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Experimental validation of a low-cost microcontroller-based rack-level thermal control prototype

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ABSTRACT

The rapid growth of data centers (DCs), driven by digital transformation and the increasing adoption of artificial intelligence (AI), has intensified challenges related to thermal management and operational reliability. Cooling systems account for a substantial portion of total energy consumption and often show limited effectiveness in mitigating localized hotspots and dynamic temperature variations in high-density server environments. This study presents the development and experimental validation of a low-cost, microcontroller-based (MCU-based) localized thermal control system. The proposed architecture integrates a temperature sensor, an Arduino-based control unit, pulse-width modulation (PWM)-driven fan actuation, and Ethernet communication for remote monitoring. The system was implemented in a standard 19-inch rack under controlled laboratory conditions using a simulated thermal load. Experimental results, based on the average of five independent tests, demonstrated that combined operation of the prototype with rack ventilation reduced the cooling time from 45 °C to 40 °C to 50 ± 2 s, compared to approximately 5 minutes with rack ventilation alone and more than 12 minutes under natural convection. The corresponding cooling rates were 0.10 °C/s, 0.015 °C/s, and 0.007 °C/s. These results indicate that simple, distributed thermal control strategies can effectively mitigate localized overheating and support rack-level thermal stability in data center microenvironments.

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1. INTRODUCTION

The rapid expansion of the digital economy has placed data centres at the center of the global debate on energy consumption, infrastructure resilience, and operational sustainability. As information technology equipment becomes increasingly dense and computationally intensive, thermal loads rise proportionally, and cooling systems account for a significant share of operational costs and indirect emissions [1]–[5]. In this context, energy efficiency is no longer merely an economic requirement but a strategic factor for service continuity, infrastructure reliability, and environmental responsibility [3].

Historically, data centre efficiency has been evaluated through metrics of availability, redundancy, and computational performance. However, the growing energy demand and environmental impact of large-scale digital infrastructures have required reassessment of traditional paradigms. Studies indicate that a substantial portion of total energy consumption is devoted to cooling, often exceeding what is strictly necessary for thermal stability, revealing structural inefficiencies and opportunities for targeted optimization [2], [3], [6]–[9]. Conventional cooling architectures are typically designed for global peak loads or average conditions, rather than dynamic and spatially heterogeneous thermal distributions [1], [3].

As computational density increases at rack level, localized hotspots emerge as a critical challenge. Thermal gradients develop within confined microenvironments, increasing the risk of performance degradation or hardware stress. Deficiencies in airflow management, such as improper rack placement, insufficient sealing, inefficient hot and cold aisle organization, and absence of localized control, further compromise thermal performance and increase energy demand [3], [7], [10]–[15]. These limitations expose the rigidity of centralized cooling solutions under dynamic rack-level conditions [3], [7], [10].

To mitigate these issues, current approaches include advanced airflow management, frequency-controlled ventilation, intelligent heating, ventilation, and air conditioning (HVAC) architectures, liquid cooling, and hybrid systems. Although technically robust, these solutions operate mainly at facility scale and require substantial investment and complex integration. In high-density environments, especially those driven by artificial intelligence (AI) workloads, servers with graphics processing units (GPUs) and tensor processing units (TPUs) operate at elevated power densities, intensifying localized heat accumulation within racks [1]–[3], [7], [10], [15]-[26] . In this context, computational fluid dynamics (CFD) has become an essential tool for analysing airflow patterns and temperature distributions in three-dimensional space. Figure 1 presents a representative CFD simulation of a data centre environment, illustrating how rack configuration and ventilation conditions influence thermal gradients and hotspot formation [10], [15], [16], [23]-[30].

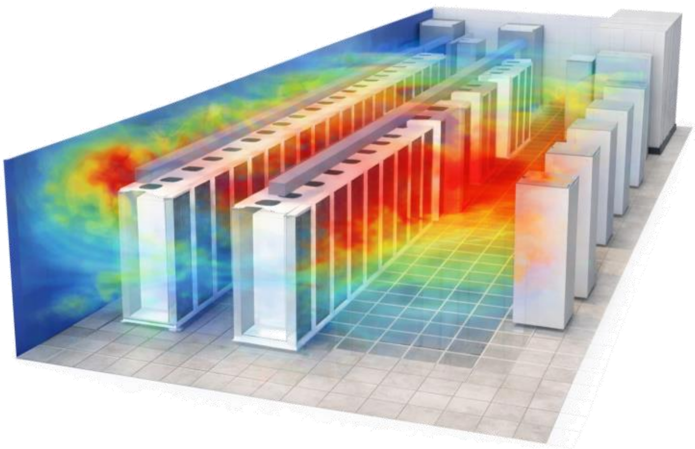
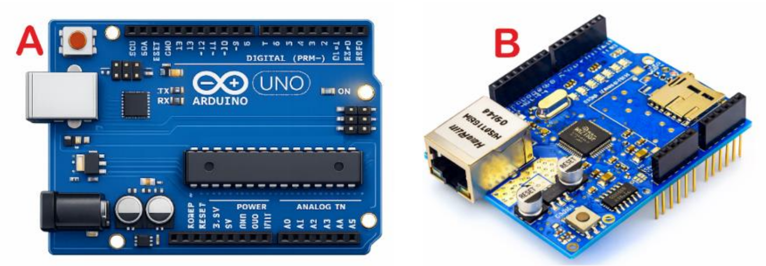


Figure 1. CFD simulation of the temperature distribution in a server

While CFD-based approaches provide valuable insights during design and optimization phases, they are predominantly employed for modelling and structural assessment rather than real-time localized actuation or distributed control implementation. Parallel to structural cooling strategies, the green data centre paradigm promotes enhanced energy performance through integrated monitoring, automation, optimized resource allocation, and improved infrastructure design [1]-[3], [7], [10], [15], [16], [19], [20], [23], [27], [30]. Nevertheless, much of the existing literature remains concentrated on large-scale energy optimization, workload scheduling, or system-wide thermal management. Comparatively less attention has been directed toward experimentally validated, low-cost, distributed control architectures specifically designed to address rack-level microenvironments characterized by localized heat concentration [10], [15], [16], [19].

A critical examination of current research reveals a gap between facility-scale cooling redesign and purely monitoring-oriented internet of things (IoT) implementations. While several studies focus on temperature sensing, predictive scheduling, or advanced control algorithms at system level, limited emphasis has been placed on modular, economically accessible rack-level control strategies that integrate distributed sensing, direct ventilation actuation, and communication capabilities within a localized closed-loop configuration [3], [7], [10], [16]–[19]. Figure 2(a) presents the Arduino Uno microcontroller and Figure 2(b) the Ethernet Shield W5100 communication module, which serve as the hardware foundation for the proposed control architecture. The Arduino Uno integrates a processing unit, digital and analog input/output interfaces, and pulse-width modulation (PWM) capabilities, while the W5100 Shield enables transmission control protocol/internet protocol (TCP/IP) network communication through an Ethernet interface. These components are widely used in monitoring and automation applications and provide a low-cost, modular platform suitable for investigating localized rack-level thermal control strategies.



(a) (b)

Figure 2. Arduino microcontroller and network communication interface: (a) Arduino Uno microcontroller and (b) W5100 Ethernet Shield communication module

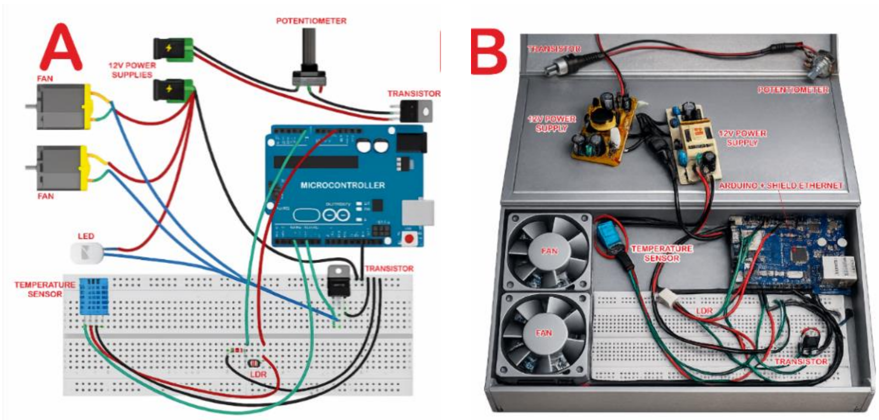
Within this framework, there is a clear need for experimentally grounded investigation of localized thermal control strategies that operate as complementary layers to conventional cooling infrastructures. Rather than replacing centralized HVAC systems or redefining facility-scale architectures, such approaches aim to intervene directly at rack level, where dynamic thermal gradients and localized heat accumulation are most critical. The objective of this study is to develop and experimentally validate a rack-level localized thermal control prototype based on a low-cost microcontroller architecture, through quantitative comparison of cooling performance under different ventilation conditions. The investigation focuses on analysing heat dissipation dynamics and cooling time in order to determine whether a modular, distributed, and economically accessible solution can produce measurable improvements in localized thermal response. The novelty of the research lies in experimentally positioning a low-cost, microcontroller-based architecture as a complementary rack-level intervention strategy, bridging the conceptual gap between structural cooling optimization and monitoring-only IoT implementations. The scientific contribution consists of providing quantitative comparative evidence of localized thermal response modification under controlled experimental conditions, thereby advancing understanding of how distributed control architectures can integrate into the broader landscape of data centre thermal management without necessitating large-scale infrastructure redesign.

2. RESEARCH METHODOLOGY

The experimental methodology was structured to quantitatively evaluate the thermal behaviour of a rack-level microenvironment under different controlled ventilation conditions. The study was conducted in a laboratory environment using a standard 19-inch rack as the test volume, representative of configurations employed in data centres. The rack structure was maintained laterally closed, allowing controlled configuration of front and rear ventilation according to the experimental regime adopted. As a thermal source, a 2000 W electric heater was installed inside the rack in order to simulate a concentrated thermal load typical of high-density equipment. The power was maintained constant throughout all experimental cycles, ensuring reproducible heating conditions and enabling direct comparison among the different operating regimes analysed.

Three distinct experimental regimes were defined: combined operation of the localized thermal control system and rack ventilation, operation of rack ventilation only, and absence of active ventilation, characterizing a natural convection regime. Each experimental condition was repeated five times, resulting in a total of fifteen complete heating and cooling cycles. In each test, the rack was initially heated until reaching the thermal level established in the experimental protocol, followed by the cooling phase under the corresponding regime. Between cycles, the system returned to the initial condition to ensure repeatability of the measurements.

The internal rack temperature was continuously monitored throughout all experimental phases. From the obtained thermal curves, the total cooling time and the average heat dissipation rate, expressed in degrees celsius per second, were determined. For each regime, mean values and variations among repetitions were calculated, allowing quantitative comparison among the three tested scenarios. The heat generation condition was kept constant in all tests in order to isolate the effect of the localized control system on the thermal dynamics of the microenvironment. Figure 3(a) shows the electrical schematic of the thermal control system, highlighting the interconnection between the microcontroller, sensors, actuation devices, and power supplies. Figure 3(b), the system prototype is presented, illustrating the arrangement of components, including the Arduino module with Ethernet Shield, sensors, fans, and power circuits.



(a) (b)

Figure 3. Schematic prototype design: (a) electrical schematic diagram of the thermal control system and (b) system prototype showing the arrangement of components

The system is cantered on an Arduino Uno R3 microcontroller, responsible for acquiring signals from the sensors, processing the information, and driving the fans. The microcontroller is powered via the universal serial bus (USB) port, which provides the 5 V required for its operation. The embedded program controls fan speed as a function of the temperature values measured by the digital humidity and temperature 11 (DHT11) sensor, enabling automatic adjustment of ventilation according to the thermal conditions of the monitored environment. The fans and the power transistor are supplied by 12 V sources, with the transistor acting as the actuation element and also as a controlled heat source, simulating the thermal behaviour of a server in operation through variation of a potentiometer resistance. The light-dependent resistor (LDR) sensor is employed as an auxiliary component for acquiring data related to ambient light conditions [17], [27], [29].

The Arduino Uno R3 platform operates at a clock frequency of 16 MHz and is based on the ATmega328P microcontroller, which provides sufficient processing capability for real-time signal acquisition and PWM-based actuation without introducing computational latency in the control loop. The selection of this platform was aligned with the objective of ensuring hardware accessibility, reproducibility of the experimental setup, and compatibility with standardized communication modules. Network communication is enabled through an Ethernet Shield W5100 coupled to the Arduino board, allowing transmission of the collected data to an external monitoring device using standardized protocols and enabling remote monitoring of system variables via an RJ-45 interface. This architecture ensures that the thermal control system operates independently of the main computing infrastructure, increasing the robustness and reliability of the experimental setup [17], [27], [29].

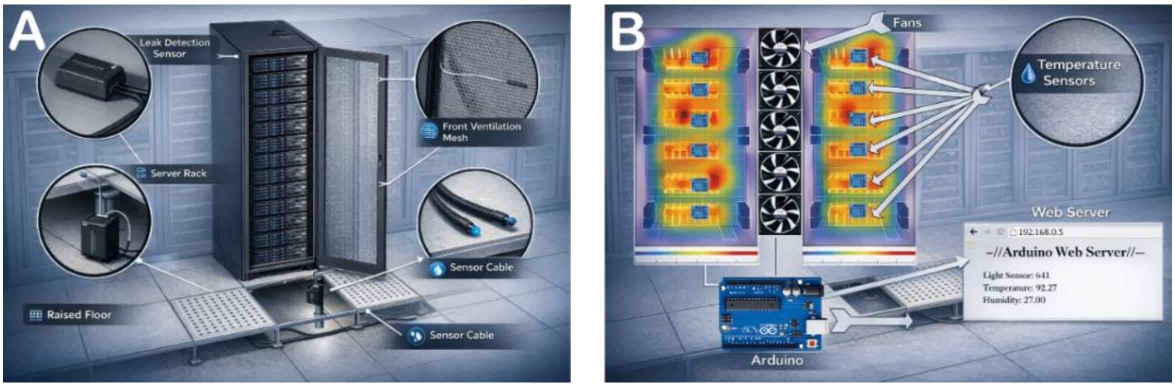
The W5100 chip integrates a hardware TCP/IP stack, reducing the computational burden on the microcontroller and ensuring stable packet transmission during continuous temperature monitoring. The use of wired Ethernet communication minimizes latency and avoids interference typically associated with wireless transmission in high-density electronic environments. Once the schematic was defined, the prototype assembly process was carried out. Initially, the Arduino pins assigned to each device were established, identifying the DHT11 as the temperature and humidity sensor, the LDR as the light sensor, and the TIP120 as the power transistor for fan actuation. Subsequently, the Ethernet Shield was attached to the microcontroller board. The fans, breadboard, communication module, and power supplies were then placed inside an appropriate enclosure, and the electrical conductors were interconnected in strict accordance with the pinouts defined in the project.

The TIP120 Darlington transistor was configured in a low-side switching arrangement, enabling amplification of the control signal generated by the microcontroller and allowing stable modulation of the 12 V supply delivered to the ventilation units. Proper grounding and separation between logic and power circuits were maintained to prevent electrical noise from affecting sensor readings. In the experimental system, two fans of the Berflo model 60×60×25 mm were used to promote forced ventilation and heat removal from the monitored environment. The technical specifications of these fans, such as nominal operating voltage, current, rotational speed, and airflow rate, were considered in the evaluation of the thermal control performance based on forced convection. At the end of this process, a fully assembled and functional prototype was obtained, suitable for the proposed experimental tests. With the circuit fully assembled, the software implementation phase was initiated. The project code was developed and compiled using the Arduino integrated development environment (IDE) and subsequently uploaded to the microcontroller through the upload process. Fan speed control is performed using the PWM technique, which allows analogy-like behaviour to be simulated from digital signals by generating a square wave alternating between 0 V and 5 V and varying the time the signal remains at a high level within each period [9], [17], [27], [29].

The PWM signal stability and response characteristics were considered in relation to the thermal inertia of the rack environment. Given that temperature variations occur over time scales significantly longer than the PWM period, the modulation frequency of approximately 500 Hz was sufficient to ensure smooth and stable fan operation without perceptible oscillations. In the Arduino environment, the PWM signal operates by default at a frequency of approximately 500 Hz, corresponding to a period of 2 ms. The $analogWrite()$ function uses an integer scale ranging from 0 to 255, where $analogWrite(255)$ represents a 100% duty cycle and $analogWrite(127)$ corresponds to approximately 50% duty cycle [4], [12], [30].

In the project source code, PWM control is implemented using the instructions $pwm = map(t, 15, 45, 15, 255)$; and $analogWrite(fan, pwm)$, in which the $map()$ function converts the temperature measured by the sensor into a proportional PWM output value. As a result, fan rotation speed varies directly and proportionally with the detected temperature, ensuring automated and efficient thermal control of the system [1], [5], [9], [17], [27], [29]. The linear mapping strategy establishes a proportional control behaviour without implementation of integral or derivative compensation terms. This simplified approach was intentionally adopted to evaluate the feasibility of localized thermal intervention using minimal computational complexity while preserving the low-cost and modular characteristics of the proposed architecture.

The proposed model was conceived for application in data centre environments characterized by high equipment density and the localized formation of microenvironments with heat accumulation, where more refined and responsive thermal control is required to act directly on critical heat dissipation regions [3], [7], [10], [15], [16], [20], [23], [27], [30]. The system architecture is based on the distributed use of temperature sensors and fans, enabling continuous monitoring of thermal conditions and localized action at points of highest heat generation, thereby contributing to the reduction of temperature gradients along server racks. Figure 4 presents the conceptual architecture of the model, highlighting sensor placement, fan control, and integration with the microcontroller unit (MCU) and the web server [1], [5], [9], [16], [19], [23], [27], [29], [30]. Figure 4(a), a typical physical configuration of a server rack in a data centre is illustrated, emphasizing sensor positioning and integration with the infrastructure. Figure 4(b), the conceptual operation of the proposed system is shown, including the distribution of temperature sensors, fan activation for localized heat removal, and communication with the web server for real-time monitoring and control.



(a) (b)

Figure 4. Application architecture of the thermal control model in a datacentre environment: (a) a typical physical configuration of a server rack in a data centre and (b) the conceptual operation of the proposed system

3. RESULTS

One of the main outcomes of this work is related to the economic feasibility of the proposed prototype. From a financial perspective, the system presents a significantly reduced implementation cost, resulting from the selection of low-cost electronic components with wide commercial availability. Table 1 presents the cost estimate of the main elements used in the construction of the prototype, considering average market values in U.S. dollars. As presented, the total estimated cost of the complete system is approximately USD 70, including the Arduino microcontroller, the Ethernet communication module, sensors, ventilation devices, and auxiliary electronic components. This value encompasses the entire functional architecture required for data acquisition, processing, actuation, and network communication. The individual cost analysis shows that the components with the greatest financial impact are the Arduino microcontroller (USD 25) and the Ethernet Shield W5100 module (USD 15). In contrast, the sensing and ventilation elements, including the DHT11 sensor (USD 9) and the two axial fans (USD 6), represent a relatively small fraction of the total investment. Passive components and accessories contribute marginally to the overall system cost.

Table 1. Cost estimate of prototype components in US dollars

Components	Estimated cost
Shield Ethernet W5100	15.00
Arduino microcontroller	25.00
Fans (2 units) - Berflo model 60×60×25 mm	6.00
Electronic components (light-emitting diodes (LEDs), transistors, resistors, cables and potentiometer)	8.00
DHT11 temperature and humidity sensor	9.00
Breadboard	7.00
Estimated total cost	70.00

The selection of the DHT11 sensor, although simpler when compared to industrial alternatives such as thermocouples, PT100 sensors, or higher-resolution digital sensors, was intentionally aligned with a cost-oriented design philosophy. The objective of the study was not high-precision thermal metrology, but rather the comparative evaluation of localized thermal behavior under different ventilation conditions. In this context, the magnitude of the experimentally observed temperature variations and cooling time differences is substantially greater than the intrinsic uncertainty associated with the selected sensor, ensuring a clear distinction between the evaluated scenarios.

The adoption of more sophisticated sensors would imply a significant increase in cost and system complexity. For example, thermocouple-based systems typically require signal conditioning circuits, dedicated amplification modules, or higher-precision analog-to-digital converters, increasing unit cost and altering the economic positioning of the proposed solution. The present work prioritized accessibility, replicability, and large-scale implementation feasibility, consistent with the central objective of validating a localized, distributed, and economically scalable thermal control strategy.

In addition, in multi-point deployment scenarios, cost per unit becomes a critical factor. Even modest increases in individual component cost may result in significant financial impact when installation across multiple racks or microenvironments within the same data centre is required. The low-cost characteristic favours distributed applications, in which conventional commercial solutions may become economically impractical when applied at scale.

This aspect is particularly relevant in practical situations where overheating is localized and does not justify structural interventions in the HVAC system or the adoption of complex liquid cooling solutions. In such cases, a targeted, modular, and low-cost approach may provide a more rational and proportional cost-benefit balance. Therefore, the demonstrated economic feasibility does not constitute a secondary attribute of the system, but rather a central element of the proposal, reinforcing its applicability as a complementary rack-level thermal mitigation strategy.

The prototype was installed inside a standard 19-inch server rack with a usable height of 47U and approximate dimensions of 800 mm in width and 1200 mm in depth. These specifications are consistent with high-density racks widely employed in corporate and academic data centre environments, particularly in installations designed to accommodate medium- and large-scale server infrastructures. The selection of a rack with these characteristics aimed to ensure that the experimental environment was representative of real operational conditions, both in terms of internal volume and structural configuration.

The metallic rack structure is equipped with perforated front and rear doors, enabling front-to-back airflow, which is the standard configuration adopted in modern data centre facilities. This airflow arrangement supports hot-aisle and cold-aisle separation strategies and promotes longitudinal air movement across installed equipment. The perforated surfaces reduce pressure losses and facilitate controlled ventilation within the enclosure, contributing to a more realistic simulation of airflow behavior typically observed in server racks operating under significant thermal loads.

During the experimental campaign, the ambient laboratory temperature was maintained constant at 23 °C, as regulated by the local air-conditioning system. Maintaining a stable ambient condition was essential to minimize external environmental influences and to ensure experimental reproducibility. By controlling the surrounding temperature, it was possible to evaluate the comparative performance of the different ventilation configurations with greater reliability, ensuring that the observed differences in cooling rates were predominantly associated with the implemented control strategies rather than fluctuations in external thermal conditions. Considering the dimensions of the rack used in the experiments, the prototype and its temperature sensor were positioned in a region of higher thermal concentration within the enclosure, with the objective of monitoring the potentially most critical point in terms of heat accumulation. This region was defined as the central section of the rack, as it represents an intermediate zone between the lower cold-air intake and the upper warm-air exhaust, and is typically more susceptible to the formation of thermal gradients.

Given that the rack has a total height of 47 U, equivalent to approximately 2.09 meters, the prototype was installed at an average height of about 1 meter from the base, corresponding to the vertical midpoint of the structure. This positioning was selected to ensure thermal representativeness while avoiding bias associated with extreme regions, such as the bottom or top of the rack. The two prototype fans were oriented downward in order to induce forced air circulation within the central region and promote localized removal of accumulated heated air. This configuration enabled evaluation of system performance within a representative microenvironment prone to hotspot formation, reproducing, at a controlled scale, thermal concentration conditions typically observed in high-density server racks. Throughout all experimental trials, the prototype remained fixed in the same geometric position and orientation, ensuring methodological consistency and eliminating variability associated with physical repositioning of the system.

A 2000 W Bimar HF195 electric heater with a fan and adjustable thermostat was installed in the lower region of the rack, with airflow directed vertically upward. This setup was chosen to create an upward thermal gradient, replicating the typical behavior of high-density racks, where heated air accumulates in the upper regions due to natural convection. The nominal power of 2000 W was selected to represent a concentrated thermal load, equivalent to the heat dissipation of multiple servers operating simultaneously. Heating continued until the monitored region reached approximately 45 °C, a value chosen because it represents a relevant thermal stress condition for Information Technology equipment. Figure 5 shows a schematic drawing of the installation position of the thermoforming prototype.

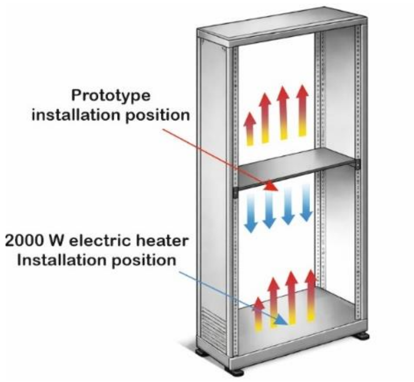


Figure 5. Schematic representation of rack experimental thermal configuration

After the final positioning of the prototype and heating system inside the rack, experimental tests were conducted under three distinct operating conditions, while keeping other system variables constant, such as ambient temperature, sensor position, and physical configuration of the components. This approach enabled direct comparison between different heat dissipation mechanisms, ensuring methodological consistency and reproducibility of the results.

The conditions analysed were: (i) simultaneous operation of the prototype with the original rack ventilation system, providing both localized and global forced ventilation; (ii) operation of only the rack ventilation system, with the prototype deactivated, allowing evaluation of conventional air circulation alone; and (iii) absence of active ventilation, with both systems switched off, so that heat dissipation occurred exclusively by natural convection. Tests were repeated five times for each condition, keeping the laboratory ambient temperature (23 °C), sensor position, and fan orientation constant to ensure reproducibility and comparability between scenarios.

When the temperature in the monitored region reached 45 °C, the cooling phase began under the defined experimental condition. In the combined operating scenario (prototype plus rack ventilation), the system automatically activated the fans via PWM control, reducing the temperature to 40 °C in an average time of 50 ±2 s. The average cooling rate was approximately 0.10 °C/s, indicating high efficiency in localized heat removal and rapid reduction of the thermal gradient.

With rack ventilation only, the time required for the same 5 °C reduction was approximately 5 min, resulting in an average rate of 0.015 °C/s. Although air circulated inside the rack, the absence of localized action significantly reduced the efficiency of thermal extraction. In the absence of active ventilation, dissipation occurred exclusively by natural convection. In this condition, the time required to reduce the temperature from 45 °C to 40 °C exceeded 12 min, with an average variation of ±27 s between tests. The average cooling rate was approximately 0.007 °C/s, highlighting the intrinsic limitation of natural convection in confined microenvironments with high thermal density.

Comparatively, the system with localized thermal control showed significantly superior performance to the other scenarios, with a cooling rate approximately 6 to 7 times higher than with rack ventilation alone and about 14 times higher than with natural convection, demonstrating the effectiveness of targeted action in reducing exposure time to critical temperatures and mitigating thermal gradients in confined microenvironments. These results show that distributed and localized action substantially reduces the system's exposure time to critical temperatures, mitigating risks associated with hotspots and abrupt thermal variations. Figure 6 shows the cooling curves for the three conditions analysed, highlighting marked differences in the slope of the thermal curves and the dynamics of heat dissipation.

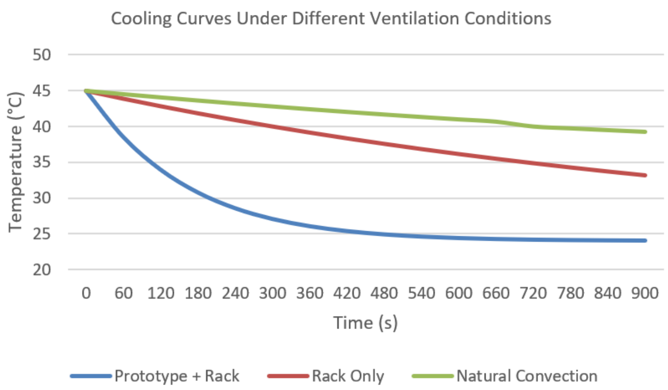


Figure 6. Cooling curves under different ventilation conditions

It was also verified that ambient temperature exerts a direct influence on the thermal adaptation speed of the system. Under higher ambient temperature conditions, the reduction of the thermal gradient between the heated element and the surrounding environment resulted in lower heat dissipation rates. Nevertheless, even in these scenarios, the condition with prototype operation maintained significantly superior performance compared to the other configurations, confirming the robustness of the adopted control strategy.

In addition, the microcontroller-based control system exhibited a response time of less than 2 s between temperature increase detection and effective fan activation. The use of PWM control enabled progressive fan operation, automatically adjusting ventilation intensity according to the measured temperature. For moderate temperatures, between 30 °C and 35 °C, the system operated with duty cycles below 40%, whereas for temperatures above 40 °C, PWM values approached 90% to 100%, maximizing heat removal only when required. As a result, a reduction of approximately 70% in the thermal gradient between the heated point and the ambient environment was observed within the first two minutes of forced ventilation operation, while without active ventilation, a similar reduction was only achieved after periods exceeding 6 min. Overall, although the experiments were conducted in a laboratory environment, the obtained results are representative of real microenvironments with heat concentration, such as high-density server racks. The data indicate that the application of local, distributed, and low-cost thermal control strategies can effectively contribute to the thermal and operational stability of such systems, while significantly reducing the exposure time of equipment to critical thermal conditions.

4. CONCLUSION

From a technological perspective, the prototype demonstrated that simple, distributed, and low-cost solutions can effectively operate as a complementary layer to conventional cooling infrastructures, contributing to reduced thermal response times and mitigation of critical temperature excursions without requiring major structural modifications. Its primary contribution lies in the practical feasibility of localized implementation, enabling rapid intervention in confined microenvironments where hotspot formation occurs. As a technical improvement, the adoption of more advanced PWM control strategies is recommended, including adjustments to the microcontroller switching frequency and possible implementation of adaptive modulation algorithms. Such refinements may provide smoother fan speed regulation, improve dynamic response, and reduce oscillatory behavior under transient conditions. Future developments may include remote control functionalities for fan activation and speed adjustment, evaluation of higher-capacity fans with variable frequency control, and detailed measurements of electrical power consumption to more rigorously quantify potential efficiency gains. The integration of CFD analyses could further enhance understanding of airflow patterns and temperature distribution within server racks and data centre layouts, strengthening the technical basis for optimizing sensor and actuator positioning. Additionally, the use of humidity data collected by the sensors may support the development of automated hygrometric control strategies, broadening the scope of environmental management. Finally, this work does not aim to compete with established CFD modeling techniques, liquid cooling systems, or high-performance forced convection solutions based on advanced instrumentation. Instead, it proposes a technologically viable approach for scenarios where cost constraints exist or where a simple and rapidly deployable solution is required to address localized thermal issues effectively.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Saulo Alexandre Inacio				✓					✓	✓	✓	✓		✓
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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no financial or non-financial conflicts of interest, maintain no relationships that could influence this study, and did not receive public or private funding from any company or governmental institution for the development of this work.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request. The experimental data were generated during laboratory tests of the proposed prototype and are not publicly archived but can be provided for verification and reproducibility purposes.

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