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Sustainable Heatsink Optimization for Multi-Component PC enclosure

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ABSTRACT

Overheating is a significant challenge for the widespread use of desktop personal computers (PCs). This thermal issue frequently results in operational failures and poses safety risks. While current thermal optimization often relies on integrating a single heatsink (such as the Central Processing Unit or CPU), research indicates this approach is insufficient for effectively lowering the machine's overall maximum temperature (T_{max}). To address this critical gap, this study introduces a novel passive multi-heatsink thermal solution. Utilizing Computational Fluid Dynamics (CFD) simulation, the research analyzes the strategic placement and performance of multiple generic heatsinks on various major heat-generating components inside the PC enclosure. The simulation successfully determined the optimum number and configuration of these components, verifying that distributing multiple passive heatsinks is a viable and effective method for significantly reducing the device's maximum operating temperature T_{max}.

Keywords: *Desktop PC, Heat optimization, Heatsink, CFD, System performance*

I. INTRODUCTION

The modern world is facing a myriad of challenges, such as climate change, greenhouse gas emissions, biodiversity loss, and depletion of renewable resources. Thus, sustainable solutions are continuously being explored to deal with these issues. The green computing concept has emerged as one of the leading tools for sustainable development, and it has the potential to resolve the problems regarding wearability and thermal consumption. Green computing is the efficient practice of extending the use of computers and computing-related resources by minimizing toxic materials and, to expand the lifespan of the product, automatically encouraging the concept of recycling, and wearability that can be done with factory waste and expired products [1]-[2]-[3].

One of the main applications of green computing is heat optimization. Green computing contributes to heat optimization by facilitating the design of efficient power consumption systems. Therefore, an appropriate component must be delivered within the specific temperature range to evaluate and deliver the performance. The operation executed with the external functional temperature range can result in logic errors, system performance degradation, and system damage; eventually, these problems should be prevented [4]. Thus, green technology offers a suitable opportunity for heat optimization in computer devices.

Personal Computers (PCs) are used for a wide variety of applications to enhance processing speed and multitasking capacity. Therefore, studies on PCs have been conducted to solve multiple problems caused by temperature variations, which led to overheating the internal electronic components in computer cabinets, such as the motherboard [5]-[6]-[7]. The leading cause of temperature increase in the internal electronic PC components is high voltages [6]. Most of the errors were due to the temperature attained by the specific threshold temperature that the manufacturers fixed [7].

Computational Fluid Dynamic (CFD) simulation is one of the most widely used approaches for designing and examining the heat optimization of any complex system. It has multiple techniques, such as dynamic, continuous, discrete, deterministic, static, and stochastic simulations. PC simulation offers an opportunity to optimize the thermal performance of any computing device. The primary benefit of CFD simulation is to provide an optimal result and improve computational efficiency. CFD simulations may also have the capability to reduce computational investment [8]. In this study, CFD simulation provided an opportunity to optimize the performance of adding

multiple heatsinks for efficient thermal control within a desktop PC enclosure.

Heatsinks play a critical role in the stabilization of heat optimization of devices. A heatsink is a substance or device that absorbs and dissipates unwanted heat from a component [9]. [10] Defined a heatsink as a thermally conductive device that absorbs and dissipates heat from a high-temperature source to ambient conditions. Heatsinks, which are typically made of metals with high thermal conductivities, are vital to increasing the heat dissipation from the computer chassis by increasing the heat exchange area between the solid parts (such as the motherboard, PSU, and hard drive unit) and the forced-air flow [11].

Eventually, the challenge of thermal optimization in desktop PCs persists and is intensifying with the growth of computing demands, yet a comprehensive, effective solution remains unavailable. This paper addresses this gap by investigating a novel thermal strategy: the strategic placement of multiple, single type passive heatsinks on various major internal heat-generating components of a desktop PC. The study employs different scenarios and test cases to analyze the performance and optimization of these heatsinks, specifically considering green computing parameters such as thermal efficiency and the resulting temperature variations across essential components.

Despite the known need for effective thermal solutions in desktop PCs, existing literature has predominantly investigated the use of a single heatsink attached to a single specific component [12]-[13]-[14]-[15]. This single-component approach, however, proves inadequate for substantially lowering the maximum overall operating temperature (T_{max}) of the entire system. To address this critical research gap, this study tries to answer the following question:

- What is the optimal (minimum) number of multiple passives heatsinks (CMHSs) required to achieve the lowest possible overall maximum operating temperature T_{max} within the desktop PC enclosure?

II. Related Work

Heat optimization within desktop PC enclosures has been addressed through various previous studies. In the existing literature, heatsinks and CFD simulation are two of the most widely reported and utilized approaches.

In an early study, [12] employed CFD Fluent simulation software to analyze the forced-air cooling process of a CPU within a PC. While they modeled the CPU with an attached heatsink, other major heat-generating components—such as the hard disk drive, CD drive, power supply unit (PSU), and memory cards—were intentionally excluded. The research compared two popular heatsink geometries: a straight vertical fin and a radial curved fin. Through CFD modeling, they analyzed the airflow patterns and performed thermal analysis to determine the maximum operating temperature of various components. The study successfully analyzed the influence of key parameters, including processor power dissipation, fan speed, surrounding temperature, and the air intake area, on the CPU case temperature.

In their comprehensive research, [16] explored forced-air cooling and heat transfer simulations in a whole computer chassis using the CFD simulation package Fluent™ to conduct parametric analyses. They compared the influences of different turbulence models, discretization schemes, mesh resolutions, convergence criteria, and radiative heat transfer on thermal and cooling flow mechanisms in a computer. An entire computer chassis model with fans and heatsinks was generated, and a few numerical errors regarding CFD analysis were reported. Their simulation outcomes revealed that the efficiency of a heatsink is affected by the heat transfer area and the nature of the material. Heatsinks with an embedded copper base emerged as the most effective in enabling heat conduction. The simulation results were like those of available experimental findings.

Additionally, [17] performed a study to design and analyze three different commercial heatsinks. They accomplished the study using CFD simulation packages Icepack and Fluent. According to their outcomes, it is observed that the flow circulation inside the chassis of a common ATX personal computer desktop affects the heatsink temperature distribution. Although they have designed different geometries of heatsinks, all of them are selected and modified to have a lower maximum temperature variation. Another outcome was that the heatsink material significantly affected heat performance. Specifically, it was established that using Aluminum instead of copper as the heatsink material improves the general heat performance inside the chassis.

Furthermore, [18] proposed a new modeling design for a CPU cooler based on an active heatsink integrated with heat pipes. The cooler could maintain a more efficient heat dissipation capacity. Their idea is to develop an active heatsink that has a more efficient heat performance while at the same time maintaining low noise levels and minimal cost. The CPU and RAM cooler was designed using CFD simulations, and the results were validated with corresponding physical experiments. According to their findings, the proposed solution provided a high thermal resistance at a lower noise level.

Focusing on dimensional reduction, [19] attempted to minimize the overall system size by designing a heatsink for cooling a PC with a 5W CPU. They employed Fluent software to design and compare three two-dimensional (2D) heatsink models: circular fin, rectangular coated fin, and uncoated rectangular fin. The uncoated rectangular plate heatsink was found to achieve optimum heat dissipation and CPU cooling performance, which was attributed to the higher surface area available for heat dissipation in that specific model.

Moreover, [20] investigated the forced convection cooling of heatsinks mounted on the CPU. They designed three types of heatsinks, Alpha heatsinks, Ever Cooler heatsink, and Cooler Master heatsink, which all have given maximum heat dissipation. In their results, stocking too many fins in the heatsinks is not a solution for reducing the hot spots since they may prevent the movement of air passing from the fan to the hottest center parts. They also noted that selecting the fin material is critical because Copper performs much better in decreasing heat than Aluminum. In addition, they stated that the base plate's thickness helps the heatsink to perform better. However, it should accumulate with the space limitation of the computer chassis. Furthermore, their main conclusion was that a Cooler Master heatsink performs much better than Alpha and Ever Cooler heatsinks due to the advantages of using Copper plate material.

A study proposed by [21] performed a numerical analysis to cool down a Micro-ATX computer chassis. In this research, different fan revelations are calculated to analyze the heat dissipation under the idle and full-load operational modes of a computer using a CFD simulation package. The research outcomes showed that when the computer is under idle operation, the main components of the computer have a relatively lower temperature, that requires a low fan revelation for adequate cooling. On the other hand, when the computer is under full-load operation, a higher fan revelation is required to effectively keep the system at a safe operating temperature of operation.

In a recent study, [22] conducted numerical studies of a heatsink geometry for a CPU. They examined the performance of a rectangular fin heatsink installed in a PC chassis. The thermal performance of the heatsink was optimized by examining the effects of fin height, fin quantity, and thickness of the baseplate. Optimum thermal performance was achieved for a heatsink with 36 fins of 25 mm in height and a baseplate thickness of 2 mm. The authors further established that thermal performance was optimized when the fin channel was in a perpendicular location to the surface of the outlet.

In another study, [23] optimized the thermal performance of a heatsink with hemispherical pin fins to determine the optimum pin configurations. The best thermal performance was achieved when the ratio of the channel diameter in the heatsink was higher than 0.833. Moreover, perforation patterns were found to play a role in the performance of the heatsinks, and greater thermal performance was achieved for the perforation patterns with the highest number of holes. The findings of this study showed similar outcomes to another study by [24], in which they conducted a CFD simulation analysis of the thermal performance of different heatsink shapes and perforations. In their study, they used grooved, perforated, and twisted pin fin types to optimize the overall heat dissipation. The findings revealed that groove shapes with circular perforation achieved higher thermal performances than the other pin fin types. Overall, this study suggests that pin fins' geometry and physical configuration may play a critical role in heatsink performance.

Finally, a new study by Song and Zhang [25] provided a comprehensive review on energy and materials efficiency in advanced electronic packaging, emphasizing the necessity of integrating sustainability into the fundamental design process. Their work highlights that sustainable design strategies must prioritize the minimization of material usage in advanced electronic packaging to effectively reduce manufacturing waste and overall environmental footprint. They argue that critical design decisions, such as component selection and count, have a direct and measurable impact on a product's life cycle and its adherence to contemporary green computing principles.

III. METHODOLOGY AND CONFIGURATION

A. Study Approach

In this paper, the simulation analysis is performed using Computer-Aided Design (CAD) and ANSYS CFD commercial packages. CAD is used to generate the appropriate PC configuration with specified geometry, while ANSYS CFD modules are used for computational studies of heat transfer simulation and thermal consumption in a desktop PC enclosure.

The proposed configuration includes the chassis, motherboard, PSU, hard drive unit, CD drive unit, and floppy drive unit. The reason for including only these components is that these components are the essential major source of heat generation and thermal waste production in any typical desktop PC [12]-[25]-[26]. Thus, performing the right thermal simulation analysis in this study area is considered a key solution to the thesis objectives. To understand the depth of this research, Fig. 1, explains the study approach in detail.

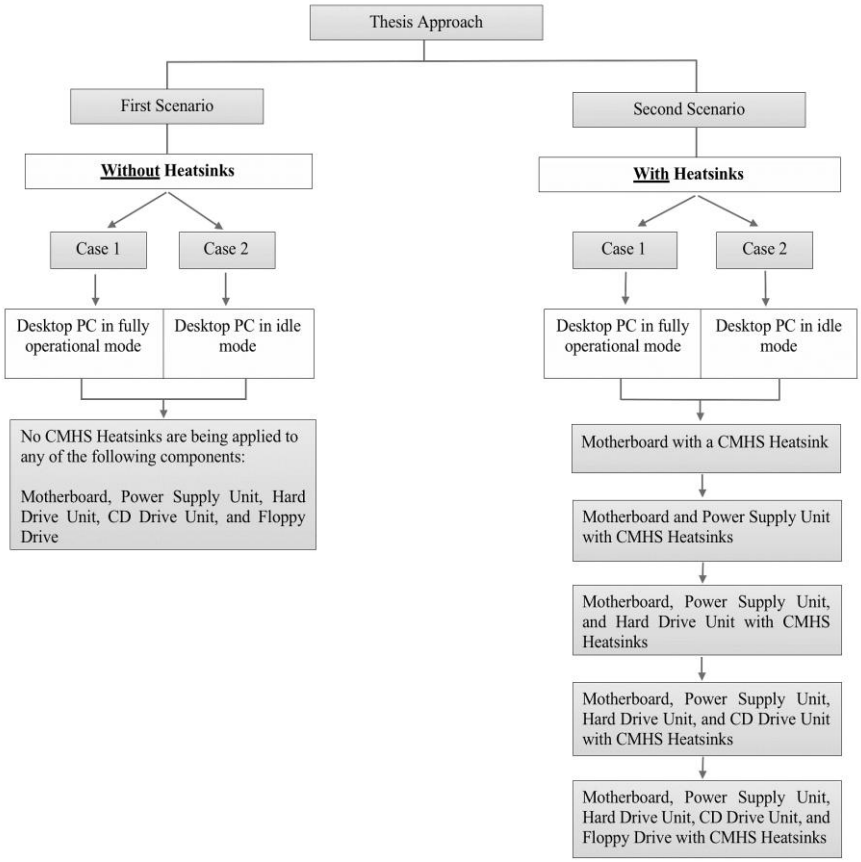


Figure 1. Comparative Flowchart of the Two-Scenario Thermal Analysis Approach for Desktop PC Enclosure.

1) *First Scenario: Baseline Thermal Optimization*

As detailed in Fig. 1, the research begins by establishing a baseline thermal profile where no passive heatsinks are applied to any major internal heat-generating components. CFD simulations are conducted under two distinct operational states: Case 1 (PC in fully operational mode) and Case 2 (idle mode).

This initial investigation provides crucial data on the temperature behavior and distribution within the unmitigated system, which serves as the control for subsequent comparative analysis [27].

2) *Second Scenario: Multi-Heatsink Optimization*

Following the baseline analysis, the second scenario introduces the novel passive multi-heatsink solution using Cooler Master Heatsinks (CMHSs). This scenario uses a sequential, iterative simulation approach to determine the optimal configuration. CMHSs are progressively added, starting with the highest heat-source component (the motherboard) and continuously proceeding to components with lower heat contributions (e.g., PSU, hard drive, and finally, the floppy drive unit) [26]-[28]. This systematic step-by-step methodology will enable the study to precisely quantify the thermal reduction achieved by each added heatsink and ultimately identify the minimum number required for optimal system-wide cooling.

B. *Test Cases*

This study employs a two-scenario investigative approach, with each scenario comprising two distinct test cases, all conducted under a constant air velocity. The comprehensive results from both scenarios will be analyzed to determine an optimal solution for mitigating the problem of thermal consumption in desktop PC devices.

In both the baseline and multi-heatsink scenarios, the following boundary conditions are consistently applied [29]:

- *Inlet Air Condition:* Air enters the enclosure at a static temperature of $T_{in} = 300$ K.
- *Outlet Air Velocity:* Air exits the enclosure at a fixed velocity of $V_{out} = 0.6$ m/s.

Heat flux ($q^{\cdot}$) is applied to all major heat-generating components. As per established definitions, heat flux represents the rate of thermal generation across a given surface area [28]. To comprehensively model the operational extremes of the PC, the following detailed Table I will be examined across both scenarios.

TABLE I. STUDY TEST CASES

Test Cases	Operational Mode	Heat Flux Applied ($q^{\cdot}$)	Air Velocity (V)
Case 1	Fully Operational (Peak Load)	200 W/m^2	0.6 m/s
Case 2	Idle Mode (Low Load)	20 W/m^2	0.6 m/s

The investigation focuses exclusively on these two extreme operational states because they represent the critical design boundaries essential for robust thermal management and optimization. This approach is computationally efficient, as the thermal behavior of any intermediate operating state can be reliably interpolated from the data of these two extreme cases [21].

1) Case 1: Fully Operational Mode (Peak Load)

This state simulates the absolute worst-case thermal scenario where all major heat-generating components (such as the CPU, GPU load during rendering, gaming, or heavy computation) are operating at or near their maximum thermal design power (TDP).

A maximum heat flux ($q^{\cdot}_{max}$) of 200 W/m^2 is uniformly assigned to all major PC components for a conservative and robust analysis. Applying this amount of heat flux was made according to [21]-[26]-[28]. They agreed that the average amount of heat flux produced from these major components in a fully operational PC is estimated to be between 140 W/m^2 and 210 W/m^2. Therefore, it is assumed that all the components have a heat flux value fixed at 200 W/m^2 for the best representation of heat analysis.

It is critical to acknowledge that the motherboard usually generates the highest amount of heat flux compared to the rest of the desktop components. This is due to the motherboard's role as the foundation of the PC, facilitating the interaction, data sharing, power distribution, and command routing among all different parts. Moreover, several important components, including the CPU, GPU, and Random-Access Memory (RAM), are directly attached to the motherboard, leading to a concentrated heat production area.

2) Case 2: Idle Mode (Low Load)

This state simulates the absolute minimum heat generation scenario when the PC is powered on but performing only essential background tasks (e.g., waiting for user input, running an operating system idle loop). Hence, a small amount of heat flux generation is expanded to the surrounding. Reflecting literatures suggest that heat generation for desktop PCs in idle mode is typically falls within the range of a few mW/m^2 up to 30 W/m^2 [21]-[26]-[28]. Therefore, it is assumed that all the components have a heat flux value to be uniformly fixed at 20 W/m^2 for the best evaluation of heat generation.

By isolating these two thermal extremes, the study efficiently captures the full range of thermal behavior. The performance characteristics and thermal stability of any intermediate operating state (e.g., web browsing, light office work) can be reliably interpolated from the results obtained at these two critical boundaries, thereby minimizing computational cost while ensuring the robust validation of the proposed cooling solution [26].

C. PC Configuration Model

CAD software is recognized as an effective and essential platform for analytical design development and manufacturing, particularly in modeling complex systems like desktop PCs [30]. Since CAD allows for the representation of design components at varying levels of detail, it is a crucial requirement for this study [31]. Therefore, the proposed PC configuration will be designed and modeled as a basic 3-dimensional (3D) representation of the desktop computer hardware using CAD software package.

Fig. 2, illustrates the proposed desktop hardware configuration as generated through CAD modeling. The dimensions of the chassis and all internal components were accurately modeled after a standard mid-tower desktop PC, ensuring the geometry conforms to the specifications typically associated with the American National Standards Institute (ANSI) standards for hardware [32].

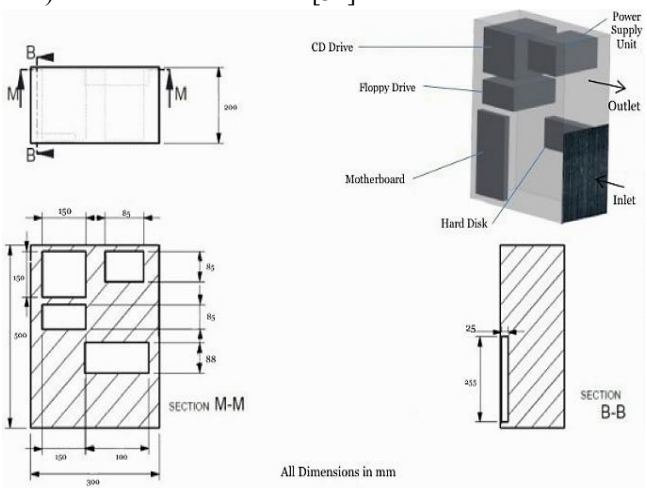


Figure 2. The Geometric Model of a Standard Mid-Tower Desktop PC, Showing the Internal Hardware Layout Developed in CAD for the CFD Simulation.

The system under investigation is modeled as a rectangular aluminum chassis with a depth of 200 mm. The geometric configuration, detailed in Fig. 2, accurately reflects a realistic arrangement of PC hardware components, including the strategic placement of the cooling airflow inlet and outlet.

The inlet is positioned at the bottom, and the outlet is positioned at the top on the same side, facilitating natural convection where cooler air enters at the bottom and warmer air exhausts at the top. This configuration simulates the function of a typical chassis, where an exhaust fan is usually situated at the outlet to aid in expelling heated air.

For the CFD simulation, the fan's geometry was simplified: its drawing was excluded from the CAD model to minimize complexity, simulation time, and cost [12]. However, the specified outlet area will be numerically treated as the active fan area during the CFD process.

Although the proposed configuration does not include every minor component of a real desktop PC, it retains all major heat-generating components. The exclusion of minor components is justified as they are not expected to significantly impair the thermal results, given that their operation is unlikely to substantially influence the overall heat optimization of the machine [27]-[28]. Consequently, these minor components are considered inactive and have been negated in this study to maintain the efficiency and focus of the thermal simulation.

D. Heatsink Configuration Model

A primary consideration for PC designers is utilizing heatsinks to enhance heat transfer and ensure efficient cooling of components that generate considerable thermal energy [33]. This study focuses specifically on passive heatsinks rather than active solutions, as they are generally cost-effective, require no external power, and contain no mechanical components, thus increasing system reliability [9].

The investigation utilizes a specific passive device, the CMHS a commercial product design which has been demonstrated to effectively increase direct heat conduction between hot spots and the heatsink metal [12]-[20]. While passive heatsinks are inexpensive (typically ranging from $0.15 to $60), the CMHS model employed in this research, detailed in Fig. 3, is designed with rectangular fins atop a 5 mm thick, 80 mm diameter Copper base plate, a feature integral to maximizing thermal conductivity for efficient heat absorption and dissipation.

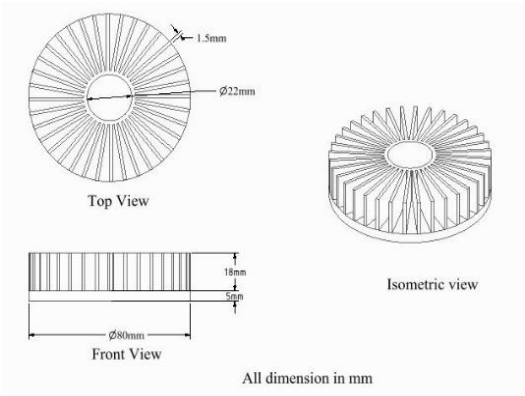


Figure 3. The Geometric Model of the CMHS, Showing the Detailed Design Layout Developed in CAD for the CFD Simulation.

TABLE II. DESIGN PARAMETERS AND SPECIFICATIONS OF THE CMHS MODEL

Parameter	Specification
Heatsink diameter	80 mm
Heatsink base thickness	5 mm
Rectangular curved fins	36 Fins
Thickness of the fin	1.5 mm
Height of radial curve fin	18 mm

Following the geometric modeling of CMHS, the model will be integrated into the baseline CAD drawing of the proposed desktop hardware configuration Fig. 2. The methodology employs a sequential and iterative simulation approach. This process involves progressively adding the CMHS to each major heat source component, after which the entire system model is re-simulated using CFD to analyze the thermal impact of each addition.

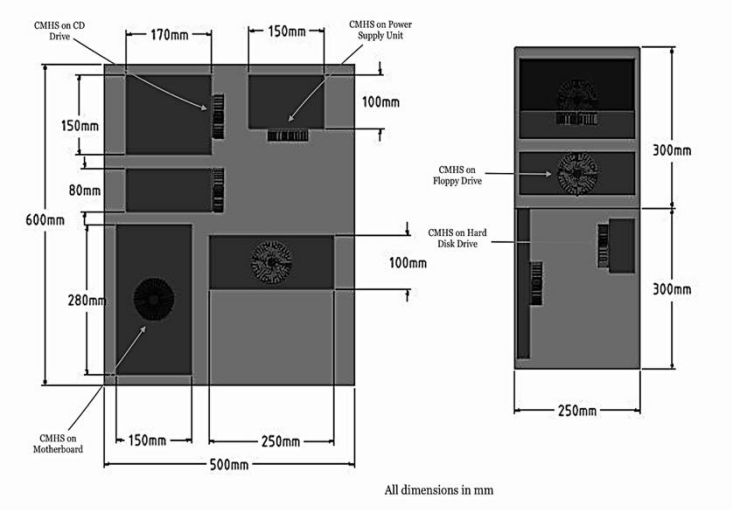


Figure 4. The Placement of Multi-CMHSs on All Major Heat Generation Components Inside the Desktop PC Configuration.

Fig. 4, illustrates the final system configuration for the second scenario, featuring CMHSs systematically integrated onto all major internal components, including the motherboard, PSU, hard drive unit, CD drive unit, and floppy drive unit. The primary objective of this integration is to mitigate the overall maximum temperature T_{max} within the PC enclosure.

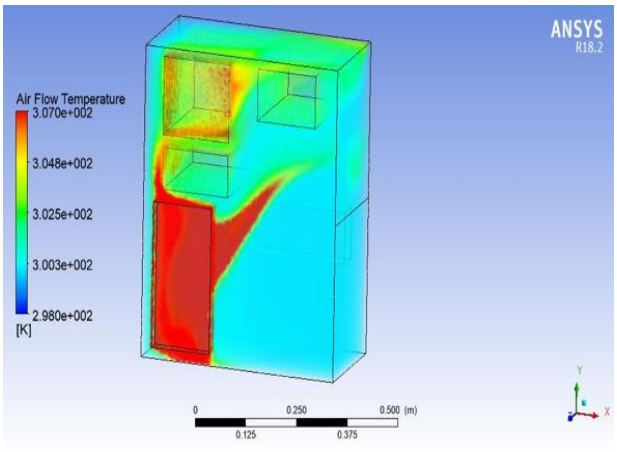
In contrast to the baseline model shown in Fig. 2, the configuration presented in Fig. 4, utilizes CMHSs designed with extended surface areas. The specific shape and size of these CMHS units were selected to maximize heat dissipation effectiveness across the components. This fully equipped model represents the final, optimal state for comparison in the thermal simulation analysis.

IV. SIMULATION ANALYSIS

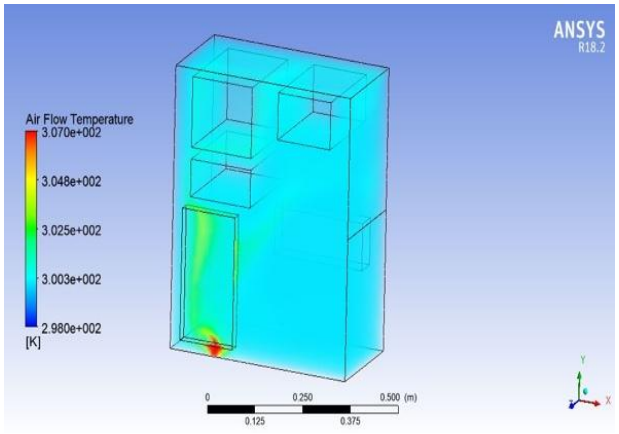
A. *First Scenario: Baseline Thermal Analysis Without Heatsink Addition.*

The First Scenario is designed to establish the baseline thermal performance of the desktop PC system without the implementation of CMHSs**.** This section details the simulation of two fundamental test cases—Case 1 and Case 2—to provide a comprehensive view of the system's unmitigated thermal state.

The simulations for both cases are conducted with a constant outlet air velocity of 0.6 m/s. The differentiation between the two operational modes is defined by the applied heat flux ($q^{\cdot}$) is fixed at a maximum of 200 W/m^2 for Case 1 and reduced to 20 W/m^2 for Case 2. These two test conditions provide the necessary control data to quantify the system's inherent thermal distribution before implementing the proposed cooling solution.



(a) Case 1: PC in Full Operation Mode.



(b) Case 2: PC in Idle Mode.

Figure 5. Contour Plot Illustrating the Internal Airflow Temperature Distribution of the Baseline PC Model Without Heatsink Implementation.

The simulation results for the baseline configuration, illustrated in Fig. 5, reveal a significant difference in thermal performance between the two test cases.

- Case 1 (Peak Load): The analysis indicates that without the implementation of heatsinks, the maximum overall temperature T_{max} within the entire domain reached 386.5 K. This elevated temperature reflects the critical thermal stress placed on internal components during high-performance tasks.

- Case 2 (Idle Mode): As expected, a substantially lower thermal profile was observed during the low-load state, where the T_{max} was recorded at 310.6 K.

These baseline figures serve as the control data for evaluating the effectiveness of the CMHS integration. The high T_{max} observed in Case 1, in particular, highlights the necessity for an optimized thermal management strategy to prevent component throttling or failure.

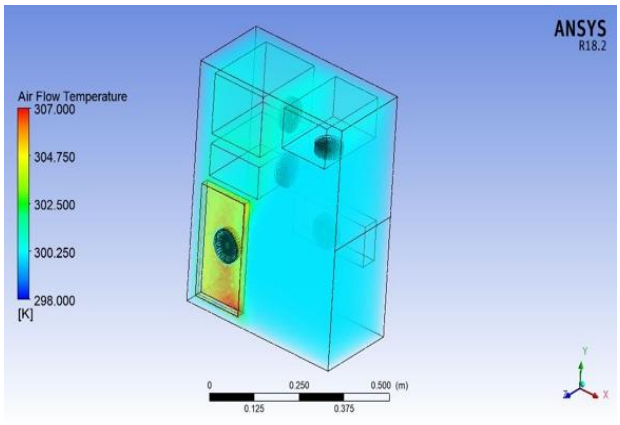
B. *Second Scenario: Comparative Thermal Analysis With Heatsink Integration.*

This section presents the simulation results for the second scenario, where the thermal performance of the desktop PC is evaluated with the addition of CMHSs.

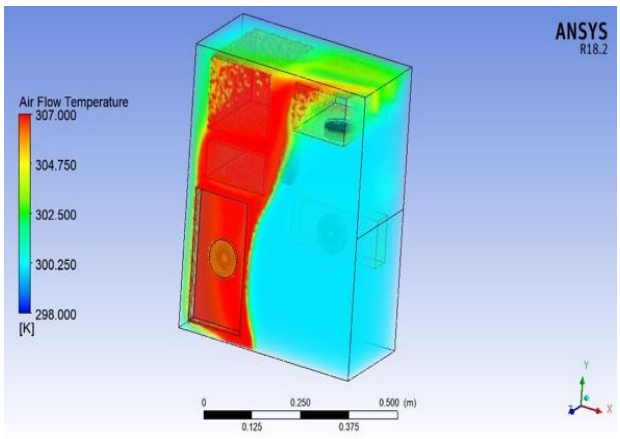
The analysis maintains the same two test cases—Case 1 and Case 2—with a constant outlet air velocity of 0.6 m/s and heat flux values ($q^{\cdot}$) of 200 W/m^2 and 20 W/m^2.

The distinguishing feature of this scenario is the sequential integration of multiple CMHS units. These heatsinks are progressively attached to the major heat-generating components in the following order: the motherboard, PSU, hard drive unit, CD drive unit, and finally, the floppy drive unit. By simulating the system after each addition, the study identifies

the incremental thermal reduction and determines the optimal number of heatsinks required for system stability.



(a) Case 1: PC in Full Operation Mode.



(b) Case 2: PC in Idle Mode.

Figure 6. Contour Plot Illustrating the Internal Airflow Temperature Distribution of the Desktop PC Model with the Fully Integrated Multi-Heatsinks Solution.

The implementation of multiple CMHSs resulted in a significant reduction in the overall maximum operating temperature T_{max} across both simulated test cases, as illustrated in Fig. 6. The numerical findings are summarized as follows:

- Case 1(Peak Load): The T_{max} within the entire domain was reduced to 350.4 K. This represents a substantial thermal mitigation of approximately 36.1 K compared to the baseline temperature of 386.5 K recorded when no heatsinks were utilized. This significant drop demonstrates the effectiveness of the multi-heatsink strategy under high-stress computational conditions.
- Case 2 (Idle Mode): The thermal benefit in the low-load state was less pronounced but still evident, with the T_{max} decreasing to approximately 304.0 K. This compares favorably to the T_{max} of 308.6 K recorded for the idle baseline configuration, indicating that at lower thermal outputs, the passive heatsinks contribute to more stable thermal environment.

The disparity in temperature reduction between the two cases suggests that the passive heatsink solution is increasingly effective as the component heat flux increases, making it a robust solution for peak operational demands.

V. SIMULATION RESULTS AND DISCUSSION

TABLE III. A COMPREHENSIVE SUMMARY OF THE OVERALL MAXIMUM OPERATING TEMPERATURE T_{MAX} RESULTS FOR THE DESKTOP PC ACROSS BOTH BASELINE AND MULTI-HEATSINK SCENARIOS.

Parameter	**First Scenario**		**Second Scenario**	
Test cases	***Case 1***	***Case 2***	***Case 1***	***Case 2***
Desktop PC performance	Fully operational mode	Idle mode	Fully operational mode	Idle mode
Overall maximum temperature T_{max}	386.5 K	310.6 K	350.4 K	304 K

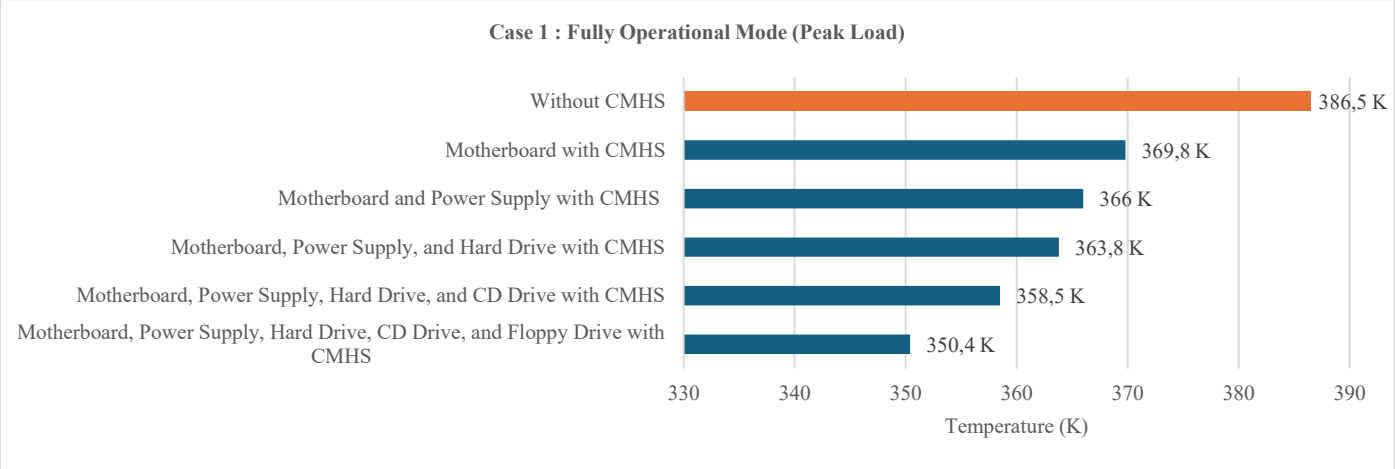


Figure 7. Comparison of the Overall Maximum Operating Temperature T_{max} for Case 1 (Fully Operational Mode) Across Both the Baseline and Multi-Heatsink Scenarios.

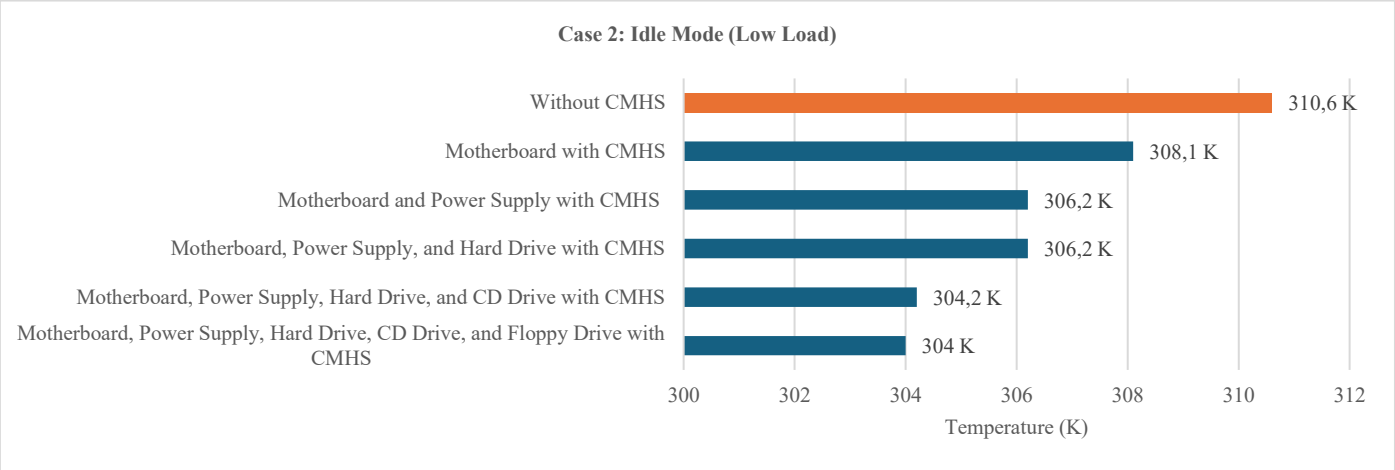


Figure 8. Comparison of the Overall Maximum Operating Temperature T_{max} for Case 2 (Idle Mode) Across Both the Baseline and Multi-Heatsink Scenarios.

Table III, comprehensively summarizes the simulation results, quantifying the reduction in the overall maximum operating temperature T_{max} achieved by implementing multiple CMHSs.

The thermal mitigation was significant across both test conditions:

- *Fully Operational Mode (Case 1):* The T_{max} dropped substantially from 386.5 K (baseline) to 350.4 K (multi-heatsink configuration).
- *Idle Mode (Case 2):* A notable temperature decline was also observed, with T_{max} falling from 310.6 K (baseline) to 304.0 K.

These findings confirm that the addition of multiple CMHSs provides an effective solution to the overheating problem in desktop PCs.

A critical observation from the baseline scenario is that operating a desktop PC without an active thermal management system resulted in temperatures (386.5 K) that approach levels capable of negatively impacting device performance and longevity. Consequently, an effective thermal solution is necessary to maintain the overall operating temperatures of these components within safe limits. This necessity validates the central hypothesis of the present study: that the strategic implementation and simulation of multiple single-type CMHSs attached to various heat source components must be implemented to achieve adequate thermal control.

Fig. 7, visually summarizes the reduction in the overall maximum operating temperature T_{max} for Case 1 across both the baseline and multi-heatsink scenarios.

The analysis demonstrates that progressively integrating CMHSs into the desktop PC components effectively reduced

the system's thermal load. The reduction sequence, starting from the baseline temperature of 386.5 K (no heatsinks), is detailed below:

TABLE IV. CASE 1 CUMULATIVE T_{MAX} REDUCTION.

Component CMHS Added	Cumulative T_{max} Achieved
Motherboard	369.8 K
Power Supply Unit	366.0 K
Hard Drive Unit	363.8 K
CD Drive Unit	358.5 K
Floppy Drive Unit	350.4 K

The final configuration, incorporating CMHSs on all five major components (motherboard, PSU, hard drive, CD drive, and floppy drive unit), resulted in a minimum overall T_{max} of 350.4 K.

This finding is critical for thermal optimization, as the recommended maximum temperature for a PC under full operational condition is typically slightly below 353 K [34]-[35]. Therefore, the data presented in Fig. 7, conclusively demonstrates that five CMHSs must be attached to all major components to successfully maintain the overall maximum temperature of the desktop PC cabinet below the required optimum threshold, ensuring no adverse effects on the device's performance or operation.

On the other hand, Fig. 8, summarizes the overall maximum operating temperature T_{max} for Case 2 across both the baseline and multi-heatsink scenarios. A consistent decline in T_{max} was observed with the sequential addition of passive CMHSs.

The baseline T_{max} for the unmitigated system (no heatsinks) was recorded at 310.6 K. The progressive integration of CMHSs yielded the following results:

TABLE V. CASE 2 CUMULATIVE T_{MAX} REDUCTION.

Cumulative CMHS Addition	Cumulative T_{max} Achieved
Motherboard	308.1 K
Power Supply Unit	306.2 K
Hard Drive Unit	306.2 K
CD Drive Unit	304.2 K
Floppy Drive Unit	304.0 K

The continuous application of CMHSs successfully reduced the T_{max} to a final value of 304.0 K, confirming that this solution ensures a safe thermal setup for idle mode PCs. Notably, the overall change in T_{max} was minor compared to case 1, given the low baseline heat flux.

Several points regarding thermal distribution were observed:

- A significant temperature drop of 2.5 K (from 310.6 K to 308.1 K) was achieved solely by adding the CMHS to the motherboard.
- The temperature values stagnated at 306.2 K after adding the heatsink to the hard drive unit, and again at 304.2 K and 304.0 K following the integration on the CD and floppy drive units, respectively.
- The effect of each individual CMHS became less observable at the end of the sequence, indicating a point of diminishing thermal return.

Considering that the recommended temperature for a PC in standby mode is estimated to be 308 K, the initial reduction achieved by adding just one CMHS to the motherboard is sufficient to ensure the desktop PC operates below this lowest allowable temperature [34]-[35]. Therefore, while adding CMHSs to all components (as in Case 1) ensures optimal safety, a single CMHS on the primary heat source is critical for meeting the 308 K threshold in idle mode. Overall, the study confirms that the use of multiple CMHSs effectively lowers the overall maximum temperature in both operational scenarios (Case 1 and Case 2).

A. Study Primary Question.

The analysis of the simulation results directly addresses the study's primary research question:

What is the optimal (minimum) number of multiple passives heatsinks (CMHSs) required to achieve the lowest possible overall maximum operating temperature T_{max} within the desktop PC enclosure?

The findings demonstrate that the optimal number of CMHSs required is contingent upon the operational mode of the PC:

- *Case 1 (Fully Operational Mode):* Optimal cooling was achieved using five CMHSs. This required attaching one single-type CMHS to each of the five major heat-generating components (motherboard, PSU, hard drive unit, CD drive unit, and floppy drive unit). This configuration was necessary to reduce the overall T_{max} to the recommended thermal threshold.
- *Case 2 (Idle Mode):* The optimal solution required only one single CMHS, which was strategically attached to the motherboard. This minimal configuration was sufficient to ensure the overall T_{max} remained below the lowest allowable temperature for standby operation.

B. Study Novelty and Contribution.

This research successfully adopted a novel and robust approach for minimizing the overall maximum operating temperature of a desktop PC, leading to enhanced thermal stability. The study's unique contribution lies in its sequential integration methodology, which determined that the optimal thermal optimization is contingent upon the PC's operational state.

Key Contributions:

1) *Sequential Integration Approach:* The systematic, step-by-step addition of CMHSs was novel, allowing for the precise quantification of each heartsink's contribution to system-wide thermal mitigation. This approach was essential for establishing the minimum required quantity for optimal performance.
2) *Comprehensive Two-Case Analysis:* The research design was unique in its comparative analysis, utilizing both fully operational mode and idle mode scenarios to provide a complete understanding of thermal performance. This focus on two extreme boundary conditions (maximum load and minimum load) is computationally efficient, as the thermal behavior of intermediate operating states can be reliably interpolated from the data of these two critical cases [36]-[37].
3) *State-Dependent Optimal Solution:* The findings demonstrate two distinct optimal configurations:
    - *Fully Operational Mode (Case 1):* Required five CMHSs to achieve the lowest overall operating temperature, successfully maintaining the system below the recommended threshold of 353 K [34]-[35].
    - *Idle Mode (Case 2):* Required only one CMHS strategically attached to the motherboard, sufficient to meet the thermal requirements.
4) *Sustainability and Material Efficiency:* The proposed multi-heatsink strategy directly supports sustainability goals. By precisely identifying the minimum number of heatsinks needed for effective thermal control, particularly in the idle state (one CMHS), the approach ensures material efficiency by directly minimizing component usage and associated manufacturing waste [25]. Furthermore, maintaining components at lower temperatures significantly extends the lifespan and reliability of the PC hardware, directly reducing the frequency of replacement and contributing to a substantial decrease in electronic waste (e-waste) [38]. This focus on maximizing performance while minimizing material and failure rates aligns the thermal solution with contemporary green computing principles.
5) *Simplicity and Accessibility:* The transparent and structured methodology ensures that the findings are simple to follow and easily understandable for researchers and industry professionals interested in thermal management and system optimization.

C. Study Validation.

For enhanced validation of the current findings, Table VI summarizes established benchmarks and results from the existing literature, noting the methodological deviations and distinct approaches employed in those previous investigations.

TABLE VI. COMPARATIVE SUMMARY OF PREVIOUS BECHMARKS UTLIZING ALTERNATIVE METHODOLOGIES.

Reference No.	Title	Year	Aim	Study validation
[19]	Experimental and Transient Thermal Analysis of Heatsink Fins for CPU Processor for Better Performance.	2017	The primary objective of this study is to minimize the overall system volume by designing and analyzing a rectangular plate heatsink, featuring an aluminum base plate, for integration within a mid-tower PC chassis	While both studies utilized mid-tower desktop PCs for their analysis, this article bases its design on aluminum-based heatsinks, in contrast to the copper-based heatsinks employed in the current research. Furthermore, their investigation was limited strictly to CPU cooling, whereas the present study provides a comprehensive thermal examination of multiple internal components.
[21]	Numerical Analysis of Cooling Down a Micro ATX Computer Chassis.	2018	The primary objective of this study is to conduct a numerical analysis using CFD to investigate and optimize the thermal performance of a Micro-ATX computer chassis across both fully operational and idle modes.	This research has numerically analyzed the cooling processes of Micro-ATX computer chassis, whereas the current study focuses specifically on a mid-tower desktop chassis. Furthermore, prior investigations often calculated varying fan speeds to analyze heat dissipation under idle and full-load operational modes; in contrast, this study proposes and evaluates the sequential addition of multiple passive heatsinks as the primary method for thermal optimization.

[39]	Computational Fluid Dynamics Simulation on the Heat Sink Performance of a Graphics Processing Unit Thermal Management.	2019	This study examines the sensitivity of thermal energy transfer efficiency to variations in heatsink surface area, total volume, and geometric configuration.	This study evaluated the efficacy of various heatsink types, the primary distinction from the present investigation lies in the scope of the components analyzed; that study focused specifically on the thermal performance of a GPU, whereas the current research evaluates multiple internal components of a desktop PC. Furthermore, the previous model utilized an aluminum-based plate, in contrast to the copper base plate evaluated in the current study.

Table VI. summarizes previous benchmarks that share similar ideas but pursued distinct objectives or methodologies. These previous investigations provide essential context for the present study's validation.

- *System Miniaturization and Single Component Focus:* A study by [19] aimed to minimize the overall system dimension by designing a rectangular plate heatsink with an aluminum base plate specifically for PC cooling. The authors effectively demonstrated temperature reduction by attaching heatsinks directly to the CPU only.
- *Alternative Computer Chassis Analysis:* A study by [21] redirected efforts toward a different computer cabinet. For instance, a numerical analysis was conducted on a Micro-ATX computer chassis. Utilizing a CFD simulation package, the author calculated the optimal fan revolutions needed for heat dissipation under idle and full-load operations. The study concluded that the main components registered lower temperatures during standby mode, requiring lower fan revolutions, whereas full-load operation necessitated higher fan revolutions to maintain safe operating temperatures.
- *Heatsink Design Optimization:* Another investigation by [39] focused purely on optimizing heatsink geometry and specifications for enhanced thermal performance. This research evaluated how parameters such as heatsink volume, surface area, material suitability, and the number of fins influenced heat transfer efficiency. Crucially, this study provided support for the assertion that rectangular shaped heatsinks offer superior heat transfer effectiveness compared to cylindrical designs.

VI. CONCLUSION

This study successfully introduced and validated a novel thermal management strategy utilizing multiple, strategically placed passive heatsinks CMHSs to address the persistent issue of thermal optimization in multi-component desktop PC enclosures. By employing CFD simulation across two critical operational boundaries—fully operational mode (peak load, Case 1) and idle mode (low load, Case 2)—the research precisely determined the optimal heatsink configurations for both thermal performance and material efficiency.

The key findings are twofold:

A. *Thermal Optimization (Case 1):* The maximum overall temperature T_{max} was reduced to its lowest effective level only when five CMHSs were applied to all major heat-generating components. This demonstrates that the common practice of single-heatsink optimization is insufficient for achieving robust system-wide cooling under peak load conditions.

B. *Material and Energy Efficiency (Case 2):* Critically, the system maintained thermal stability $T_{max} < 308$ K during the idle mode by requiring the strategic attachment of only one CMHS to the motherboard. This finding establishes the minimum effective component count necessary for basic operational control.

This research contributes to the field by providing quantitative evidence that effective thermal management is contingent upon the operational mode, enabling a targeted and efficient design approach. The results offer a reliable methodology for balancing robust thermal control with the contemporary mandates of green computing, specifically by minimizing the materials required while ensuring reliable performance and extending component lifespan. Future work should focus on experimental validation of this configuration and the development of intelligent switching systems to activate CMHSs based on real-time load conditions.

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