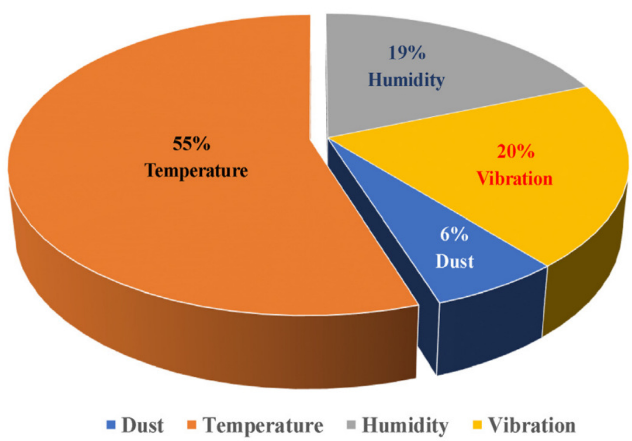

Figure 1.3 Factors contributing to failure in electronics [6]

Waste heat production in electronics is an unavoidable byproduct of their operation. Resistive losses in electronic components occur when electrical current passes through materials with inherent resistance, such as conductors and semiconductors. This effect, called Joule heating [9], converts a portion of the impeded electrical energy into waste heat. For materials with higher resistance, more energy is lost and dissipated as heat, leading to higher operating temperatures and an increased need for cooling.

The governing equation for Joule heating is:

$$Q = I^2 Rt \qquad \text{(Equation 1)}$$

Where:

- Q = heat energy generated (in joules)
- I = current (in amperes)
- R = resistance of the conductor (in ohms)
- t = duration of current flow (in seconds)

Another source of waste heat production is switching losses in semiconductor devices, primarily MOSFETs. As the transistors within these devices switch between on and off states, a portion of the energy is converted to waste heat, primarily due to gate capacitance charging and discharging [10]. The frequency of this switching determines the quantity of heat generation, and as this waste heat accumulates, it can harm electronic systems' performance and helpful lifespan [7]. Therefore, achieving proper heat dissipation in electronic systems will help ensure their continued functioning and reliability.

1.5.1 Heat Removal

The dissipation of waste heat in electronic components is most commonly achieved through heat transfer mediums like air, water, oil, or other gases and liquids. These fluids are selected for their specific thermal properties, including viscosity, heat transfer rate, and application area. In these cooling systems, heat is transferred away from the components primarily through convection, where the heated medium absorbs thermal energy from the component. This process is typically facilitated by a heat sink or heat exchanger that increases the surface area for heat transfer to enhance overall cooling efficiency [6].

1.5.2 Air Cooling

Air cooling is the simplest and most widely used thermal management technique. Fans or blowers move air over electronic components equipped with finned heat sinks or other devices that increase the heat transfer surface area. This method is popular due to its low cost, high reliability (contributing to its low complexity and minimal number of components), relatively simple installation, and ease of maintenance [11].

A finned heat sink (Figure 1.4) is the typical method for dissipating heat from electronic components, usually relying on air as the heat transfer medium. It consists of a base plate in contact with the component and a series of extended fins designed to increase surface area, thereby enhancing heat transfer from the heat-producing component to the local environment [11, 12].

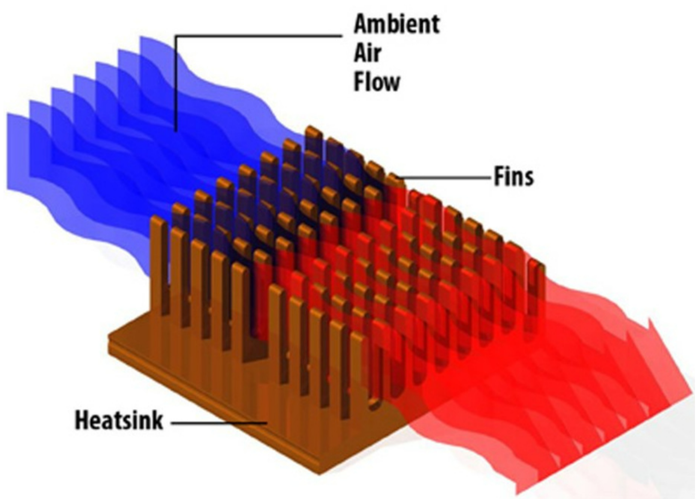

Figure 1.4 Finned heat sink operation: Heat is transferred from the component to the heat sink, where the fins increase surface area to enhance heat dissipation through convection [12].

The performance of finned heat sinks depends on factors such as material type, fin geometry, and airflow. Materials with high thermal conductivity, such as aluminum or copper, and an optimized fin surface area improve heat dissipation [12]. These fins transfer heat from the component to the surrounding air through convection, either via natural convection or forced convection using fans or other devices.

1.5.3 Liquid Cooling

However, the use of air cooling is less efficient at removing waste heat due to its lower heat transfer coefficient compared to that of water, the most typically used cooling fluid due to its higher heat transfer ability and capacity (Table 1.1). Accounting for this lower coefficient necessitates an increased heat transfer surface area, thereby increasing the size and bulk of the cooling system. Additionally, due to requiring the continues replenishment of cool air, air cooling systems may be unsuitable for applications where air circulation is limited, or ambient temperatures render air cooling inefficient. [13, 14].

Table 1.1 Air vs Water Heat Transfer Coefficient comparison [14].

Condition		Convective Heat Transfer Coefficient ($W/m^2 \cdot K$)
Natural Convection	Air	1–10
	Water	200–1000
Forced Convection	Air	20–100
	Water	1000–15000

In liquid cooling systems, a pump circulates water-based coolant through cooling tubes or channels in direct contact with heat-generating components. This process transfers heat away from the components, which is then dissipated through a radiator or heat exchanger (see Figure 1.5). Liquid cooling primarily does not rely on local environmental conditions for its cooling principle, as it is a closed system, thus allowing it to be more compact but heavy. Additionally, this closed nature and the complexity incurred by including pumps, pipes, and heat exchangers make liquid cooling less versatile than air [13, 14, 15].

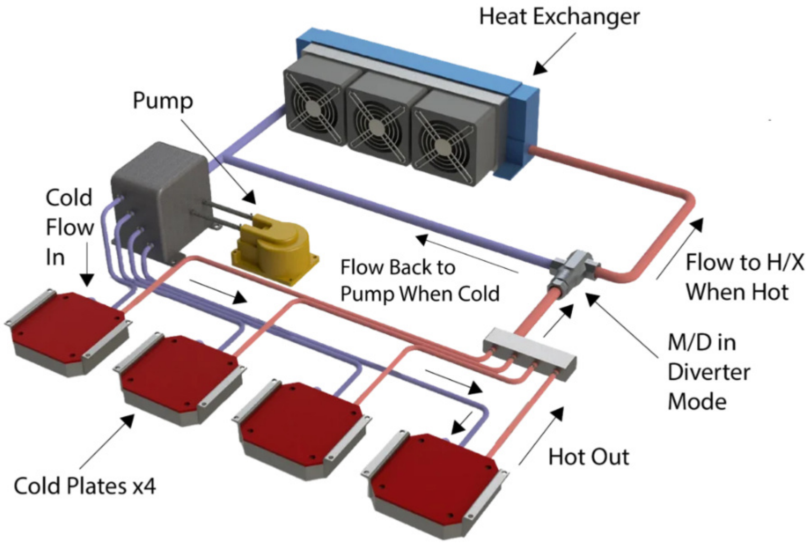

Figure 1.5 Typical arrangement of components in a liquid-cooled system: coolant is pumped to heat-producing components, heated, and then circulated to a radiator or heat exchanger to dissipate heat from the system [15].

In the above example, heat is expelled from the system using an air-cooled radiator that transfers heat from the coolant to the local air. However, for systems that require it, a liquid-to-liquid heat exchanger system may transfer the heat into a separate cooling loop to be then dissipated into the local environment.

1.6 Challenges of Liquid Cooled Systems

Liquid cooling systems are closed-loop systems commonly used in smaller or mobile applications like vehicles and electronics. Unlike air-cooled systems, which continuously replace heated air, liquid cooling systems circulate and recirculate coolant in a heating, cooling, and reheating loop. Maintaining proper coolant flow rate, and thus heat extraction is essential to ensure these systems function properly and prevent malfunctions or failures in components.

1.6.1 Blockage Formation in Liquid Cooling Systems

One challenge in maintaining the proper operation of a liquid cooling system is preventing the introduction and accumulation of foreign materials in the cooling network. The accumulation of these materials can impact the system's cooling efficiency and performance. In water cooling applications using a coolant rich in dissolved minerals—such as municipal (tap) water—attention must be given to minimizing mineral buildup in the system. This mineral buildup, known as "scale," occurs when "hard water" (mineral-rich water) is used as the primary coolant. Hard water can contain high levels of dissolved calcium in the form of carbonates and bicarbonates [16, 17].Over time, this scale can accumulate in the cooling channels of water-cooled electronics and other inline components, such as pipes (see Figure 1.6), heat exchangers, or other heat-transferring surfaces.

Figure 1.6 Scale buildup in a pipe section, restricting flow and potentially impacting the efficiency of the cooling system [17].

In addition to affecting the heat transfer of these surfaces, scale buildup may eventually progress to a point where coolant flow is significantly reduced. In more severe cases, the scale may break off and become carried by the coolant flow. This detached scale can then be deposited in the cooling channels of critical equipment, such as heat exchangers (see Figure 1.7), potentially leading to blockages.

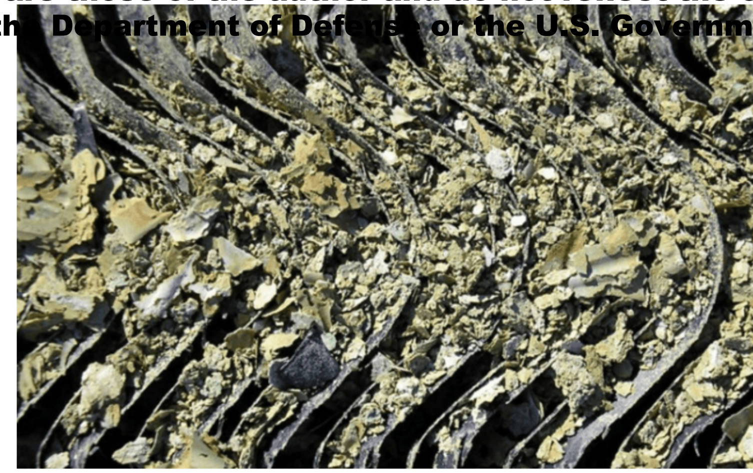

Figure 1.7 Damaged plate heat exchanger caused by scale buildup in the cooling system, with detached scale from plumbing depositing in the heat exchanger and blocking coolant channels [17].

Scale buildup and detachment are significant concerns in a cooling system's heat transfer equipment, such as the heating block shown in Figure 1.8. This heating block features several 3.25 mm coolant channels that experienced blockage formation issues during use in the SCEPTER (South Carolina Energy and Power Testbed for Engineering Research) lab at the University of South Carolina.

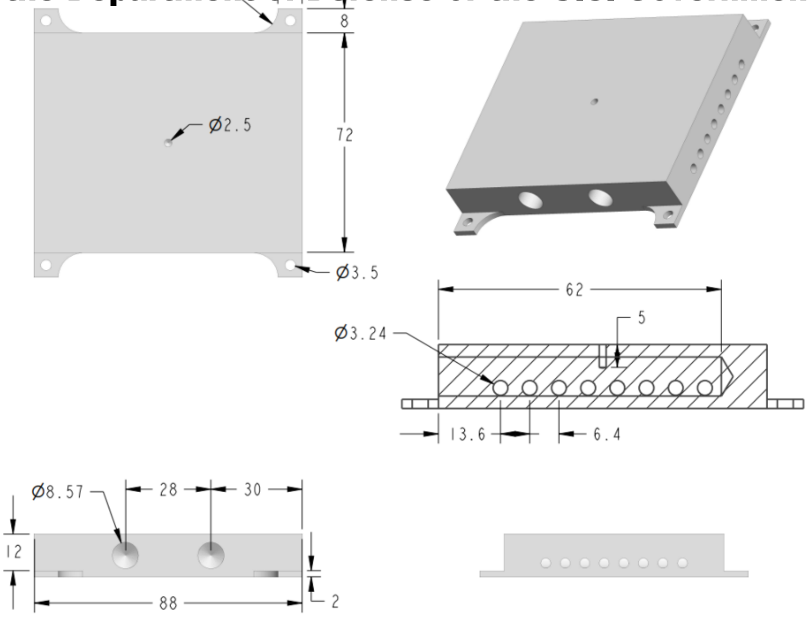

Figure 1.8 Example schematic of a heat exchanger heating block used in the cooling system for electronics. Displayed are the coolant channels and their dimensions where blockages may arise.

In the SCEPTER lab cooling system, using impure cooling water sourced from local supplies (e.g., tap/municipal water) and insufficient filtration led to a blockage formation issue within the cooling network of a power converter cabinet due to the buildup of scale and possibly due to a section of scale detaching during the activation of the coolant system, a blockage formed in the heating block of one of the power converters. This blockage resulted in a loss of coolant flow to the affected converter, as seen in Figure 1.9. The cooling loop of the affected power converter, shown in dark blue, experienced a complete loss of coolant flow

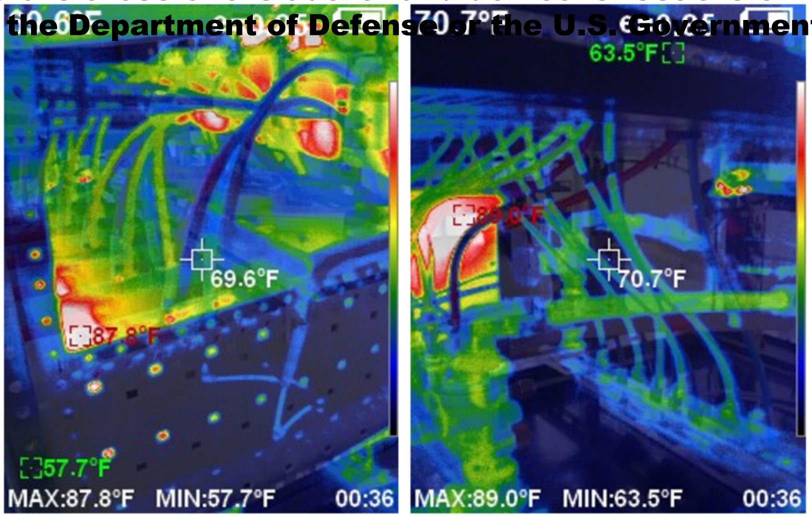

Figure 1.9 Thermal image showing a loss of coolant flow (dark blue) to the converter due to blockage, causing a rapid temperature rise and system shutdown for repairs.

This issue was caused by excessive water hardness and insufficient pressure that led to the formation of a sludge-like material that accumulated in the cooling channels, blocking coolant flow to the electronics. The problem persisted, with several other converters experiencing blockage formations, and required significant effort to resolve, including a series of backflushing operations, switching to a purer deionized water coolant, and installing enhanced filtration units to remove any remaining debris from the coolant.

1.6.2 Consequences of Blockage Formation

As a blockage forms in the cooling system of a waste heat-producing electronic device, coolant flow is restricted, leading to abnormal thermal conditions in the affected unit, such as elevated operating temperatures and abnormal heating behavior (Figure 1.10).This temperature increase can damage the electronics, potentially causing component failure or, in the case of the mentioned power converter, triggering a fault state where power is cut off to the unit to prevent further damage. Early detection systems can alert operators to potential blockages before overheating occurs, enabling a proactive approach to maintenance that can prevent costly damage or system downtime.

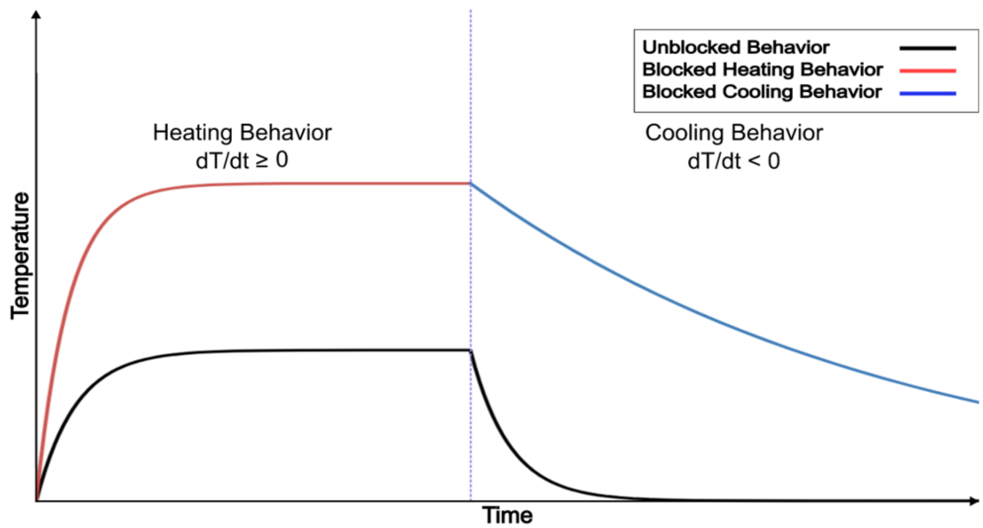

Figure 1.10 Behavior of a component's temperature under normal conditions (no blockage) and during blockage formation. This temperature variation forms the basis for the DT to diagnose blockage formation in the system.

1.7 Detection of Blockage Formations

Detecting the formation of blockages before an overtemperature event occurs is crucial, as it allows operators the time to perform maintenance or take corrective actions to prevent potential damage to the system. A DT system helps facilitate this rapid detection by comparing real-time data from the actual system to an ideal physical system model, enabling quick identification and response to abnormal behavior, such as the formation of blockages in the cooling network of electronics.

To address these challenges, this paper presents research focused on developing automated systems that can continuously monitor and diagnose abnormal behaviors resulting from blockage formation. The proposed system uses a Digital Twin (DT) to automatically detect and alert an operator or control system to blockage formation in the electronics cooling system. Figure 1.11shows an example of how this system functions. This approach aims to reduce the need for constant human oversight by enabling real-time detection and response to issues.

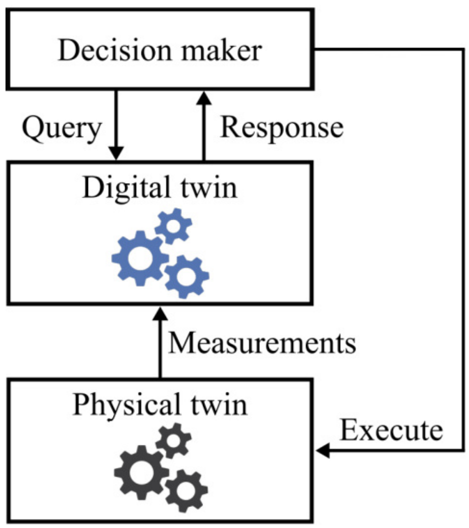

Figure 1.11 Information transfer between the Physical Twin (PT), Digital Twin (DT), and decision maker: Data flows from the PT to the DT for real-time monitoring and analysis, allowing the decision maker to make informed choices based on the digital representation of the physical system.[2]

Chapter 2

Digital Shadow-Based Detection of Blockage Formation in Water-Cooled Power Electronics

This section presents an initial attempt to detect the formation of blockages in water-cooled systems. It details the creation of a digital shadow (DS) that replicates the characteristics of a full-scale testbed to identify blockages within the system

2.1 Abstract

In response to the challenges posed by blockage formation in water-cooled power electronics systems, a thermal DS has been designed and validated to accurately simulate the thermal dynamics of the cooling system within a power converter. The simulation reveals that significant temperature increases occur in the power converters when blockage exceeds 50%, with a critical rise observed at 67.5% blockage. This validated DS supports real-time monitoring and predictive maintenance, enabling proactive interventions to prevent thermal accumulation from damaging the electrical components. Furthermore, it provides insights to decision-making entities, allowing them to schedule timely maintenance and reroute power to other electronics with adequate cooling capabilities. This strategy enhances the reliability of power electronics cooling systems and lays the foundation for applying similar predictive technologies in broader industrial settings.

2.2 Introduction

Power electronic converters are pivotal in the energy landscape, enabling the efficient conversion and control of electrical power across various applications. The thermal management of power electronic systems is critical for their efficiency and longevity [18]. While most commercial electronics typically utilize air cooling through finned heat sinks, an alternative approach involves water cooling. This method leverages water's superior thermal properties, including its higher thermal conductivity and specific heat capacity.

As a result, water cooling achieves a higher convective heat transfer coefficient than air cooling. In the context of forced convection, air cooling coefficients range from 20 to 100 $W/(m^2 \cdot °C)$, whereas water cooling exhibits significantly higher values, ranging from 1000 to 15,000 $W/(m^2 \cdot °C)$ [14]. This discrepancy highlights the enhanced cooling capability of water over air, making it a compelling option for managing the thermal loads of power electronic systems. Water cooling is achieved by circulating coolant through a heat sink attached to power electronic systems, effectively absorbing the heat generated during operation and helping to maintain temperatures within operational limits.

However, the effectiveness of this cooling method can be compromised by the presence of blockages within the cooling system. Such blockages impede coolant flow, trapping heat within the power electronic components. This causes temperatures to escalate, increasing the risk of system failure. A blockage in the cooling loop, particularly in the semiconductor switching devices of the converter, prevents the efficient dissipation of heat. This can accelerate the failure of these critical devices and cause the converter to malfunction. Please address these issues promptly to maintain the power system's overall efficiency and reliability. Digital Twin (DT) technology emerges as a promising solution to address the challenge of blockage formation within cooling systems. This critical factor compromises the efficiency and reliability of power electronic components. Defined as a digital representation of a physical asset, a DT mirrors the lifecycle of its physical counterpart and provides insights into the asset's behavior under various conditions [19].

DT technology is applied in various fields, including design, production, and health management [20]. Its application in thermal management, as demonstrated through developing a DT for predicting the thermal behavior of power system cables, showcases its potential for forecasting thermal conditions based on known load profiles [21].]. Furthermore, DTs have proven effective in estimating the health indicators of power electronic components, enhancing system reliability and efficiency [22, 23]. In the context of DT systems, a DS can be developed in the early stages. The DS receives data from the physical asset and replicates its lifecycle.

The DS can be used to estimate and predict key parameters that influence the behavior of the physical asset. This work proposes a DS-based method for detecting and quantifying blockages in coupled electro-thermal power electronic systems. The proposed method offers the capability to dynamically detect blockages in critical components of a cooling system, enabling automated decision-makers to take corrective actions or reroute power to other electrical components with adequate cooling capabilities.

This work's contribution lies in its application of Digital Twin (DT) and digital shadow (DS) technology to address a critical challenge in power electronic systems. By providing real-time monitoring and enabling automated decision-making, this method represents a significant advancement toward more efficient operation in coupled electro-thermal systems.

2.3 Materials and Methods

This section outlines the experimental methods used in this work, including the Naval electro-thermal testbed, an example of a blockage, and the developed thermal DS.

2.3.1 Overview of Testbed Configuration

Figure 2.1 shows the electrical setup diagram for this testbed, which consists of six power electronic converters interfacing with various loads.

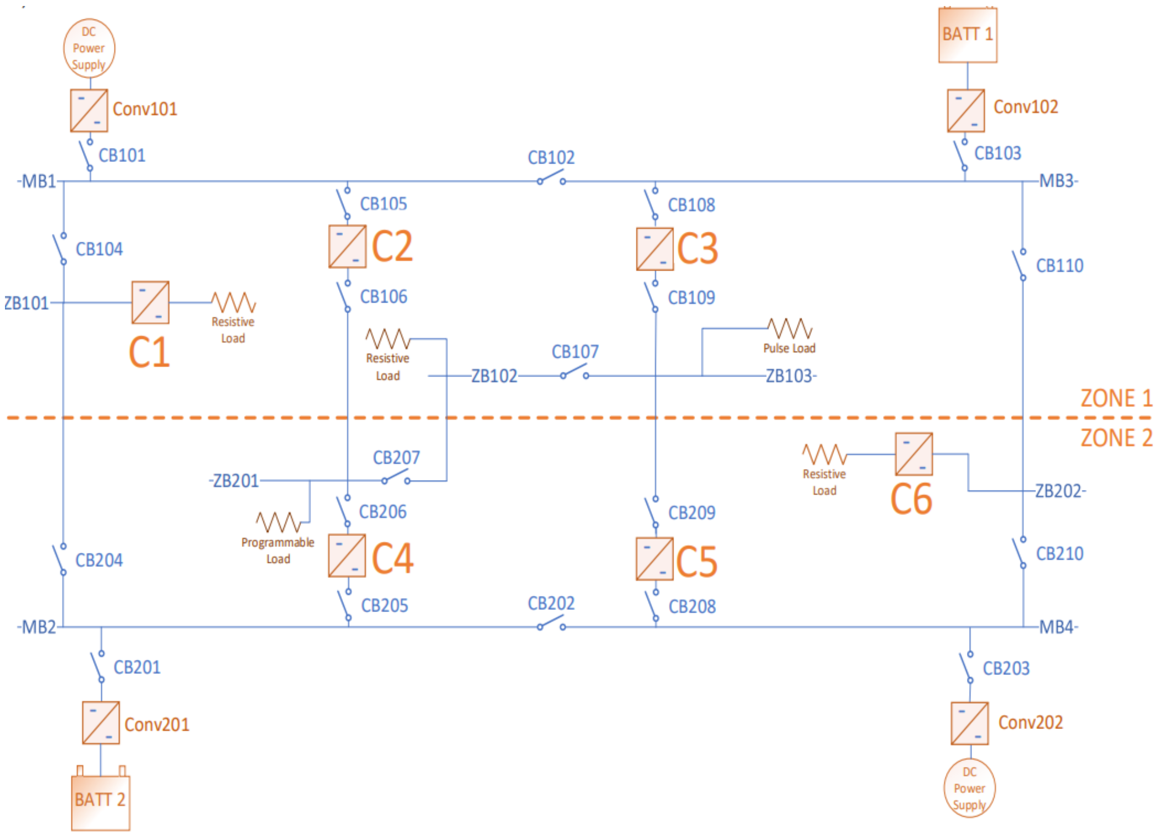

Figure 2.1 Electrical diagram of power converter system, showing the six power converters and their arrangement within the electrical system.

These power electronic converters are built using Imperix Power Electronic Building Blocks (PEB 8038 converters) [24].Each module consists of two metal–oxide semiconductor field-effect transistor (MOSFET) switching devices mounted on a shared heat sink. The six power converters are part of a more extensive coupled electrothermal testbed developed at the University of South Carolina for testing and developing Digital Twin (DT) solutions for naval applications. The converters and their cooling distribution system are connected and installed inside a DC cabinet, as shown in Figure 2.2.

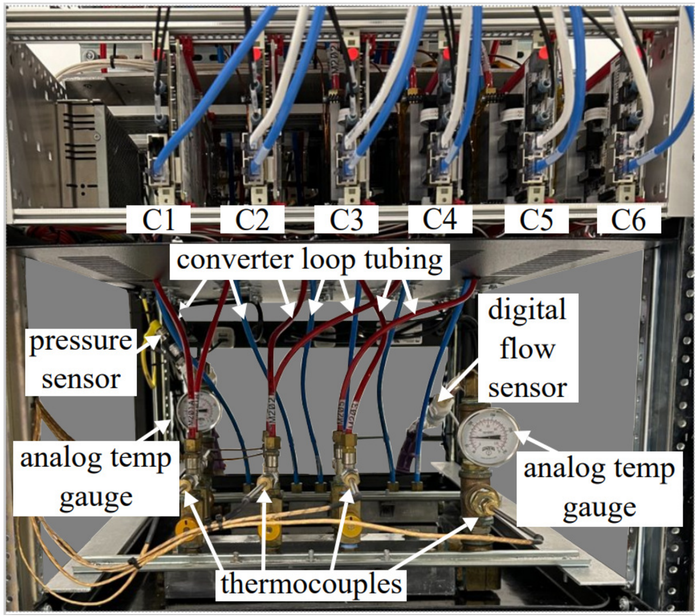

Figure 2.2 Experimental testbed showing power converter cooling network.

These converters are part of a microgrid designed to emulate a ship's naval power and energy systems, effectively replicating the ship's onboard power system [25]. Each module is designed to handle specific voltage inputs and outputs while supporting a load. The efficiency of these converters typically results in a power loss ranging from approximately 100 to 150 W [24]. These converters are crucial in distributing power across different sections, ensuring redundancy and reliability. Additionally, they can isolate and establish smaller grids within the central system, offering versatility in various usage scenarios. The fluid-flow paths for the power converters are shown in Figure 2.3.

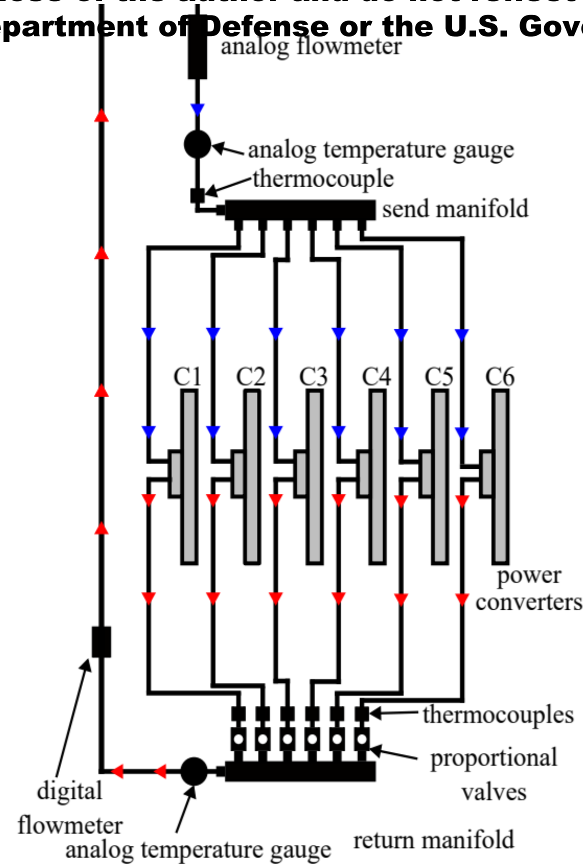

Figure 2.3 Diagram of power converter cooling loops, illustrating the converters and manifold networks along with flow rate and temperature measurement points to monitor the cooling system's performance.

The power converters are equipped with thermocouples placed around the inlets, outlets, and on the heat sink of each converter. Water flows from the inlet through the heat sink, absorbs heat from the electronic components, and exits through the outlet. The cooling network consists of three aluminum manifolds with 9.53 mm (3/8 in) inlets and six 6.35 mm (1/4 in) outlets, each with manual proportional control valves connected to the outlets on the hot leg manifold. Water flows into the cold leg manifold and then exits to the power converters through 4 mm (inner diameter) nylon tubing.

Inside the converters, two main chambers run parallel to each other and are connected by small chambers. These smaller chambers direct coolant over the MOSFETs, absorbing heat from the components. Heated water is carried out of the heating block and into the hot leg manifolds. Each manifold contains three 6.35 mm (1/4 in) inlets and one 9.53 mm (3/8 in) outlet, with flow-controlling manual proportional valves included.

The valves can be manually adjusted to limit or redistribute flow to the power converters. Temperature is monitored via thermocouples on the hot leg portion, measuring the coolant temperature leaving the individual converters. Additional thermocouples are incorporated directly into the converters to measure their temperature. The power converters have a safe operating temperature of up to 80°C, measured at the heat sink. If the temperature exceeds 80°C, the converter automatically shuts down. However, this shutdown is not ideal, as it may still cause damage to the converter and reduce its lifespan. Continued operation above 80°C can seriously damage the converter and the overall system.

2.3.2 Example of Blockage Formation

During testing of the hardware for other DT-related endeavors, it was discovered that blockages were forming in the cooling system due to precipitates in the water-glycol coolant. These precipitates, derived from mineral-rich water (including calcium and iron) and small sediment particles, contributed to the blockage formation. Additionally, organic growth and minor scaling debris from the brass components in the system exacerbated the issue. Over time, these particles accumulated in the cooling chambers of the power converters and the flow control valves. The blockage issue became apparent once sufficient waste heat caused the power converter temperature to exceed 80°C, triggering the automatic shutdown safety feature and cutting off power to prevent overheating.

To ensure safety, the outlet coolant temperature was restricted to below 45°C, after which manual shutdown would occur. The blockage issue was addressed by flushing the system with fresh coolant and installing filters capable of trapping particles larger than 5 microns to prevent further accumulation. However, the 5-micron filter introduced excess head loss in the experimental loop, limiting the coolant flow within the system. For systems with strict flow requirements, this solution may not be viable. As a result, a thermal simulation was introduced to help track the progress of blockage formation within the power converters, enabling preemptive repairs before more serious issues arise.

2.3.3 Thermal Loop and Digital Shadow Modeling

In the DS modeling of the cooling system, the simulation accurately captures the real-world dynamics of the power electronic components cooling network. This detailed model integrates both fluid dynamics and thermal properties, fully representing the multi-physical nature of the system. Key input parameters, such as the coolant's temperature (22°C) and flow rate (2.46 lpm), are configured to replicate the operational conditions observed in the physical setup. The model divides the coolant flow into six parallel paths, each connected to a power converter, as illustrated in Figure 2.4.

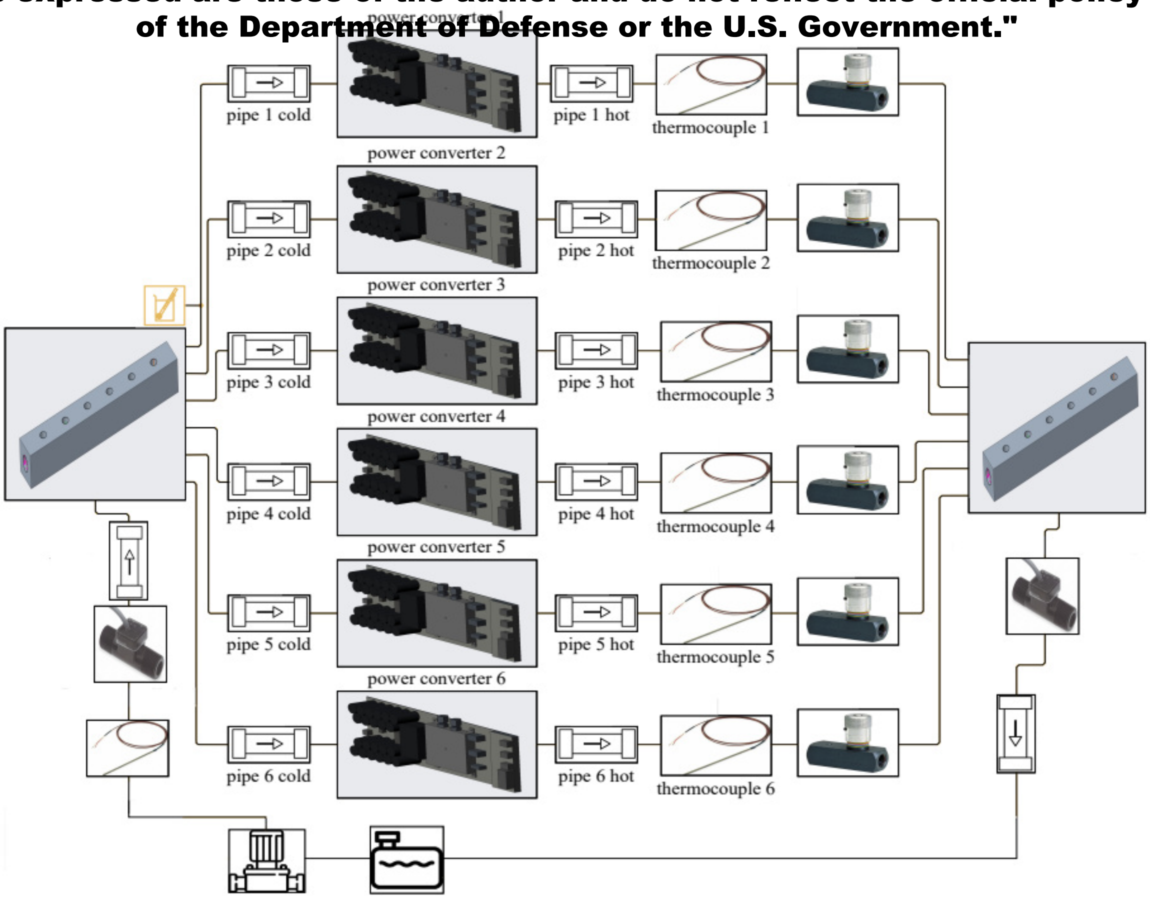

Figure 2.4 Simulation of an electronic cabinet power converter with a cooling network, featuring 4 × 150-watt inputs from the power converters operating at 100% capacity, simulating the thermal dynamics and cooling system performance.

As the coolant circulates through each loop connected to the converters, it absorbs the heat generated by the semiconductor switching devices. These devices, integral to the power conversion process, inherently produce power losses that manifest as heat. Typically, these losses amount to approximately 150 W per converter operating at full capacity. The model incorporates adjustable proportional valves in the flow paths to simulate how blockages affect the system. These valves can be adjusted from fully open to partially closed, representing various degrees of blockage. The thermal impact of these adjustments is reflected in the thermal output of each path. Temperature sensors located at the exit of each converter provide real-time data, allowing the DS to dynamically track and predict temperature increases that may signal blockage formation.

Physical experiments, combined with manufacturer data sheets, have been conducted to characterize the components of the physical cooling system thoroughly. Parameters such as thermal resistances, masses, convection coefficients, and other properties have been captured and replicated in the DS using lookup tables. This enables the model to adapt to the system's operational environment. The DS is designed to detect blockages early, reducing the risk of downtime or damage to the power electronics. Blockages are identified by monitoring abnormal rates of temperature change, dT/dt. The operator is notified of a potential blockage if this rate exceeds a predefined threshold.

By continuously monitoring these temperature changes, the DS acts as a predictive tool, alerting system operators to potential blockages before they escalate to critical levels that could compromise the system's integrity. This proactive capability is crucial for maintaining optimal operation within safe thermal limits, thus enhancing the longevity and reliability of the power converters. The integration of the DS with the predictive tool (PT) for informed decision-making is illustrated in Figure 2.5.

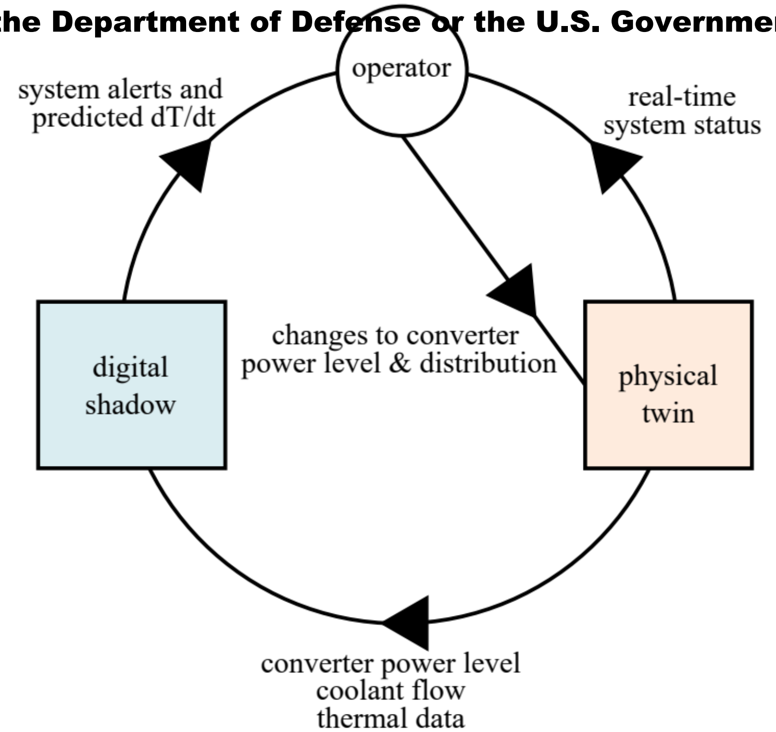

Figure 2.5 DS integration for informed decision-making: Real-time data from physical systems is captured and reflected in the DS. Data provided to operator aids in decision-making and system optimization.

2.4 Results and Discussion

An experiment was conducted using the hardware shown in Figure 13 to investigate the effects of partial blockages on the power converters under a heat load. The objective was to determine the point at which a blockage significantly increases the temperature in a single power converter. To simulate blockage formation, the valve opening of the C2 power converter was progressively reduced by 12.5% over eight tests. Each test began with the pump circulating water coolant at a rate of 2.46 lpm, with an ambient temperature of 22°C. Power converters C1, C2, C3, and C4 each supplied 2 kW, with C1, C3, and C4 serving as the control group, while the valve of C2 was manipulated to simulate the formation of a blockage. The power converters C5 and C6 remained inactive during the tests. The testing lasted approximately five hours until the system reached a quasi-steady state. After each test, the coolant temperature was returned to ambient conditions (22°C) before the subsequent reduction in the valve position.

As testing progressed, the temperature rise, and steady-state temperature followed a clear pattern: both increased as the flow restriction in C2 was progressively increased. Figure 2.6 illustrates the effect of a forming blockage on the temperature rise and steady-state temperature of the C2 power converter. The results show a marked increase in both the temperature rise and the steady-state temperature when the valve opening was reduced to 37.5%, compared to when the valve was fully open at 100%..

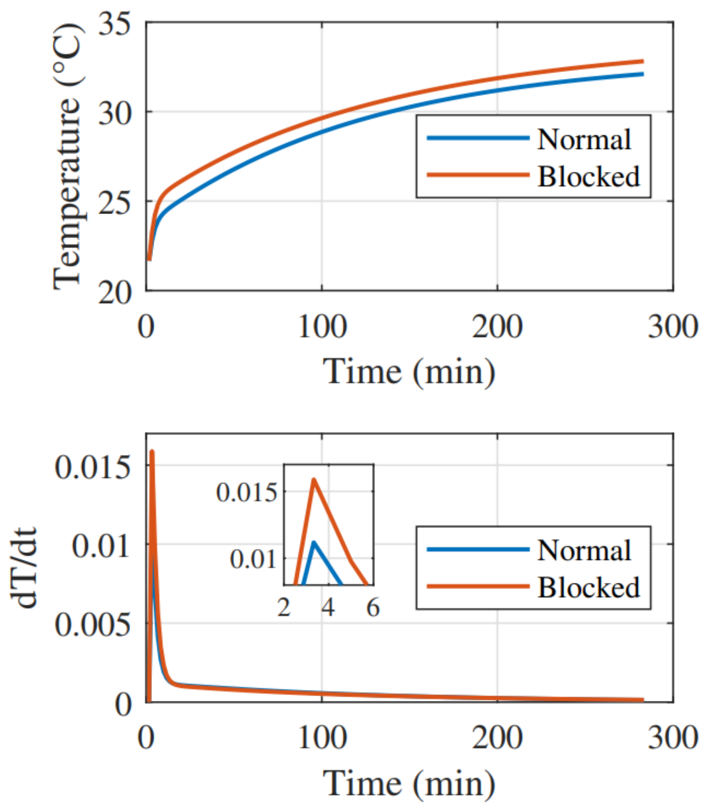

Figure 2.6 Experimental results showing temperature response under normal conditions (100% open) and during partial blockage (37.5% blocked). Blocked conditions show more rapid temperature rise and higher steady state operation temperature.

Figure 2.7 compares the simulation and physical experiment results as the C2 converter valve's opening is reduced from 100% (no blockage) to 12.5% under full power (2 kW electrical input). The percentages represent the valve's openness, with lower percentages indicating increasing blockage formation.

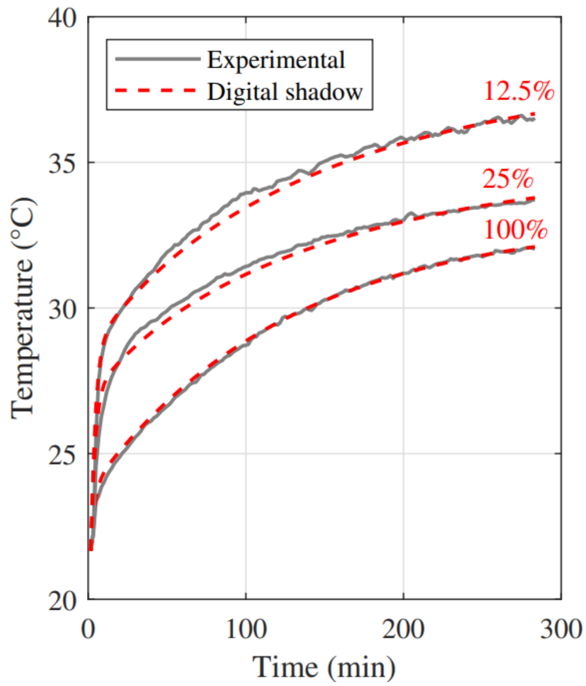

Figure 2.7 Comparison of simulation results vs experimental showing the effect of blockage formation via change in valve openness, for steady state temperature in converter 2 under full power [2 kW electrical input].

The results from the physical and simulation tests show good congruity, with progressively more significant increases in dT/dt and steady-state temperatures as the valve percentage decreases. This indicates a reduction in the power converter's cooling ability as blockage formation progresses.

2.5 Conclusion and Future Work

The results validate the accuracy of the thermal DS by effectively replicating the thermal behavior of the power converters' cooling system. This alignment provides a solid foundation for further investigating the effects of coolant blockage formation. Given the demonstrated efficiency of the thermal model, there is significant potential to develop it into a real-time monitoring and prediction system that will help enhance the proactive management of coolant blockage issues, thereby improving the reliability and performance of water-cooled electronic systems. Building on this DS, future work will focus on evolving it into a fully operational Digital Twin (DT) that runs in parallel with the hardware. This DT will continuously monitor system conditions and could automate decision-making processes. Depending on the complexity and criticality of the situation, the system will either make autonomous decisions or support human-in-the-loop interventions. This advancement will ensure that power is efficiently rerouted to other components with adequate cooling, minimizing downtime and preventing damage from overheating. These developments are poised to significantly enhance power electronic systems' operational reliability and efficiency, marking a significant step forward in integrating DTs within industrial applications.

Chapter 3

Validation of Digital Twins for Automated Dectection of Blockages in Liquid-Cooled Electronic Systems

This section continues the research into Digital Shadows (DS). It presents the development of an enhanced method for detecting blockage formation in water-cooled electronic systems using a Digital Twin (DT). The proposed DT eliminates the need for "human-in-the-loop" intervention, replacing it with an automated algorithm designed to autonomously detect blockage formation within the physical cooling system.

3.1 Abstract

Before testing the DT on an expensive real-world Physical Twin (PT) testbed, a PT emulator was developed to validate the DT's ability to detect blockage formation in a water-cooled electronics system using a series of temperature triggers. The DT was tested under three blockage scenarios: (1) a near-total blockage in one heater block during heating, (2) the same blockage under cooling conditions, and (3) partial blockages in two heater blocks. In each scenario, the DT's thermal triggers recorded simulated temperature data from the PT emulator (PTE). By comparing this data with the simulated thermal data from the DT's transient model, the DT assessed its blockage detection capabilities. In all tests, the DT's automated system successfully identified the induced blockages, with response times of 1.33 minutes, 1.58 minutes, and 5.66 minutes, respectively. The longer detection time in the third scenario was

due to the lower severity of the blockage, which required more time for the affected heater block's temperature to exceed its normal steady-state temperature. These validation experiments successfully demonstrated the DT's ability to automatically detect blockage formation in a simulated water-cooled electronic testbed. As a result, the next phase of research will focus on testing the DT's blockage detection capabilities on a real-world PT testbed.

3.2 Introduction

The first step in creating a DT that integrates real-time temperature data from a physical system with simulated data is to develop an accurate digital model (DM) of the system, capturing its geometry and operational parameters. This model is calibrated by adjusting key parameters, such as heat transfer coefficients, to match real-world conditions. Once calibrated, the DT will simulate the system's behavior and predict temperatures under various operating scenarios.

Its effectiveness must be validated before implementing the DT in a real-world system. To do this, a physical system emulator (simulation) will be used to replicate different operating conditions, enabling the DT to be tested for its ability to detect issues such as coolant blockage formation. By comparing the real-time temperature readings from the emulator with the DT's predicted values, any discrepancies can highlight potential problems, such as blockages, that may lead to temperature increases. This testing phase ensures that the DT can accurately detect anomalies before being applied to the actual system. Once validated, the DT can be deployed on a real-world testbed for further evaluation.

3.3 Materials and Methods

The use of temperature as the primary vector for detecting blockages in the electronics cooling network was influenced by an incident at the SCEPTER lab, where a blockage formed in one of the power converter's heating blocks. While the system lacked individual flow meters for each converter's cooling loop, each electronic converter was equipped with thermocouples for temperature measurement. This arrangement, coupled with the need to identify blockage formations, led to the idea of developing a DT system that uses temperature to detect blockages.

However, the absence of flow meters was not the sole reason for choosing temperature as the detection method, with several factors contributing to this decision. Temperature measurements offered a relatively simple and inexpensive way of monitoring the health of the cooling system.

3.3.1 Disadvantages of Flow Meters

The primary challenge with flow meters, including rotor-based models (see Figure 3.2), is their relatively high cost per unit (Figure 3.1). While costs vary based on the type of flow meter, commercially used flow meters are generally more expensive than temperature sensors. The cost can quickly accumulate when multiple flow meters are required in a system to monitor individual components for abnormal coolant flow behavior [26]. Additionally, certain flow meters, particularly those that require direct contact with the fluid flow, are more complex to install and maintain and require consideration for space restrictions to allow access for maintenance and servicing.

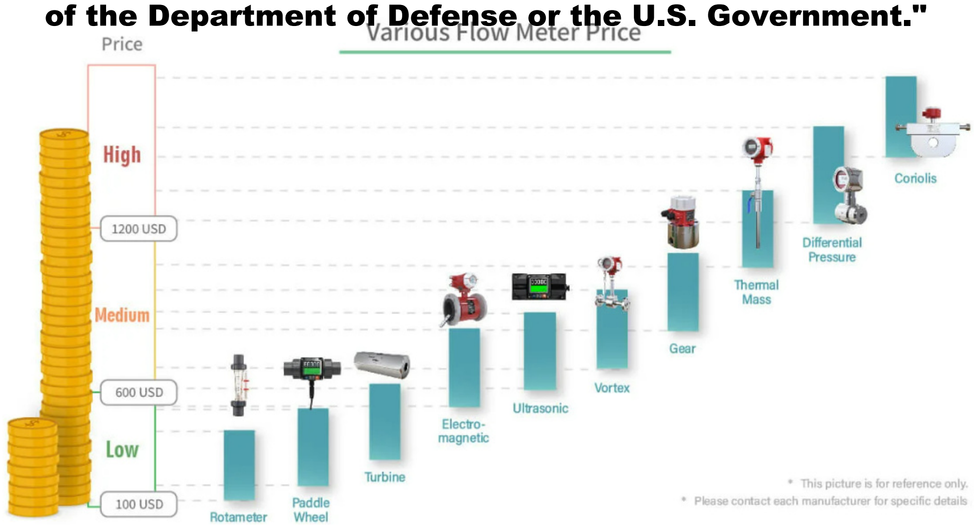

Figure 3.1 Cost comparison of different flow meter types.[26]

The rotor turbine relies on converting rotational velocity into an electrical signal that uses a K-factor that converts the electrical pulses from the flow meter into a volumetric flow rate [27]. However, these rotors are susceptible to jamming when debris, such as waterproofing tape, particles, or other obstructing materials, becomes lodged in the mechanism. This is particularly problematic when used in systems with contaminated or dirty coolant, and it can lead to inaccurate readings or even complete failure of the flow meter r [27]. Considering the potential issues, the DT's temperature-based detection offers a more robust and reliable solution for identifying blockages without the added complications of flow meter maintenance and operation.

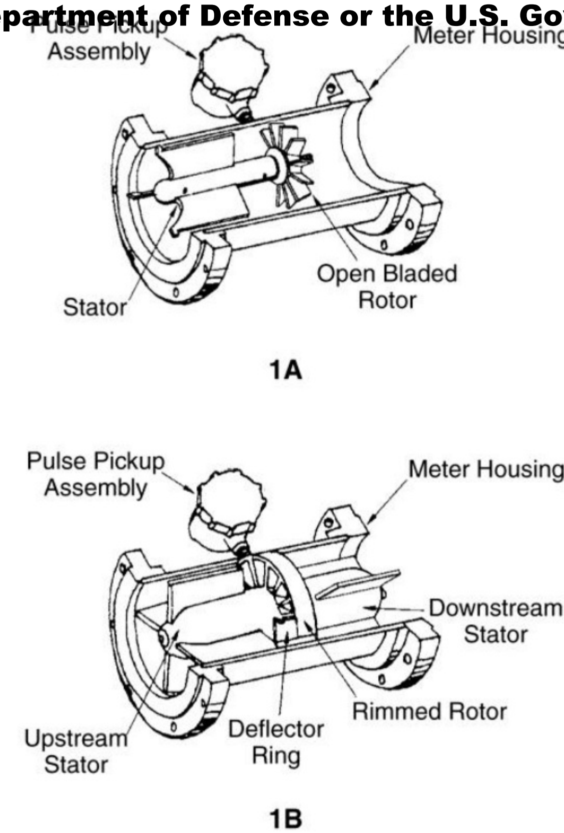

Figure 3.2 Construction of different internal assembly turbine flow meters: (a) Open Bladed Rotor (1A) and (b) Rimmed Rotor (1B).[27]

Alternative flow meters, such as ultrasonic flow meters (Figure 3.3)), eliminate the concern of mechanical obstructions in the coolant by being placed on the pipe's exterior. These flow meters operate using the 'Time Difference Method,' where two ultrasonic transducers are clamped onto opposite sides of a pipe surface. Next, one transducer acts as the transmitter, propagating ultrasonic sound waves through the flowing fluid, which are then received by the opposite transducer. The flow rate can be calculated based on the speed at which this propagation occurs through the fluid [28].

These units can handle a wide range of flow rates, are low maintenance, and are suitable for dirty and clean fluids. [28]]. However, it was determined that incorporating this type of flow meter is prohibitive due to the high cost per unit and the requirement for each heat-producing electronic component to have a unit installed.

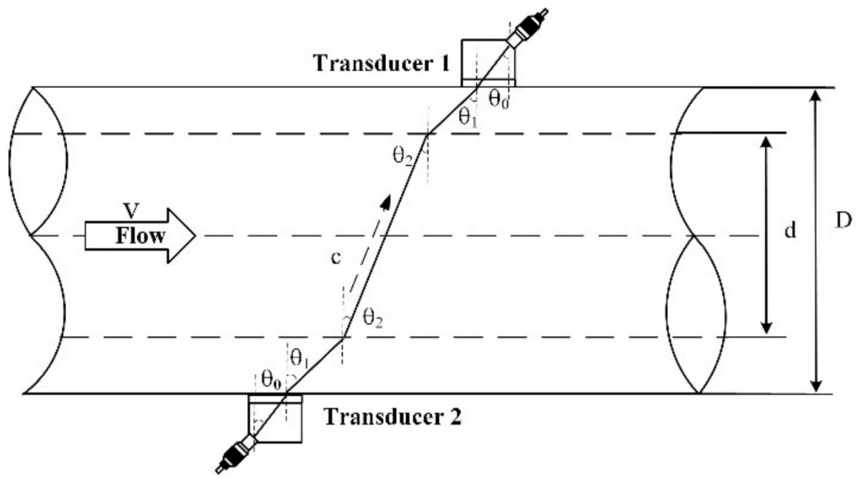

Figure 3.3 Working principle of an Ultrasonic Flow meter using time difference measurement to determine flow rate in the pipe.[28]

3.3.2 Advantages and Disadvantages of Using Thermocouples

Thermocouples operate on the Seebeck or thermoelectric effect, where two dissimilar metal wires, joined at a junction, generate a voltage proportional to the temperature difference between the junction and the ends of the wires. This effect allows for precise temperature measurement [29]. Thermocouples are simple and rugged, making them suitable for long-term use in harsh environments, whereas flow meters, like the standard turbine flow meter, are more limited in their applications [27, 30].

Thermocouple probes, like the one seen in Figure 3.4,can be placed in cooling systems through probe ports. In specific configurations, thermocouples can also be directly mounted on heat-producing components using adhesives such as epoxies, glues, or tapes [31]], eliminating the need for installation within the system. This process can be complex and costly, especially when retrofitting systems without preexisting architecture. However, direct mounting has its caveats. With tapes, insufficient contact between the thermocouple and the component's surface can introduce errors in temperature readings due to air gaps. This issue can be mitigated by using heat-conductive epoxies that eliminate these gaps. However, the epoxy's size and heat transfer capability will also influence the potential for errors [31].

Figure 3.4 Schematic of a metal sheathed thermocouple probe type with partial cross section showing connection of dissimilar metals.[30]

Of course, depending on the application area, the construction material of a thermocouple can vary greatly, as seen in figure 3.1 This variation in material types for thermocouples is essential to ensure their functionality across diverse environments. Different materials allow the thermocouple to operate effectively at varying temperature ranges and meet specific application precision requirements. [30].

Table 3.1 Construction material, thermal limit, and accuracy tolerance of various thermocouple types.[30]

Type	Alloy	Temperature	Standard Limits	Special Limits
T	Copper (+) vs. Constantan (–)	–200 ℃ to 0 ℃* 0 ℃ to 350 ℃	±1 ℃ or ±1.5%* ±1 ℃ or ±0.75%	±0.5 ℃ or ±0.8%* ±0.5 ℃ or ±0.4%
J	Iron (+) vs. Constantan (–)	0 ℃ to 750 ℃	±2.2 ℃ or ±0.75%	±1.1 ℃ or ±0.4%
E	Chromel®(+) vs.Constantan (–)	–200 ℃ to 0 ℃* 0 ℃ to 900 ℃	±1.7 ℃ or ±1%* ±1.7 ℃ or ±0.5%	±1 ℃ or ±0.5%* ±1 ℃ or ±0.4%
K	Chromel® (+) vs. Alumel®(–)	–200 ℃ to 0 ℃* 0 ℃ to 1250 ℃	±2.2 ℃ or ±2%* ±2.2 ℃ or ±0.75%	N.A. ±1.1 ℃ or ±0.4%
N	Nicrosil (+) vs. Nisil (–)	0 ℃ to 1250 ℃	±2.2 ℃ or ±0.75%	±1.1 ℃ or ±0.4%
R	Pt/13%Rh (+) vs. Pt (–)	0 ℃ to 1450 ℃	±1.5 ℃ or ±0.25%	±0.6 ℃ or ±0.1%
S	Pt/10%Rh (+) vs. Pt (–)	0 ℃ to 1450 ℃	±1.5 ℃ or ±0.25%	±0.6 ℃ or ±0.1%
B	Pt/30%Rh (+) vs. Pt/6%Rh (–)	870 ℃ to 1700 ℃	±0.5%	±0.25%

* Thermocouple wire is normally supplied to meet tolerances for temperatures above 0 ℃.
Stock materials may not fall within the sub-zero tolerances given without special selection and testing.

The expense for each thermocouple type varies depending on the material from which it is constructed. Thermocouples constructed from base materials (nickel, silicon, chromium, copper, etc.) are less expensive. These thermocouples are often used in commercial applications where precision or higher temperature tolerance is not required, such as Types T, J, E, K, and N. Other types, like Types R, S, and B, are more specialized in their application areas. They incorporate more expensive precious metals like platinum and rhodium, which give the thermocouple higher temperature tolerance and precision. [30]. In the application presented in this paper, temperatures are low, remaining below 100°C; therefore, cheaper, potentially less accurate thermocouples will still be sufficient.

3.3.3 DT-PT Connection

The proposed blockage detection method consists of two main components: the DT and the PT. The PT represents the real-world system, while the DT serves as its model. As shown in Figure 3.5, temperature data from components in the PT is fed into the DT. This data is then compared with simulated temperature data, allowing the DT to assess the health of the physical system.

In a typical heating scenario, inputting a specific quantity of heat energy should result in a corresponding rise in temperature in the medium receiving the heat. The DT calculates this expected temperature increase based on predefined parameters such as the coolant's specific heat capacity and flow rate. Simultaneously, the PT system receives the same heat input under identical conditions for direct comparison.

Coolant flow will be impeded if a blockage forms in the PT, reducing the amount of coolant available for effective heat transfer. This reduction in coolant flow will lead to a rise in temperature above normal levels. The system is designed to monitor these temperature readings continuously. If the observed temperature exceeds established thresholds, the system flags this abnormality and alerts operators to the potential formation of the blockage.

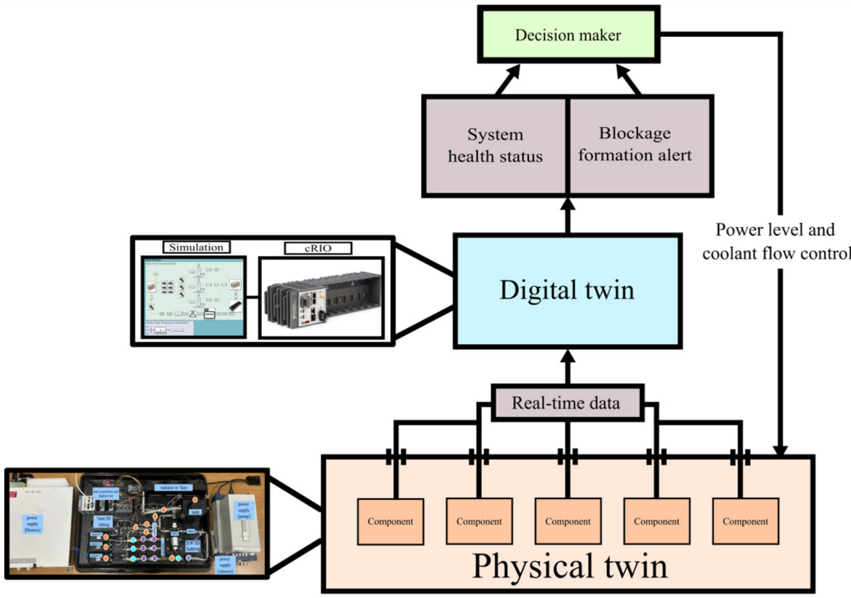

Figure 3.5 Interconnection between PT and DT systems showing flow of information from PT to DT and how the DT processes said information to provide status updates and alerts to the decision maker.

3.3.4 DT Components

The DT in this scenario consists of three main components: the Physical Twin Emulator (PTE), the transient model, and the steady-state model. The DT was constructed in MATLAB Simscape and includes computational blocks that represent the various components of the physical system, such as the pump, heaters with heat exchange blocks, reservoir tank, radiator, and others. The simulation models the thermal behavior of the coolant based on heat injection.

3.3.5 PTE Model

The PTE (Figure 3.6) is a digital representation of the physical BDPD testbed used to evaluate the DT's blockage detection capabilities before the physical testbed was developed. The model simulates the system's thermal behavior when a simulated blockage occurs in one of the heater blocks. Sensors monitor temperature changes in the affected heater block and the subsequent rise. This simulation will be the experimental testbed to test the DT's ability to detect blockages.

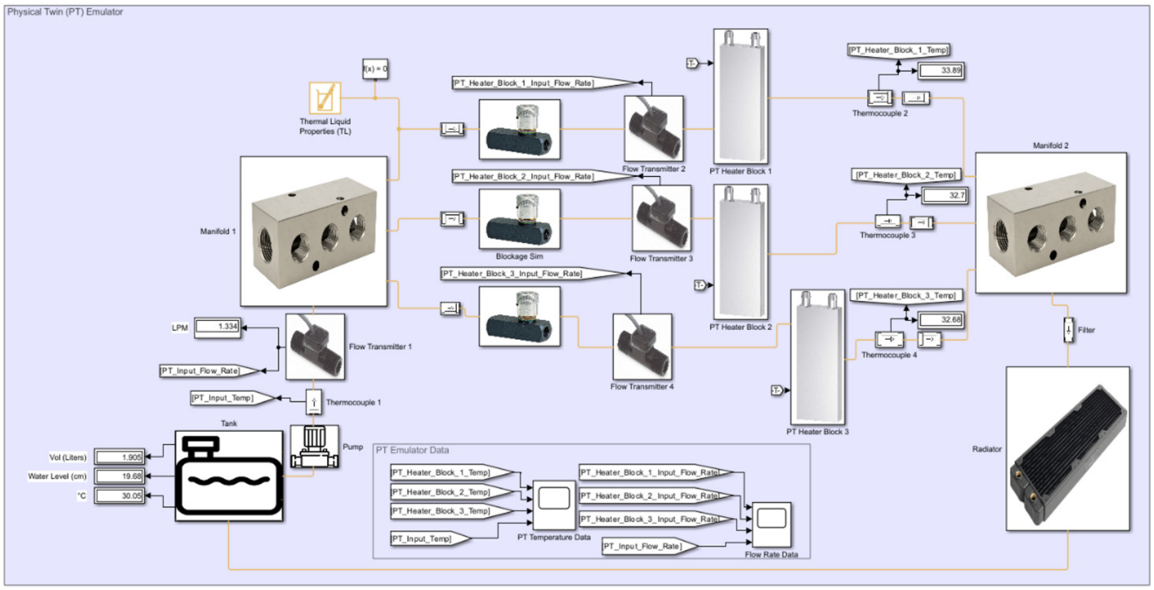

Figure 3.6 Physical Twin Emulator Simulation featuring component layout.

3.3.6 3.3.6 Transient Model

The transient model (Figure 3.7) serves as a digital representation of the physical system, simulating its normal operational state under ideal conditions—assuming no coolant degradation or contamination. This model predicts the system's expected thermal response during heating and cooling operations, helping identify any abnormal thermal behavior in both the physical and emulated systems.

As part of the DT, the transient model emulates the PT and simulates heat dissipation in real time during the PT's operation. It assumes normal operating conditions with no blockage formation. It simulates aspects of the cooling system (heater block temperature, coolant temperature, and flow rate) to represent the normal thermal behavior of the cooling system. The simulated thermal behavior, primarily the heater block temperature, predicted by this model is then compared to that recorded from the PT. If the PT's temperature exceeds the model's predictions, this discrepancy may indicate abnormal heating behavior, potentially signaling the formation of a blockage in the PT.

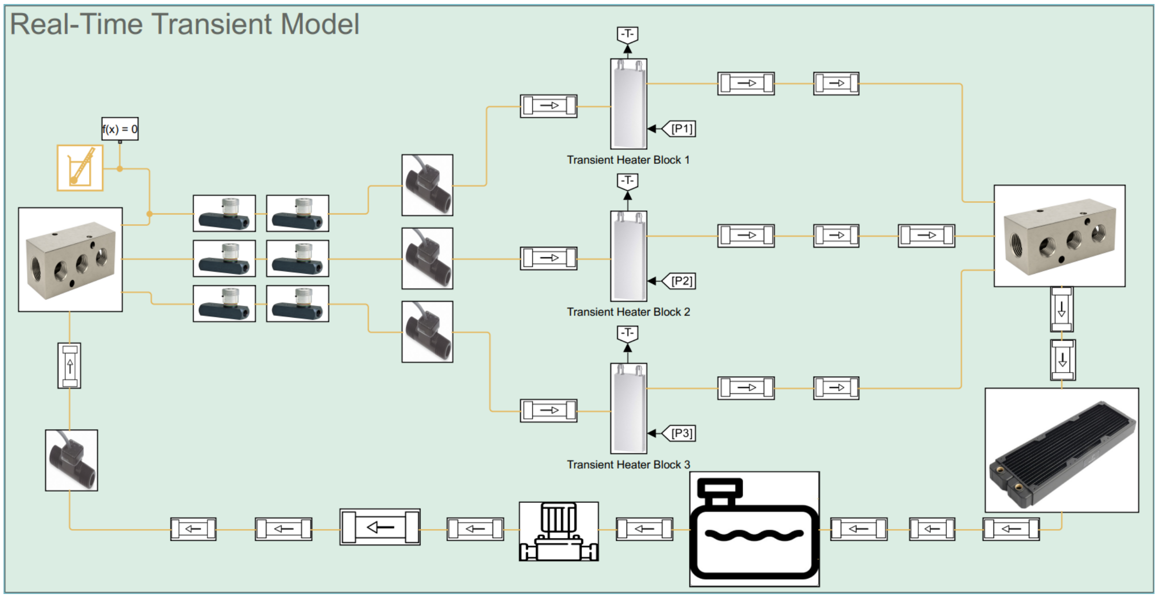

Figure 3.7 DT transient model.

3.3.7 Heater Block

As shown in Figure 3.8,heat injection into the simulated cooling system occurs through a series of heat transfer medium blocks. These blocks first simulate conductive heat transfer through the heater block material and then simulate convection into the water flowing through the heater block.

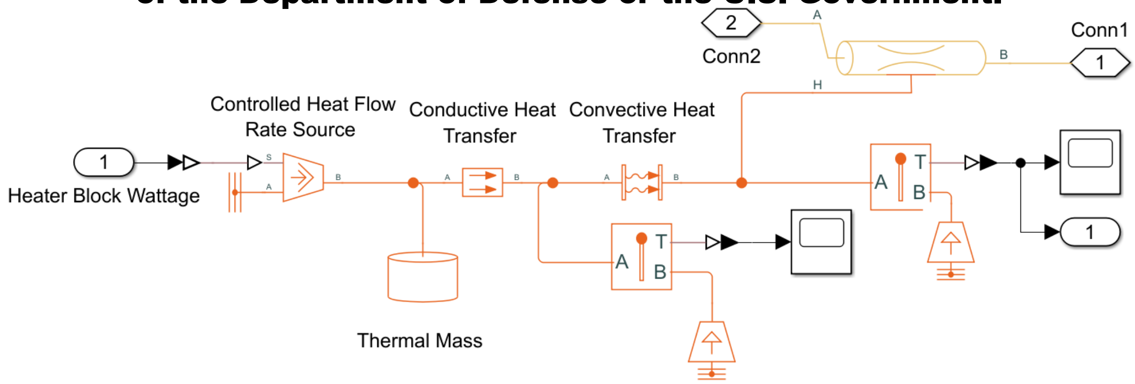

Figure 3.8 Simulated Heater block internal components.

3.3.8 Steady-State Model

The steady-state model (Figure 3.9)) consists of thermodynamic equations that calculate the maximum expected steady-state temperatures within the testbed for a given heat input to each resistive heater. During the experiments, set heat input to the heaters results in an equilibrium where heat losses balance the heat input through the radiator (which remains inactive during this test but still allows free convection to take place) and other components in the system, where convective heat transfer dissipates heat.

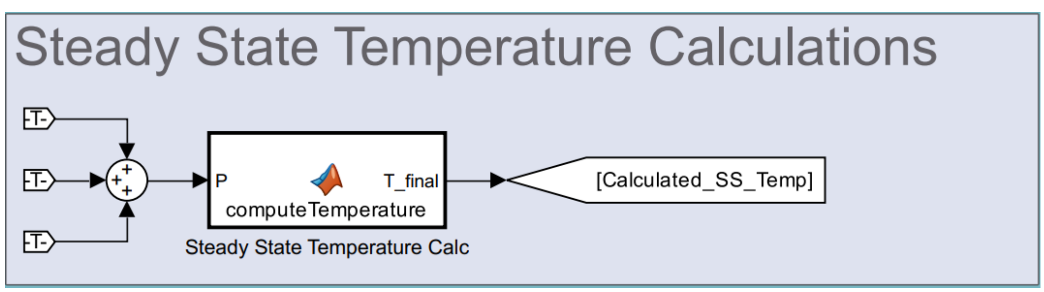

Figure 3.9 Steady-state temperature calculations modules in Simscape.

3.3.9 Automated Blockage Detection System Triggers Overview

For the DT to automatically detect the formation of blockages in the PT—or, in this case, the PTE—a series of checks and triggers are used. These triggers, shown in Figure 28, compare the temperatures of the heater blocks in both the PT and the DT emulator to identify any abnormal thermal behavior in the PT. In regular operation, an electrical load is applied to the electronics housed in the PT. Due to inefficiencies in the electrical network (i.e., conduction losses and switching losses), a portion of the electricity is converted into waste heat. This waste heat production is calculated and provided to the DT, where its transient and steady-state models simulate the heating behavior of the electronics.

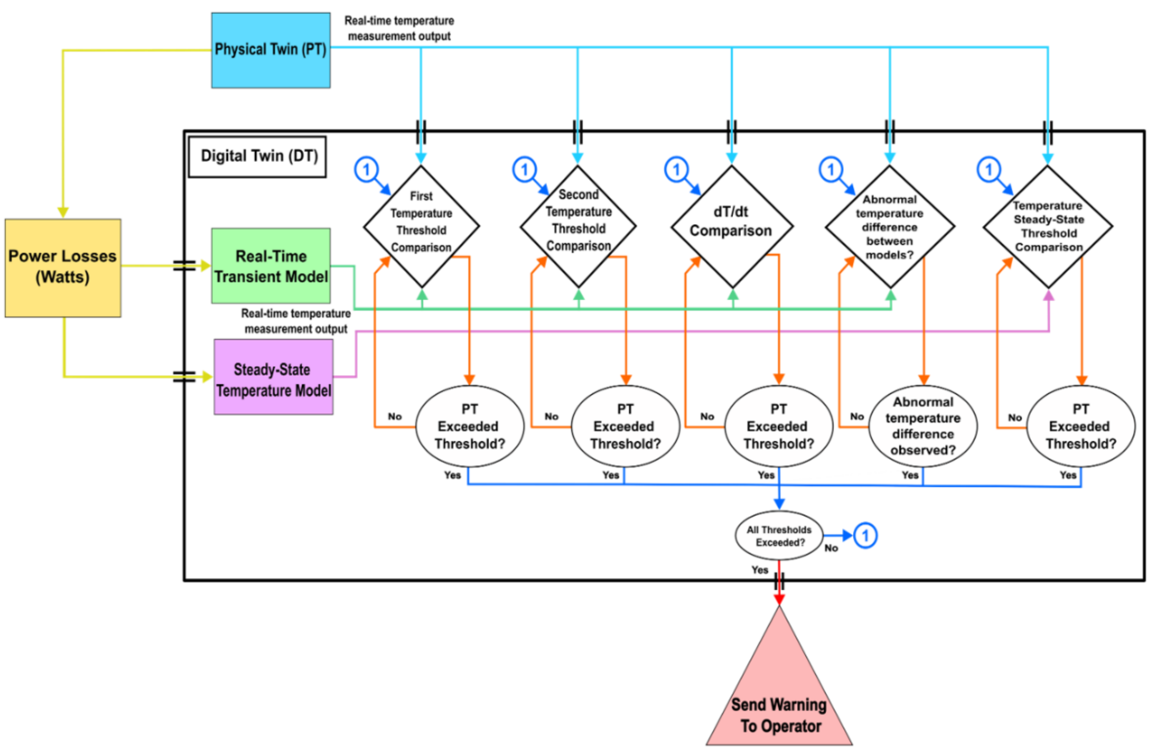

Figure 3.10 Blockage detection algorithm visualized.

To minimize the risk of false blockage detection due to sensor noise or other disruptive factors, five independent triggers are implemented:

1. **Two-Sheet Temperature Checks:** These checks compare temperatures against predefined thresholds to determine if temperatures in components are exceeding safe ranges.

2. **Rate of Temperature Change:** This trigger assesses transient temperature changes ($\Delta T/\Delta t$) in the electronics to identify excessive or abnormal temperature variations.

3. **Inter-Module Temperature Comparison:** This trigger detects temperature drops in neighboring heater blocks that indicate increased cooling in these components resulting from coolant flow redistribution due to a blockage.

4. **Steady-State Temperature Calculation:** Thermodynamic equations are used to calculate the predicted steady-state operational temperature for the electronics, assuming normal coolant flow.

5. **Cumulative Alerts for Blockage Detection:** This trigger activates when all the previous checks (1–4) are triggered and enables the blockage formation warning to be activated.

If only one or two triggers are activated, the system will not automatically send a blockage alert, as this could indicate a temporary anomaly resulting from sensor noise. However, should multiple triggers detect abnormal behavior that activate all the spoken of triggers, then the system will flag the situation and send an automatic alert to an operator or system controller, warning that a blockage is likely forming.

3.3.10 Temperature Data Comparison Between Models

Comparing the thermal behavior observed in the PT system with that emulated in the DT is essential for diagnosing changes, such as blockage formation events, within the components of the physical system. This analysis compares the temperature responses of the PT's transient and steady-state models with those emulated in the PTE (Figure 3.11). This comparison enables the identification of abnormal thermal conditions that may indicate potential failures in the cooling supply indicative of blockage formation.

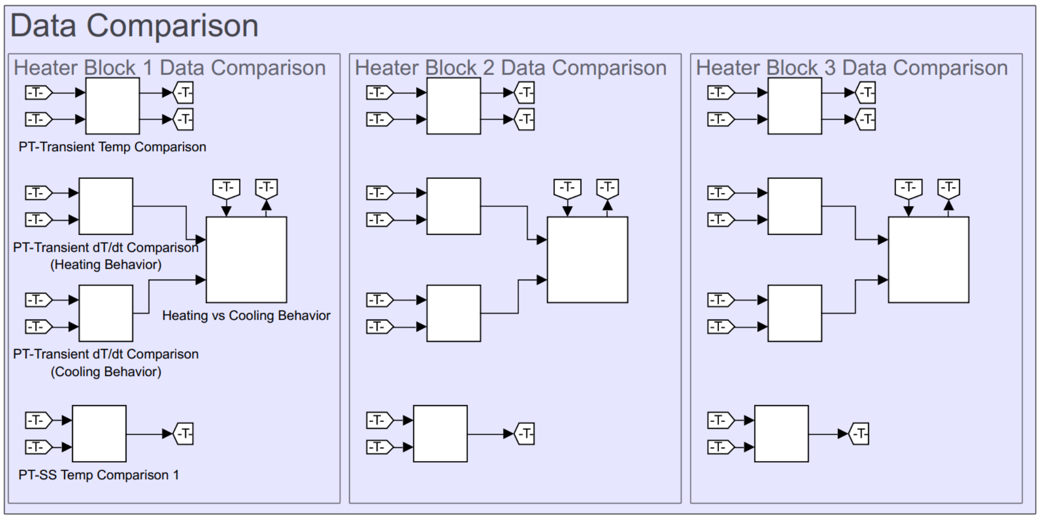

Figure 3.11 Temperature comparison between the transient, steady-state, and emulated PT models determines if abnormal thermal behavior is occurring in the PT, such as overtemperature or abnormal heating and cooling rates.

3.3.11 Neighboring Modules Temperature Behavior

Trigger three relates to an event during which a blockage in the cooling loop of a single heat sink causes an increase in coolant flow to the neighboring heat sinks on the same loop. This enhanced coolant flow improves cooling in these neighboring heat sinks, leading to an abnormal temperature drop. This trend can be used to identify blockage formation within the cooling system. An example of this behavior is shown in Figure 3.12. In this case, a blockage forms in Heater Block 1 (H1), which subsequently results in increased coolant flow through Heater Block 2 (H2) and Heater Block 3 (H3), causing a momentary drop in temperature in both. This temperature anomaly indicates a blockage likely formed in Heater 1 (H1).

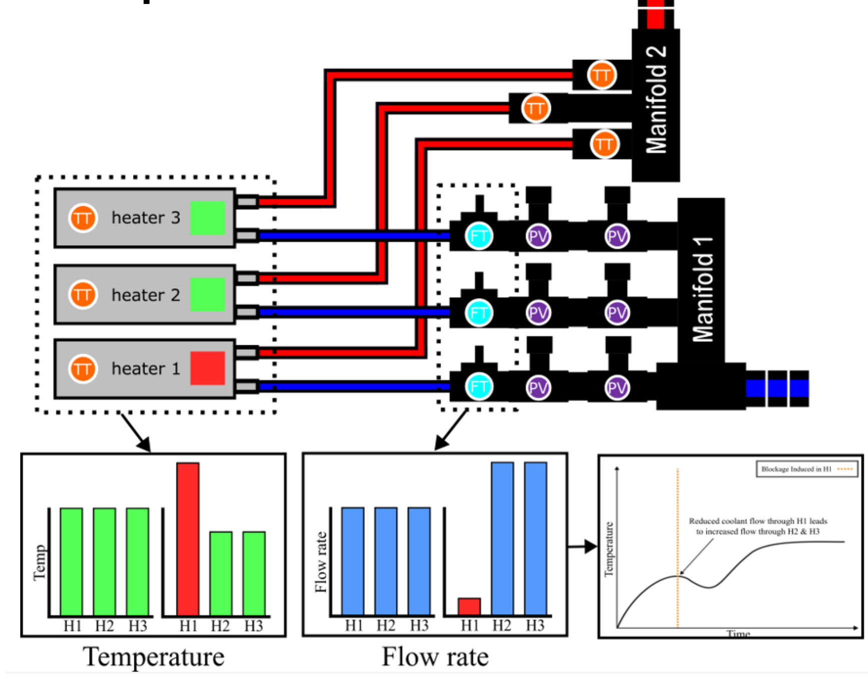

Figure 3.12 Blockage formation effect on neighboring heater blocks and how it can be used as a trigger for detecting blockage formations.

This behavior is one of the triggers used to detect blockages. An unexpected temperature drop in neighboring heater blocks indicates that coolant flow to the affected block has been obstructed, suggesting a potential blockage. By monitoring this pattern, the system can detect changes in coolant distribution and pinpoint the location of the blockage(s).

3.3.12 Trigger Activation and Warning to System or Operator

When all five checks are active, the signal passes through an "AND" logic gate (Figure 3.13),and a notification is sent to the operator indicating the potential presence of blockages. The operator can address these blockages, or the DT can automatically implement corrective measures. For instance, if a blockage is detected in one heating block, the DT can redistribute power to maintain operational capacity across the system by reallocating power to the remaining functional heater blocks. As a result of the increased power load, the temperatures of the heater blocks will rise, requiring a greater supply of coolant to prevent overheating. The DT can adjust several valves to redirect coolant flow to these heater blocks to compensate

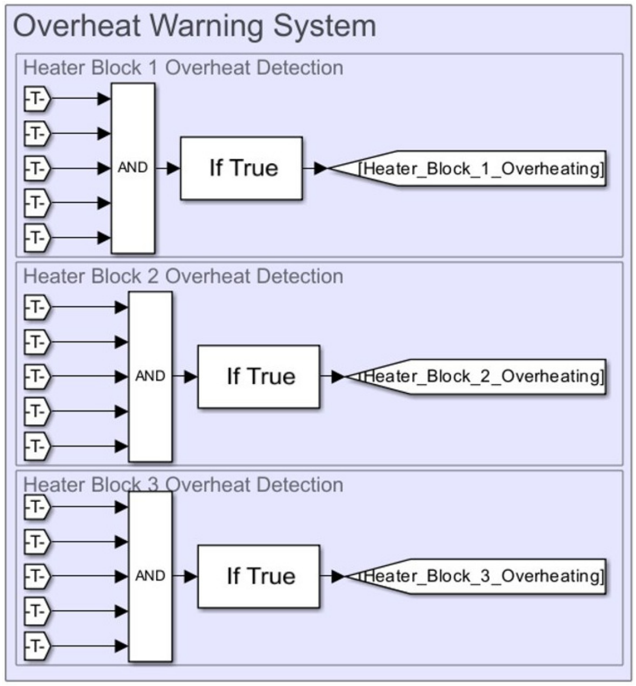

Figure 3.13 Cumulation of individual trigger into an "AND" so that only when all five triggers are active will a blockage detection alert be sent.

To reduce the likelihood of false triggers caused by brief fluctuations, specific triggers—such as the temperature rate of change ($\Delta T/\Delta t$))—are equipped with a timer that ensures they remain active for several minutes. If all four other triggers are also activated, the blockage detection warning will be triggered during this time. This approach helps filter out short-term noise, ensuring that only sustained, abnormal temperature changes lead to a blockage formation alert.

3.4 Experiments

Validating the DT's automated blockage detection method involved assessing the effectiveness of the thermal triggers under varying test conditions. These tests (Table 3.2) included three scenarios that tested the DT's ability to detect abnormal thermal behavior indicative of a blockage formation in one of the heater blocks.

Table 3.2 Validating Experiment Profiles.

Heater Block #	Test Profile 1	Test Profile 2	Test Profile 3
1	98.5% Blockage | 125W | Blockage @ 3600s	0% Blockage | 200W - 25W @ 3600s	80% Blockage | 125W | Blockage @ 3600s
2	0% Blockage | 125W	98.5% Blockage | 200W - 25W @ 3600s | Blockage @ 4500s	80% Blockage | 125W | Blockage @ 3600s
3	0% Blockage | 125W	0% Blockage | 200W - 25W @ 3600s	0% Blockage | 125W

3.4.1 Testing Procedure

Testing involved inducing the same blockage scenario in both the DT and PT models. The temperature rise in the affected heater block was recorded and compared across both systems.

- **Test 1:** A 98.5% blockage was induced in H1 at 3600 seconds, while H2 and H3 remained unaffected.
- **Test 2:** A blockage was induced in H2 at 4500 seconds during a cooling period, when the wattage was reduced from 200 watts to 25 watts. H2 was affected, while H1 and H3 remained unchanged.
- **Test 3:** 125 watts were applied to all three heaters, and at 3600 seconds, an 80% blockage was induced in both H1 and H2. H3 remained unaffected.

The DT's blockage detection system then analyzed the temperature differences between the PTE and DT models to identify blockages in the heater blocks.

3.5 Results and Discussion

The results showed that the detection time was shorter for high-level blockages (>90% blockage induction) and longer for lower-level blockages (<90% blockage induction). This is because more severe blockages cause a more significant temperature rise, which the system can detect more quickly. The system identified blockages by monitoring the temperature increases in the affected heater block(s) resulting from reduced coolant flow.

The results for each test profile were as follows:

- **Profile 1:** Detected a blockage in the affected heater block 1.33 minutes after initiation.
- **Profile 2:** Detected a blockage 1.58 minutes after initiation in a cooling scenario, validating detection even during reduced heating power.
- **Profile 3:** Successfully flagged simultaneous blockages in two heater blocks 5.66 minutes after initiation, demonstrating its ability to detect multiple blockages simultaneously.

3.5.1 Subplots

Each result figure has five subplots, each displaying key data from the models. Subplot A shows the heater block temperatures from the PTE, Subplot B displays the transient model temperatures, and Subplot C shows the calculated steady-state temperature based on the power input. Subplots D and E highlight the activation of the blockage detection triggers and the time when all triggers indicate the formation of a blockage.

A yellow vertical line marks the introduction of the simulated blockage, while a red vertical line indicates when the heater temperature exceeds the set safety threshold—80°C in this case. This threshold is arbitrary and may vary depending on the specific electronics used. Once the temperature exceeds this threshold, power to the heater block is cut off to prevent further temperature rise and potential damage to sensitive components.

3.5.2 Profile 1

In this experimental profile, from 0 to 3600 seconds, each heater block usually operates with an applied load of 125 watts to the heater block. However, at 3600 seconds, a 98.5% blockage in H1 causes an immediate and rapid rise in temperature. This increase continues until the temperature of H1 reaches the 80°C threshold (represented by a red vertical line), at which point the system deactivates to prevent overheating. The entire process, from the onset of the blockage to deactivation, takes approximately five minutes (Figure 3.14).

As the temperature rises rapidly, three blockage detection mechanisms are activated almost immediately, as shown in Subplot D.

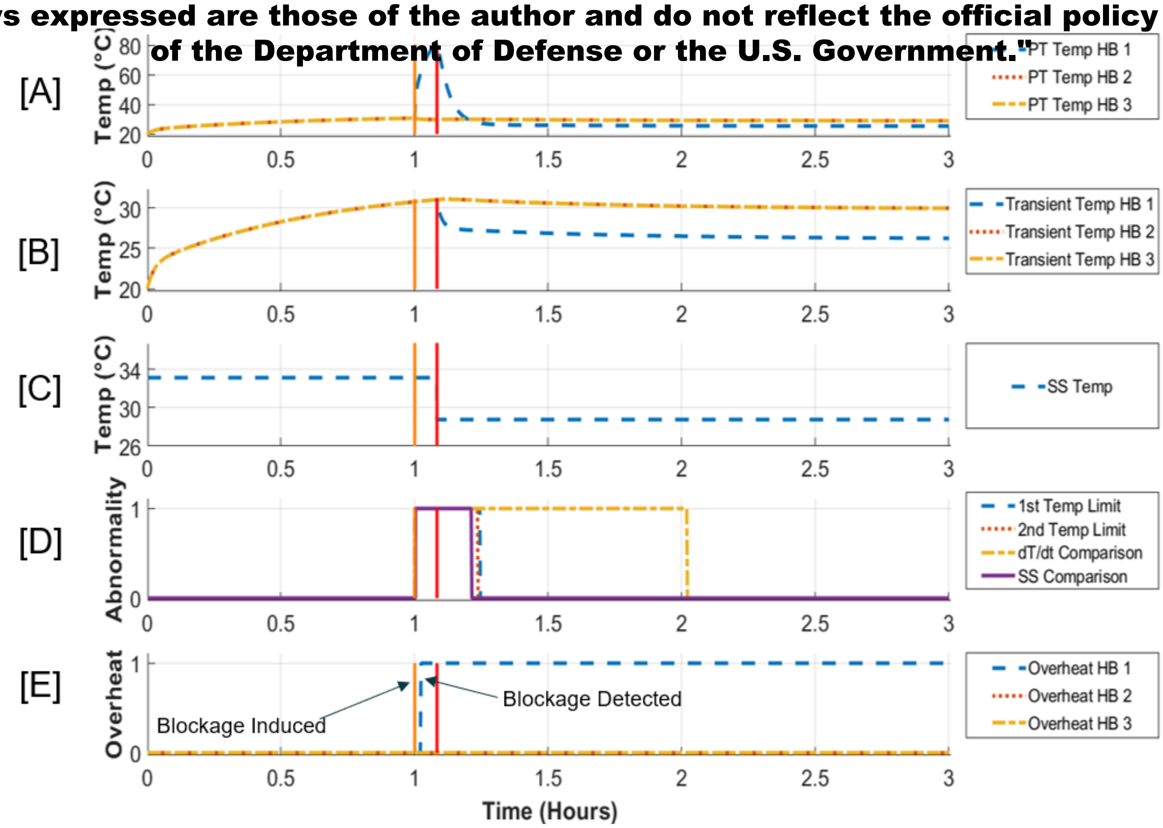

Figure 3.14 Results from test profile 1, showing that the DT can detect blockages in heating scenarios.

Additionally, while not shown here due to the time scale, the Inter-Module Temperature Comparison trigger was activated, indicating that the system observed an abnormal temperature difference between the three heaters. The last trigger to be activated was the steady-state temperature trigger, set at approximately 55°C for a power input of 125 watts. At 1.33 minutes after the blockage introduction, this final trigger was activated, and the system's blockage detection warning was triggered. The temperature reached above 80°C around five minutes after the blockage introduction, triggering the automatic shutdown of the simulated component.

3.5.3 Profile 2

Although the heater block did not reach the 80°C thermal shutoff threshold due to the decrease in input heat from 200 to 25 watts, a temperature rise still occurred due to the loss of coolant flow (Figure 3.15). As in Test 1, the overtemperature and $\Delta T/\Delta t$ triggers activated soon after the blockage was introduced, followed closely by the Inter-Module trigger.

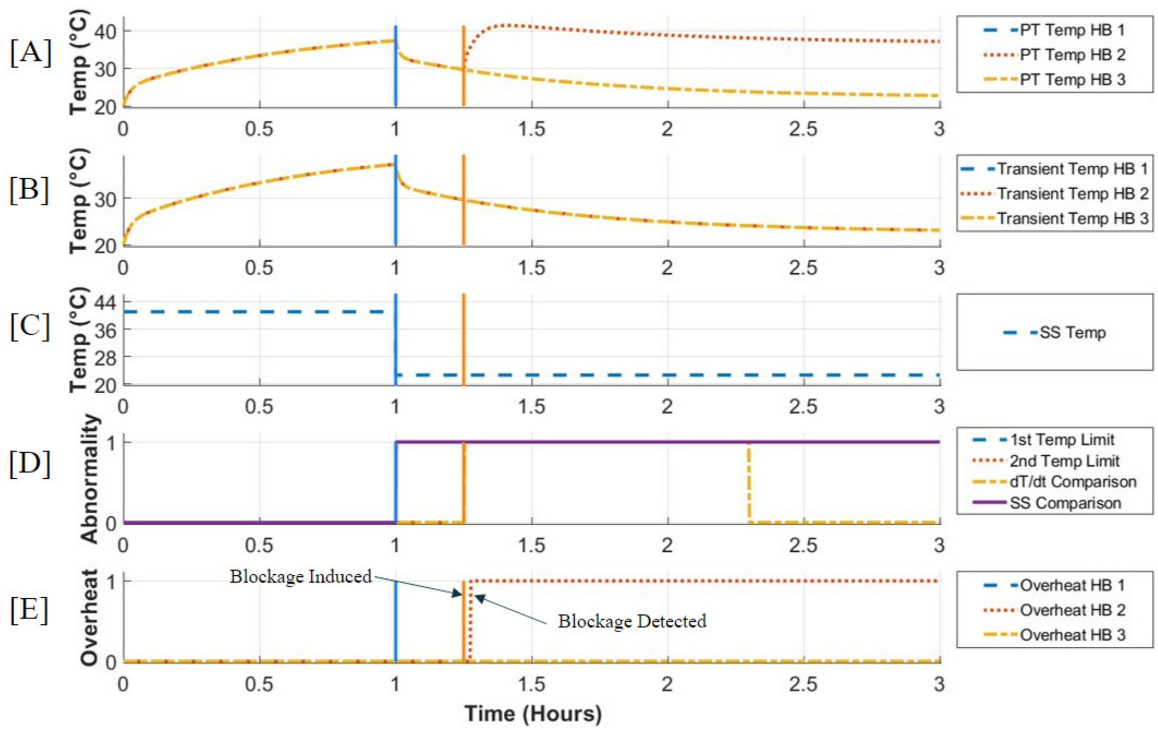

Figure 3.15 Results from profile 2, showing that the BDPD can detect blockage formations during cooling scenarios.

Interestingly, due to the drop in power input, the temperature of the heaters temporarily exceeds the calculated steady-state temperature at 3600 seconds. At 4500 seconds, upon the introduction of the blockage, the other triggers were activated 1.58 minutes after the blockage introduction, leading to the successful triggering of the blockage detection warning.

3.5.4 Profile 3

During the cooling tests, with 80% blockage formation in two heater blocks, the time required to detect the blockages was extended to 5.66 minutes (Figure 3.16). This delay was attributed to the slower rate of temperature change, as the blockages were less pronounced compared to the more significant blockage formation observed in the first case

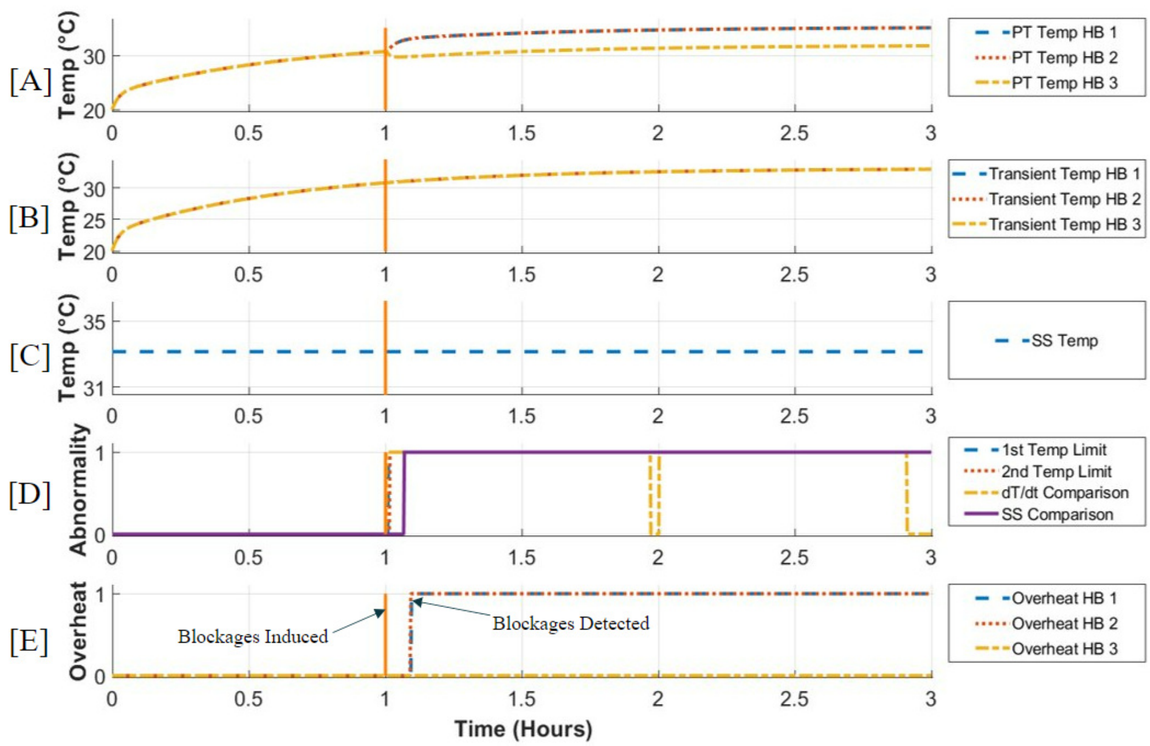

Figure 3.16 Results from third test profile showing that the DT can detect multiple blockages at once.

Although more time was required to detect the blockage formation due to the lower blockage percentage and slower rise to the steady-state temperature, the system could still detect the blockage once the temperature of the affected heater exceeded the projected steady-state value. For systems operating at a steady state, detection is expected to be prompt, as the detection algorithm will immediately identify any temperature rise above the standard (steady state) range.

3.6 Conclusion

This study details the development and validation of an automated method for detecting blockage formation in water-cooled electronics. The method involves creating a Digital Twin (DT) simulation that emulates a proposed Physical Twin (PT) testbed, incorporating a series of thermal triggers that activate in response to abnormal temperatures in the PT. These thermal anomalies signal potential blockage formation in one of the PT's components.

A Physical Twin Emulator (PTE) was used to validate the blockage detection method alongside the DT model, which includes both a transient model and a steady-state temperature model. These models were designed to simulate the normal thermal behavior expected from the PT testbed. Blockage formation was successfully detected by comparing PTE and DT temperature data.

The effectiveness of the DT's blockage detection algorithm was verified through a series of experiments involving three blockage scenarios. A digital representation of the proposed physical testbed was created to simulate the thermal behavior of water-cooled electronics, specifically focusing on how blockages in the cooling network affect system performance. The experiments included one scenario under heating conditions, another under cooling conditions, and a third involving multiple blockages in individual heater blocks. These tests confirmed that the DT system could detect blockage formation within the cooling system.

With the temperature-based blockage detection method successfully validated, the next step is to implement the DT system on a real-world testbed. This will allow testing under real-world conditions, further refining the detection algorithms, and evaluating the system's practical capabilities.

Chapter 4

Integration of Digital Twins for Blockage Detection in Real-World Systems

Given the success of the Digital Twin (DT) in detecting blockages in simulated scenarios, it was deemed viable for further implementation and testing with a physical, real-world testbed. The DT's blockage detection capabilities will now be tested under real-world conditions.

4.1 Abstract

This chapter focuses on developing a real-world Physical Twin (PT) testbed to assess the DT's ability to detect blockages in a water-cooled electronic system. After successfully demonstrating the DT's blockage detection algorithm using a simulated Physical Twin Emulator (PTE), a testbed known as the BDPD (Blockage Detection and Power Distribution) system was constructed. This testbed replicates the cooling system of electronic components, with heater blocks simulating heat-generating electronics. Sensors in the BDPD provide real-time temperature and flow rate data to the DT that operates in parallel with the PT. The DT was initially characterized through experiments on the BDPD to collect data on the system's heating behavior. Minor adjustments were made to the DT simulation to account for real-world factors and increase the accuracy and emulation of the BDPD's thermal behavior. Following this, the DT's blockage detection capability was validated by inducing a near-total loss of coolant flow to one of the heaters, causing a rapid temperature rise. The DT's

blockage detection algorithm successfully identified this temperature increase and issued a blockage formation warning to the operator 1.27 minutes after the blockage was introduced. This early detection of the blockage formation allowed operators to take corrective actions, such as cutting power to the affected heater, thus preventing potential damage. This experiment's results validated the DT's effectiveness for detecting blockage formation in liquid-cooled electronics and demonstrated its practical utility in real-world applications. However, while the testing effectively showcased the DT's detection algorithm, the testing scope was limited. Further tests may be necessary to evaluate its performance under different circumstances fully.

4.2 Introduction

Having validated the concept of using a DT for blockage detection in water-cooled electronics, the next step is to test this methodology on a physical system. The physical testbed, known as the BDPD system (Blockage Detection and Power Distribution), is a miniature model designed to replicate the cooling system developed in the DT, as well as the basic cooling mechanisms commonly seen in the cooling systems of water-cooled electronics. The testbed will provide a controlled environment to assess the performance of the blockage detection algorithm in real-world conditions. The BDPD system will be equipped with valves to introduce blockages into the cooling loops of individual components, enabling repeatable tests. This setup will allow for precise simulation of blockage formation, ensuring consistency across multiple experiments.

The DT will operate in real time, receiving temperature data from the physical testbed. By comparing the temperatures measured in the testbed's heater components with the corresponding data from the DT, the system will use the thermal triggers outlined earlier to detect the formation of blockages.

4.3 Materials and Methods

This section outlines the materials and components used in constructing the BDPD testbed and the characterization process employed to align the thermal and physical properties of the BDPD with its corresponding DT representation.

4.3.1 BDPD

The Blockage Detection and Power Distribution (BDPD) testbed, shown in 4.1, serves as a platform for testing and validating the DT system for detecting blockages in liquid cooling systems. This small-scale testbed incorporates standard components commonly found in liquid cooling systems, providing a controlled and manageable environment for evaluating the DT. In this setup, the BDPD testbed functions as the Physical Twin (PT), enabling real-time simulation of system behavior and assessing the DT's effectiveness in detecting and diagnosing cooling system blockages.

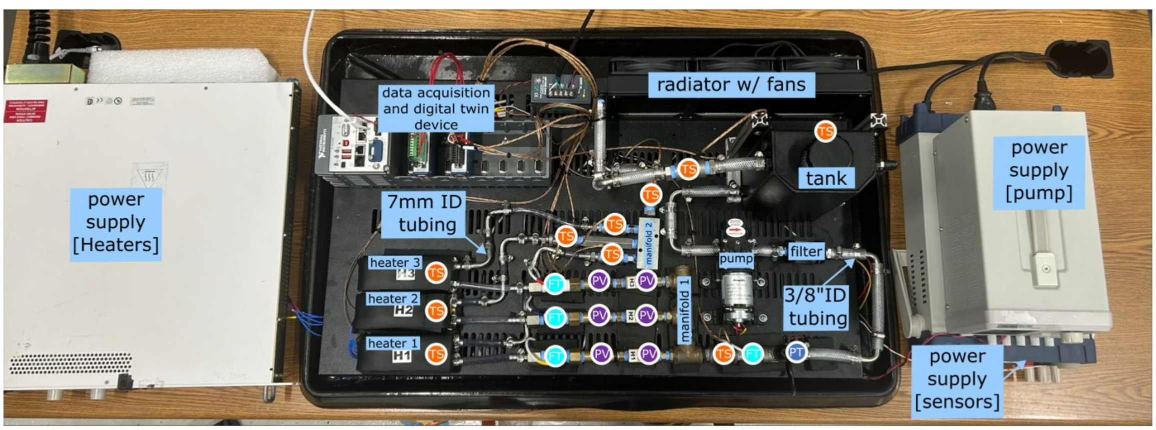

Figure 4.1 BDPD physical testbed showing component layout.

By comparing real-time temperature data from the water-cooled components with the DT's blockage detection system, abnormal Physical Twin (PT) behavior can be identified, indicating potential blockage formation. This early detection enables operators to take corrective action before any damage occurs to the affected component(s).

4.3.2 Component Integrated System

As shown in Figure 4.2, the system includes components for pumping coolant, evenly distributing it to each heater, filtering the coolant, measuring temperature changes after heating, and removing heat from the coolant using a radiator and fan system

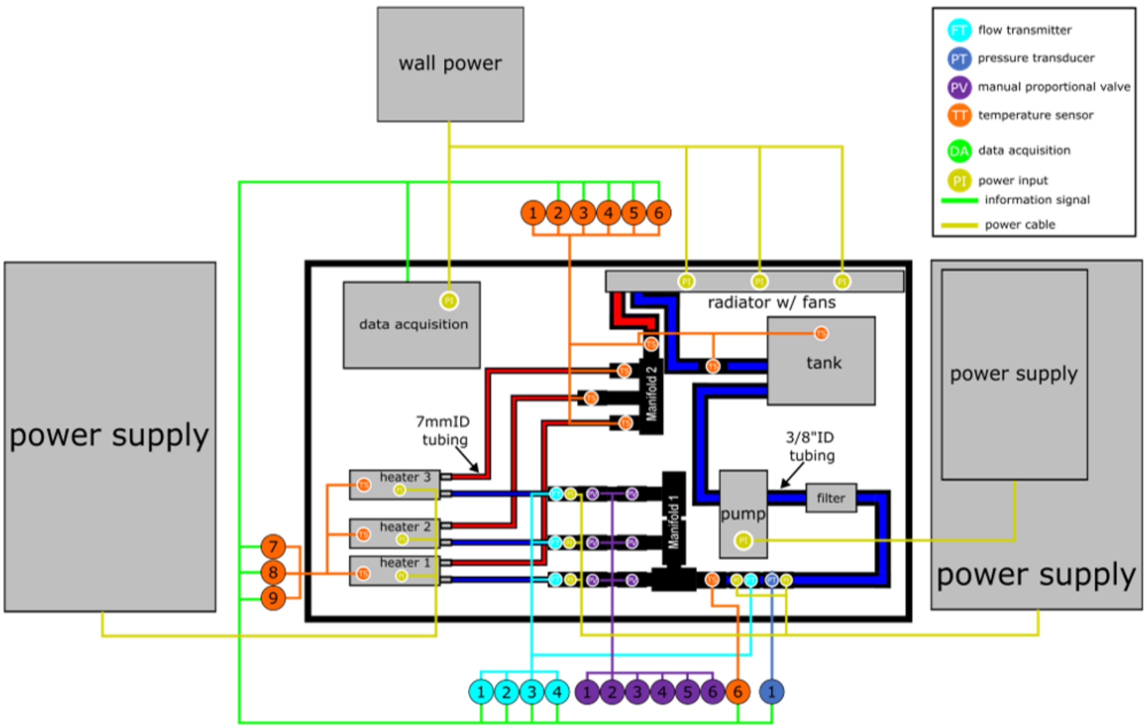

Figure 4.2 Diagram of BDPD component layout with bubble labels and information and power flow paths.

4.3.3 Heaters with Heat Exchangers

The testbed features three aluminum heating blocks, each equipped with an electric resistive heater to inject heat into the system (Figure 4.3). Water circulates through each heat exchanger to regulate the blocks' temperature. TThe resistive heater operates on a 120 V DC supply at a current of 1.7 amps, resulting in a watt density of 44 W/in² (or 6.82 W/cm²). Although these heaters are typically designed for 120 V AC, using DC voltage from the power supply is not expected to significantly affect the heat output, as the heaters function as simple resistive elements.

To optimize heat transfer between the heater and the heating block, thermal paste with a thermal conductivity of 114 W/m · K will be applied. This compound eliminates air gaps between the surfaces, enhancing thermal conductivity and improving heat transfer efficiency. The heaters and heating blocks are also insulated with high-performance thermal materials to optimize heat transfer further and reduce thermal losses. This insulation helps minimize heat dissipation to the surrounding environment, ensuring that the heat generated by the heaters is efficiently directed toward the coolant

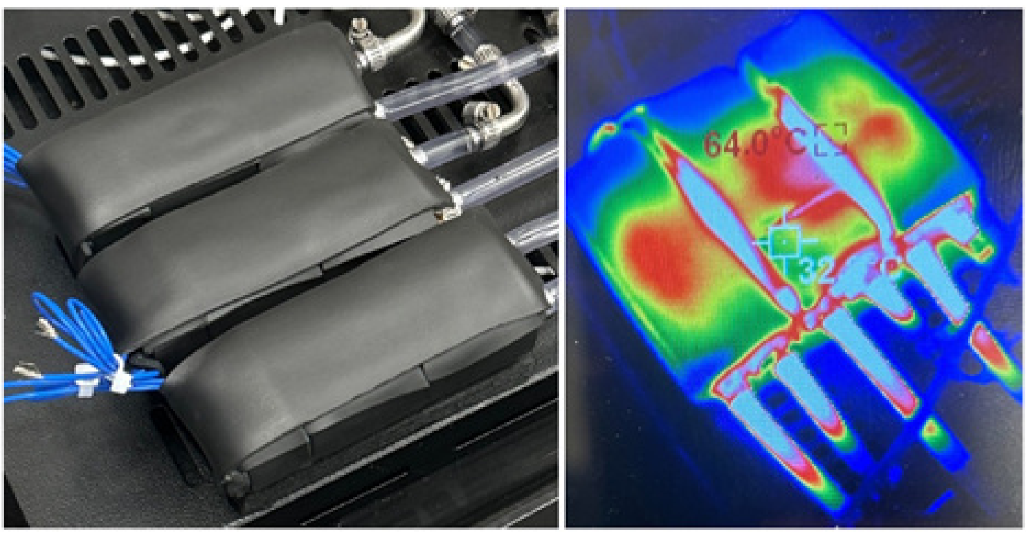

Figure 4.3 BDPD heater blocks with insulation and thermal signature during operation.

By minimizing heat loss in the BDPD system, the DT's performance can be improved. Less effort and time are required to characterize the DT and account for parasitic heat losses from local sources, like air conditioning, that may affect the system. However, based on thermal imaging, hot spots are apparent on the sides of the insulated heaters, indicating insufficient insulation. To remedy this, denser insulating material with lower thermal conductivity (K value, W/m · K) or thicker insulation layers may increase the barrier through which heat must pass before escaping into the surrounding atmosphere. The K value represents the rate at which heat (in watts) passes through a material based on its thickness (in meters) and a temperature gradient (in Kelvin) between the two sides.[32] Materials with lower K values are more thermally insulating than those with higher values. Improving the insulation of these heaters may increase heat transfer efficiency between the heater and coolant.

4.3.4 System Construction Components

In addition to the heating block components, the testbed includes several other key components that represent the cooling system of liquid-cooled electronics. These components include:

- **Power Supplies:** o Several DC power supplies provide power to the system, with larger units for the heaters and smaller units for the pump and sensors.
- **Flow Distribution Manifold:** Two manifolds distribute coolant—one for the cold loop and one for the return loop; These manifolds also serve as mounting points for sensors.
- **Coolant:** A mixture of 69.5% deionized water[1], 30% propylene glycol[2], and 0.5% corrosion inhibitor. The propylene glycol prevents organic growth, while the corrosion inhibitor protects metals from corrosion.
- **Flow meters:** Turbine flow meters are installed for each heater block to help balance flow and provide real-time data on coolant distribution to maintain even cooling ability between heaters.

[1] Deionized water is water that has had its mineral ions removed via ion exchange. [[33]]

[2] Propylene glycol is a synthetic compound used as an antifreeze and biostatic (prevents biological growth) compound in cooling systems. [34]

- **Thermocouples:** K-type thermocouples are placed throughout the system to monitor coolant temperatures, including sensors on both the send and return manifolds and on the heater blocks.

- **Reservoir Tank:** Holds 1.5 liters of coolant, providing thermal mass and helping to stabilize temperature fluctuations.

- **Radiator:** Cools heated coolant using forced convection before it returns to the reservoir.

- **Pressure Sensor:** A pressure gauge downstream of the pump monitors for excessive pressure at the system outlet.

- **Pump:** A diaphragm pump with a maximum flow rate of 1 gpm (3.785 L/min) circulates coolant within the system.

4.3.5 Flow Control Proportional Valves

The supply portion of the system includes two sets of proportional needle valves. One set works with flow meters to regulate and balance the coolant flow to each heater, ensuring consistent distribution across the system. The second set of needle valves induces simulated blockages within the cooling loops of individual heater blocks. Needle valves are preferred because they can make precise, proportional adjustments to coolant flow based on valve position. This ensures repeatable experimental conditions. In contrast, using materials such as sand or other particulates would compromise repeatability. These materials would require cleaning the testbed after each experiment, which could introduce inconsistencies and affect the calibration of the DT.

4.3.6 Characterization

For the DT to detect blockages accurately in conjunction with the physical testbed, it must replicate the system's thermal behavior with high fidelity. This includes simulating temperature variations resulting from heat injection and ensuring that the DT and the physical testbed exhibit similar temperature responses under the same heating conditions. Such alignment is crucial for maintaining consistent performance between the two systems. The model must first be characterized to develop an effective DT of the BDPD testbed capable of detecting blockages. While an uncharacterized model may provide rough approximations of system behavior, as shown in figure 4.4,it cannot be relied upon to accurately reflect real-world performance without propitiation. Therefore, experimental data is essential for verifying the DT's accuracy, ensuring it reliably mirrors the physical BDPD testbed under various operational conditions. This process of characterization and validation is critical for building confidence in the DT's ability to detect blockages and optimize system performance.

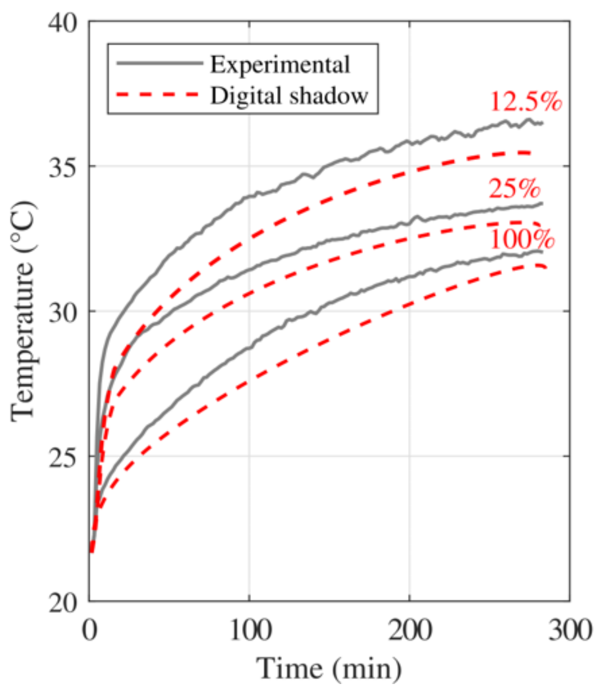

Figure 4.4 Example of thermal behavior of an insufficiently characterized digital system compared to its physical counterpart's thermal behavior.

Any discrepancies between the DT's and PT's temperature responses could undermine the effectiveness of blockage detection. Inaccurate thermal behavior could lead to false positives, triggering unnecessary interventions, or false negatives, resulting in missed maintenance needs. Ensuring that the DT accurately mirrors the thermal dynamics of the physical system is essential for reliable blockage detection and the prevention of potential system failures.

4.3.7 BDPD Testbed Thermal Behavior

Accurately representing key parameters in the DT simulation is crucial for effectively detecting blockages in the emulated physical system. Ensuring these parameters align between the physical system and the DT is vital for reliable blockage detection. Initially, a control test was performed under normal operating conditions with no blockages. Each heater block received full flow and 200W of power. Temperature data were recorded from sensors placed at various points in the testbed, as shown in Figure 4.5.

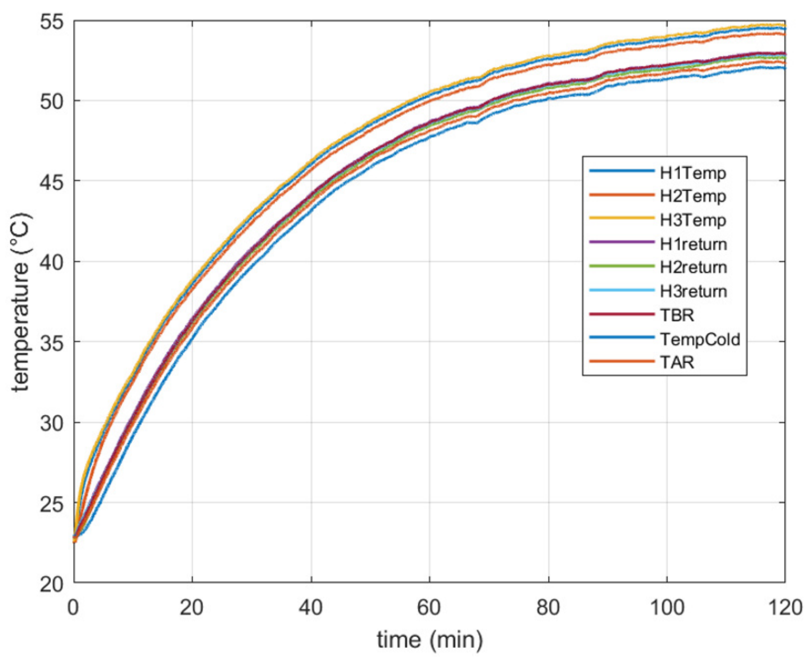

Figure 4.5 Control test of BDPD showing temperatures at various locations on the testbed. Note: H1-3 = heater blocks 1-3, H1Return-3Return = hot side return temp for heaters, TBR = Temp Before Radiator, TAR = Temp After Radiator, TempCold = main line cold temp.

The results indicate temperature rise in the system's heaters, stabilizing at a semi-steady temperature of approximately 55°C, while the coolant reaches a steady-state temperature of around 52°C. At this point, the system has reached equilibrium, where the heat input is balanced by heat loss through convective losses from components such as the inactive radiator, uninsulated tank, and uninsulated pipes. This data was then used to characterize the DT by adjusting parameters within the simulation—such as heat transfer coefficients, coolant flow rates, and specific heat capacities—to enhance the accuracy of the simulated temperatures and align them with those observed in the physical system.

4.3.8 Characterization Experiment for DT

Figure 4.6 displays the results of characterizing the DT using raw data collected from the BDPD control test. This data was compared with the DT simulation to evaluate its accuracy. Several parameters, including the heater blocks' thermal masses, heat transfer coefficients, radiator heat loss, and coolant volume, were adjusted to enhance the DT's accuracy.

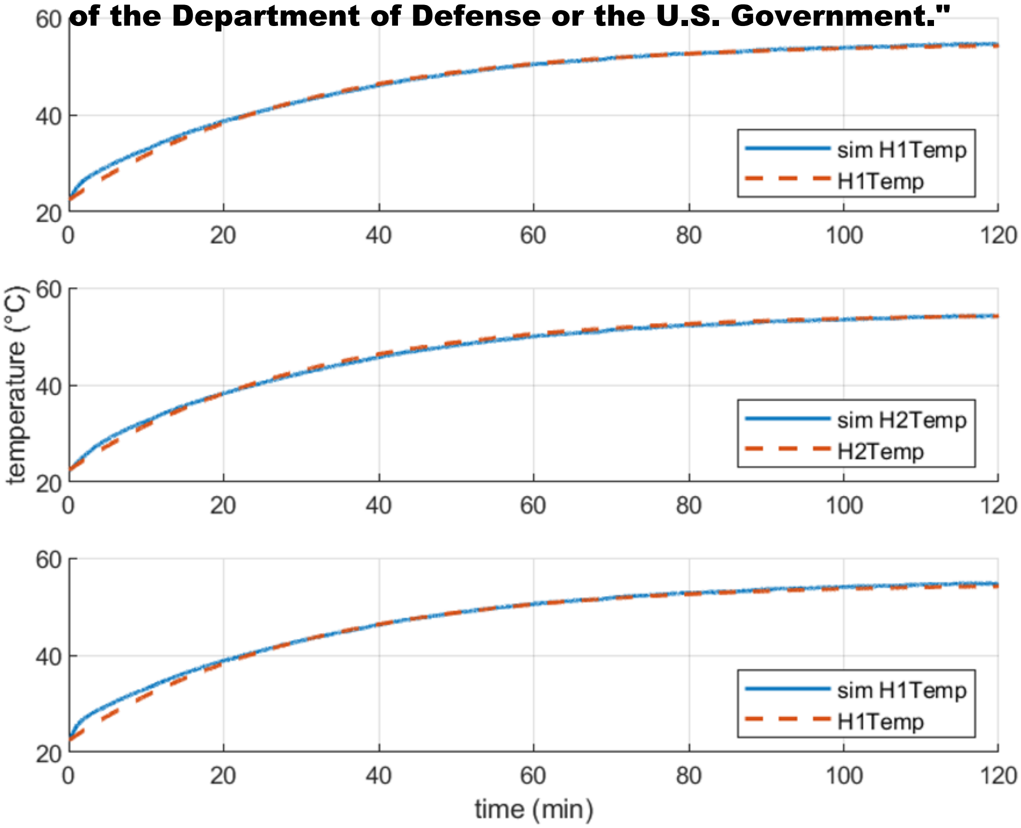

Figure 4.6 Results from characterization under normal flow conditions to test the accuracy of the DT.

After characterization, the DT accurately replicated the PT's thermal behavior under normal conditions. However, additional tests were required to evaluate how the DT would simulate thermal behavior under varying flow rates. These tests were essential to ensure that the DT could effectively model the effects of changes in coolant flow, which directly influences temperature patterns and plays a key role in detecting potential blockages in the system.

4.3.9 Different Flow Rates

In this final round of characterization (Figure 4.7), the H1 valve was set to 50% open, while the H2 heaters remained fully open at 100%. The figure compares the temperatures from heaters H1 and H2 with physical temperature readings from sensors on the

BDPD compared to their simulated counterparts from the characterized DT model. This comparison is crucial for verifying that the DT accurately reflects the thermal behavior of the physical system under the specified conditions, particularly with varying flow rates and heating scenarios. By ensuring that the simulated and physical temperatures align, the DT can be further refined to accurately detect temperature changes that indicate potential blockages in the cooling system.

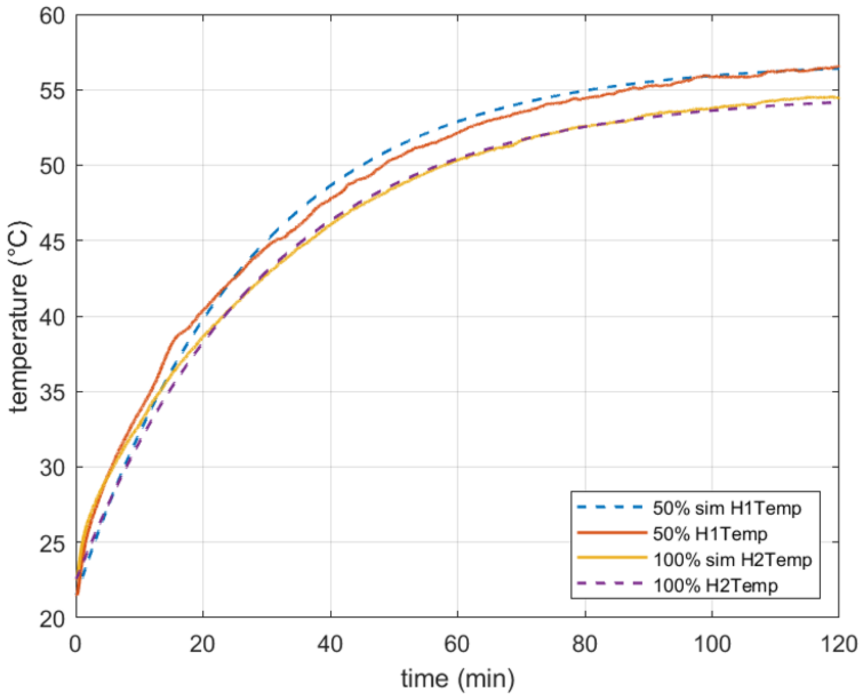

Figure 4.7 Testing of characterization of DT and PT of BDPD testbed for 100% and 50% flow rate to heater block.

Physical temperature results from sensors on the BDPD show that H1, with a 50% blockage applied, experiences a higher rate of temperature rise and a higher steady-state temperature than H2, which remains fully unblocked. This difference in thermal behavior is expected, as the blockage impedes coolant flow to H1, resulting in less effective cooling and a higher temperature rise. A comparison of the physical temperature data from H1 and H2 with their simulated counterparts in the DT confirms that the DT accurately simulates the thermal behavior of the BDPD PT.

The simulated temperature closely matches those recorded from the PT, indicating that the DT effectively models the system's response to changing flow conditions and blockages. This alignment further validates the DT's ability to detect blockages based on temperature anomalies, ensuring its reliability for real-world applications.

4.3.10 HMI

As seen in Figure 4.8, the system includes a Human-Machine Interface (HMI) that provides an intuitive diagram of the BDPD testbed. This diagram details the locations of key components and sensors in the system and a representation of the general heat flow within the system. The interface displays real-time data from primary sensors, including flow meters and thermocouples placed at strategic points throughout the testbed.

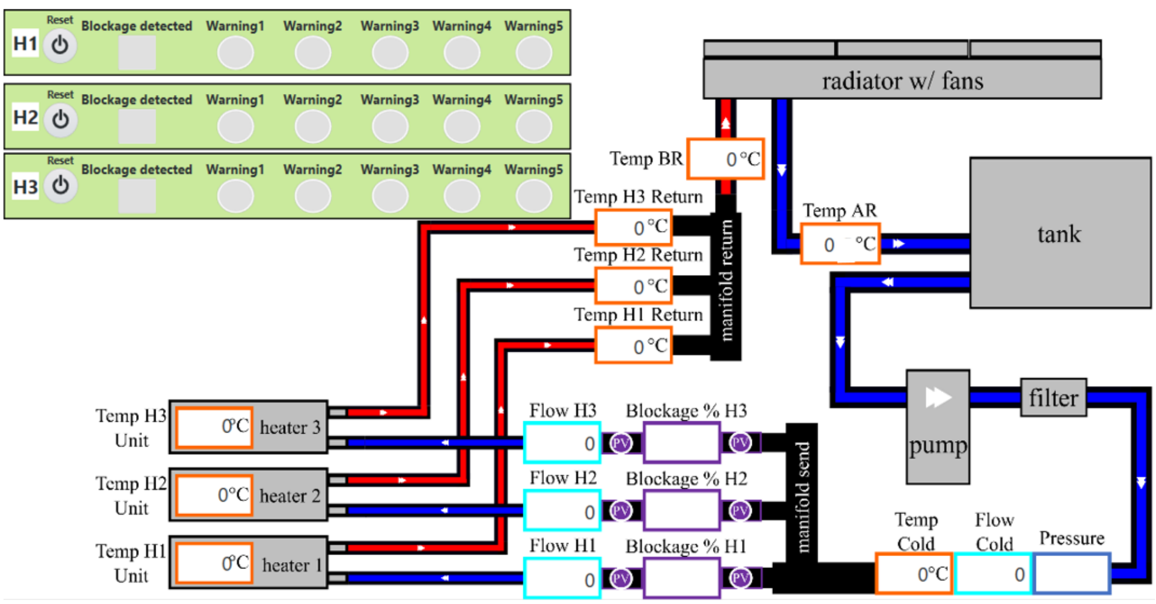

Figure 4.8 HMI screen displaying the layout of the BDPD, including temperature sensors, flow sensors, and a blockage detection alert panel for real-time monitoring.

These sensors provide temperature and flow data and are essential for monitoring the system's performance and detecting anomalies, such as blockages. While other sensors, including the pressure gauge and blockage percentage indicators, are not yet active, plans are in place for future integration. The blockage detection panel features indicators for the various blockage detection triggers and lights up in response to their activation. Once all triggers are active, the "Blockage Detected" indicator lights up, indicating the presence of a blockage formation in one or more of the heater blocks. Operators may reset the triggers once the cause of the blockage(s) has been resolved.

4.4 Experiment

After completing the PT testbed, the next step is to test the DT's capability to detect blockage formation under real-world conditions. These conditions will involve variables that may differ from idealized scenarios, such as fluctuations in local environmental temperatures, irregular heat dissipation from the heat-producing electronics, and potential interference from electromagnetic noise affecting sensor accuracy.

Unlike simulated environments, real-world applications introduce unpredictability and challenges that must be accounted for in the DT's modeling and detection algorithms. The DT will be tested against these real-world variables to assess its ability to accurately replicate and respond to the dynamic behaviors of the physical testbed. Factors such as:

- **Environmental Variability**: Local temperature fluctuations can impact the cooling system's performance, leading to deviations in temperature readings, which may cause false positives or result in missed blockages

- **Uneven Heat Dissipation**: Heat distribution within the system may be non-uniform, leading to uneven heating of the heater blocks, which could be misinterpreted by the DT, mainly if the model needs to be accurately calibrated to reflect the specific thermal dynamics of the testbed..

- **Electromagnetic Interference (EMI):** Interference from nearby electrical systems or devices may introduce noise into the sensor readings, potentially affecting the DT's accuracy and compromising the reliability of blockage detection.

4.4.1 Testing Profile

The testing profile involved a 90% reduction in flow for heater block H1. Each heater operated at a power load of 200 watts, with the pump functioning at 37.5% of its capacity (1.8 liters per minute, Lpm), resulting in a flow rate of 0.6 Lpm per individual heater block. Blockage induction occurred once the temperature of the heater blocks reached 35°C.

4.5 Results and Discussion

Figure 4.9 displays the temperatures of each of the three heaters in the BDPD during testing. The predicted temperatures, calculated by the DT based on wattage input, flow rate, and characterization data, are shown in blue. The actual temperatures recorded from each heater block in the physical testbed are shown in orange. Upon the introduction of the near-total blockage, the coolant flow to the H1 heater block was restricted, causing a decrease in heat transfer and a rapid temperature rise. The neighboring heater blocks (H2 and H3) experienced an increase in coolant flow due to the blockage in H1, which led to a temporary drop in their temperatures.

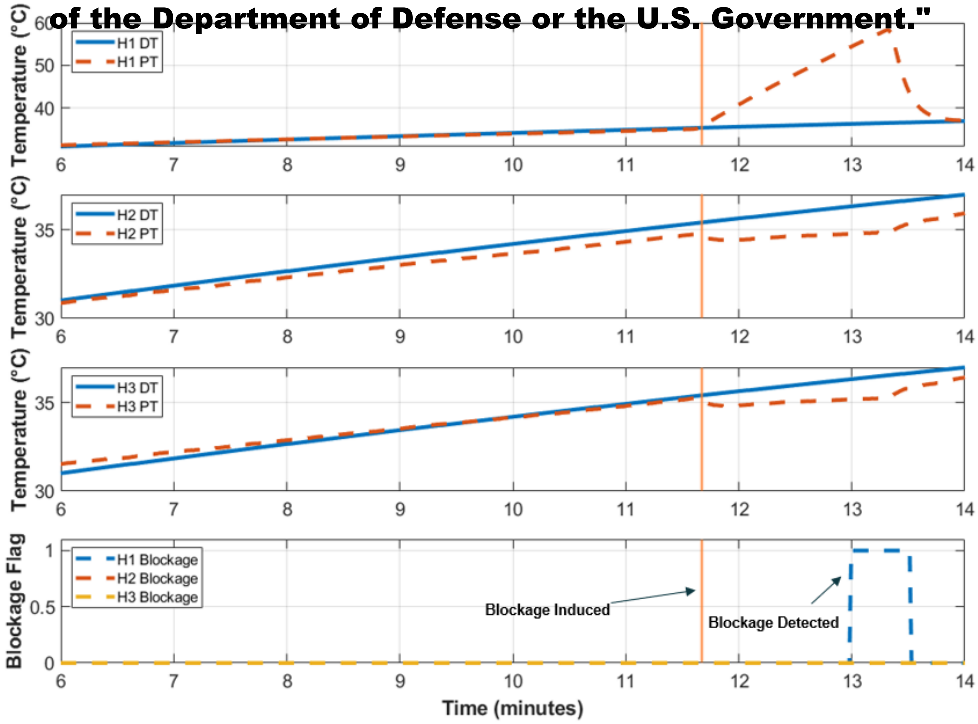

Figure 4.9 Physical real-world blockage detection experiment using the integrated DT with the PT testbed, demonstrating the system's ability to detect blockages in real-time.

The rapid rise in temperature sequentially activated triggers for abnormal dT/dt and over-temperature conditions. Heater blocks 2 and 3 showed a decrease in temperature due to the increased coolant flow, activating the trigger. The temperature then quickly activated the steady-state trigger. Once all triggers were activated, a blockage warning was displayed on the HMI. With all abnormal thermal triggers activated and the blockage formation alert sent to the operator, the DT successfully detected and warned of the blockage formation in the PT's H1 heater block, thus proving its effectiveness in detecting blockages in water-cooled electronics. However, while these results are promising, additional testing of the DT's capabilities in blockage detection under varying scenarios is ongoing.

4.6 Conclusion

In conclusion, the validation experiment results indicate the DT algorithm's viability for detecting blockages. The system accurately replicated the thermal behavior of the real-world PT testbed under both normal operating and blocked conditions. Upon the induction of the simulated blockage, there was a rapid increase in temperature followed by a rise in coolant flow to neighboring heater blocks, resulting in the timely activation of the DT's blockage detection algorithm triggers. Once all triggers were activated, 1.27 minutes after blockage induction, a blockage detection warning was issued.

These results confirm the viability of the DT in detecting the formation of instant or rapidly growing blockages. However, the current testing still needs to address scenarios where blockages form gradually over time, such as partial or slowly progressing obstructions. In these cases, the temperature changes may be more subtle, and the thermal signatures might not trigger immediate or significant deviations from regular operation.

This raises questions about the DT's sensitivity and responsiveness to slower blockage formations, which may require different detection methods or additional triggers. Therefore, further testing is needed to assess the DT's ability to detect blockages that develop gradually.

Chapter 5

Conclusion

This paper investigated the integration of Digital Twin (DT) technology into water-cooled electronic systems for detecting blockage formations in cooling channels. Blockages disrupt coolant flow, reducing heat dissipation and causing temperature buildup in affected components. This can lead to overheating, performance degradation, or component damage, resulting in costly and time-consuming repairs. The proposed detection method involved creating a digital representation, or "DT," of the physical system "PT," accurately replicating the system's thermal behavior, flow rates, coolant type, system geometry, and material composition. By operating the PT and DT in parallel, real-time temperature comparisons allowed for the detection of abnormal thermal behavior indicative of blockage formations in the PT. The initial phase of the research focused on using temperature data to identify blockages in a full-scale coolant system. A Digital Shadow (DS) simulation was created to replicate the system's thermal behavior under varying flow rates, successfully calculating the "normal" thermal response. While the DS method could highlight discrepancies between expected and actual responses, it relied on operator observation and was prone to human error. Additionally, the large-scale testbed for the PT presented challenges in heat transfer consistency, and the DS's unidirectional communication (from PT to DS) limited interaction between the systems. To address these challenges, a new, smaller testbed—the Blockage Detection and Power Distribution (BDPD) testbed—was developed, along with an upgraded DT. This more controlled system allowed for faster experiments and was connected to the PT in real-time via a cRIO device. The new

DT featured an automated blockage detection method using thermal triggers that activated in response to abnormal thermal behavior (e.g., elevated temperatures, rapid temperature increases, etc.), sending warnings to operators or automatic controllers. The DT successfully detected blockages in a simulated physical twin emulator (PTE), with detection times of 1.33 minutes for near-total blockages in heating operations and 5.66 minutes for less severe blockages. Further validation through real-world testing with the BDPD confirmed the DT's ability to detect blockage formation within 1.5 minutes of its introduction. However, a limitation of the current system was its inability to detect gradual blockage formation. Slow blockages may not have triggered the system's thermal triggers due to subtle temperature changes, meaning the system could fail to issue a warning in such cases. Future research should address this issue by integrating a progressive warning system that gives operators insights into the transient health status of components. Overall, this research demonstrated that incorporating DT technology into water-cooled electronic systems offers a promising approach to improving cooling system reliability and maintenance. However, more research and development are needed to fully optimize the system's capabilities.

Chapter 6

Future Work

6.1 Electrothermal DT

Potential future enhancements to the project include integrating automatic recalibration methods, such as particle swarm optimization, to maintain the DT's accuracy. A DT for the electrical system will also be developed to differentiate between temperature increases caused by blockages and those resulting from power fluctuations. The goal is to enable full interaction capabilities, allowing the DT to adjust the parameters of the PT for proactive blockage mitigation.

The electrical DT will be integrated with the thermal DT to distinguish whether a temperature rise is due to a blockage or an electrical fault. This integration will create an electro-thermal DT (Figure 6.1), representing the PT's electrical and thermal components. The DT aims to accurately diagnose the root cause of any abnormal thermal behavior in the PT, distinguishing between temperature increases caused by blockages in the cooling network and those caused by electrical faults. Ultimately, this integration will provide a more comprehensive approach to diagnosing abnormal or faulty behavior in water-cooled electronic systems

6.2 Maintaining Calibration of DT

The DT currently relies on manual recalibration and periodic recharacterization to address potential changes in the PT that may cause accuracy drift in the digital emulation. However, incorporating algorithms such as Particle Swarm Optimization

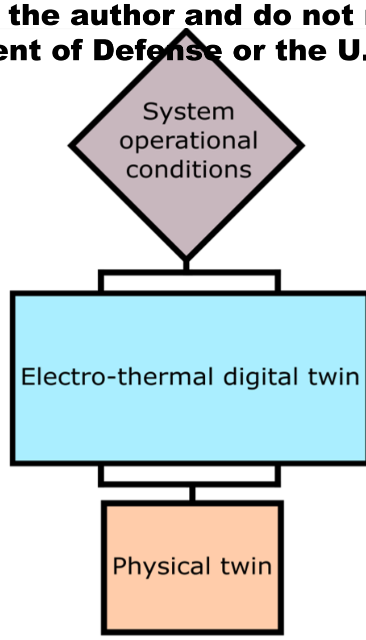

Figure 6.1 Future integration of an electrical DT with thermal DT to create a combined electro-thermal DT.

(PSO) could automate and improve this recalibration process. PSO is a stochastic optimization technique inspired by the social behavior of animals, particularly birds, and how flocks or swarms work together to find food. Each member of the swarm adjusts its search pattern based on individual experiences and the group's collective behavior. [35].

In PSO, particles update their positions and velocities in response to environmental changes, optimizing for proximity and quality. The swarm is not confined to a fixed path but continuously searches the entire solution space for the optimal solution.

PSO can be employed to fine-tune the DT's parameters by minimizing discrepancies between its outputs—such as temperatures, flow rates, and other parameters—and the real-world data from the PT. By continuously adjusting model parameters to reduce errors, the PSO will help maintain the DT's accuracy against drift, even as the PT changes due to wear, environmental factors, or other disruptions.

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