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Original Article

Computational Fluid Dynamics Study on the Impact of Axial Fan Configuration on Thermal Management in Gaming Desktops

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Abstract - *The heat dissipation capacity was compared between an ATX format case, which obtained low temperatures with three fans, keeping the processor and the graphics card below 55°C and 82 °C, respectively. Subsequently, correlations were sought between the results in both cases to identify patterns of temperature, pressures, and flow rates, obtaining highly positive correlations between the power supply and the graphics card. Finally, the results were validated physically using 3DMark software, comparing the performance and stability of the equipment obtained by changing the positioning of the fans, thus providing options for optimal configurations with three and six fans, allowing a high-performance computer with an ATX format case to operate efficiently with scores close to 1990 points in graphics tests.*

Keywords - *Computational Fluid Dynamics (CFD), Axial fan, Thermal management, Gaming PC Cooling, Airflow.*

1. Introduction

The thermal efficiency of computer cases has been extensively studied through Computational Fluid Dynamics (CFD) simulations, which have made it possible to understand airflow patterns and their influence on the heat dissipation of critical PC components, such as the CPU and GPU. In this context, [1] conducted a numerical and experimental study on thermal dissipation in PC cases, demonstrating that increasing the intake air velocity significantly improves temperature distribution, reducing the temperature of sensitive components by up to 35%. Likewise, other authors have investigated the effect of different ventilation configurations and heat sinks. For example, in [2], three patterns of intake and exhaust air placement found that the design of airflow passages directly influences the efficiency of fined heat sinks, with configuration pattern 1 being the most effective in reducing CPU temperature. Regarding the specific modeling of axial fans, [3] demonstrated the applicability of the Multiple Reference Frame (MRF) methods to accurately simulate the interaction between fans and internal airflow in electronic devices, highlighting the difference between simplified models and realistic physical fan modeling. Finally, recent research, such as [4], proposed Thermoelectric Cooling (TEC) systems assisted by CFD as an efficient alternative for controlling temperature in cases with high-power CPUs. Their effectiveness was validated by simulating a case with multiple heat sources and comparing it with analytical and simulation models. While these results are important, this paper expands the understanding of these effects by quantitatively mapping the correlation between fan layout, components and critical temperature zones, providing a more complex picture of these effects and an approach to designing impedance curves to determine the operating point of fans concerning cabinets and their systems. This study introduces a methodology based on CFD simulations of an ATX cabinet (XPG VALOR AIR) with 14 fan layout configurations for forced cross-flow inlet and outlet. This approach allows studying thermal behavior under different pressure and flow regimes, establishing an experimental model of reproducible analysis to optimize ventilation in high-performance systems. Likewise, the calculation and interpretation results through thermal correlation matrices between the main electronic components are presented, representing an innovative proposal that allows identifying quantitative relationships between the GPU, CPU and MOSFETs. This approach provides a novel perspective on the distribution of cooling components by ventilation, integrating elements of cross-analysis that have little explored in the current literature. It is also suitable for a non-specialized audience. Finally, experimental validation was incorporated using bechmarking tools (3DMark and HWmonitor), which allowed for verifying the coherence of the simulated results from the perspective of the overall thermal stability of the system. This strategy represents an indirect method of validation of CFD simulations, which, although it does not replace the detailed physical experimentation, represents a methodological novelty by opening new possibilities to contrast thermal configurations in simulation environments with observable correlations in real conditions.

2. Justification

It is now widely assumed that the study of ventilation cooling conditions in enclosures is not so necessary since the manufacturers of both fans and enclosures ensure optimum ventilation performance and that the typical arrangement of three front and one rear fan is more than sufficient, as demonstrated in [5], using ANSYS CFD in a turbulent regime, the temperature in areas without direct ventilation rises to 40% higher than the front areas, but not including thermal correlations; Likewise, works such as [6], that through individual simulations of the CPU, chipset and power supply by varying the airflow with the rpm of the fans, managed to increase efficiency by 30% for the original design.

More sophisticated approaches, like [7], performed a thermal optimization of the Big Sur server for Machine Learning with high thermal consumption GPUs by varying airflow, card position and dynamic fan speeds using CFD and transient simulations, demonstrating that a correct component position can reduce the temperature up to 20% to the original design, concluding that an optimized flow allows achieving thermal uniformity within +-5ºC in all components, so this false idea has diverted the interest to demonstrate quantitatively that the customs could not provide the expected performance, generating oversizing and non-optimal configurations for performance in the margin of improving efficiency, noise and energy consumption.

Recent studies, such as [8], focus on analyzing how fan speed affects the temperature of the main components of a personal computer (CPU and GPU) and, therefore, its computational performance. Unlike exclusively simulated studies, Blosen's approach is empirical and comparative to identify an optimal operating point that balances three key factors such as temperature reduction, fan noise level and overall system performance (FPS and benchmark); he used a stable test environment, running load tests on the CPU and GPU using standardized benchmarks and thermal monitoring programs. This methodology recorded the maximum temperatures reached, the computational performance in terms of FPS (frames per second) and the level of noise generated.

Unlike the works in the literature, this paper explains how specific configurations achieve better thermal performance, demonstrating that an efficient configuration with three fans can outperform one with six by optimizing the flow distribution. According to [9], it is concluded that a higher fan operating speed allows for high air flows, which maintain lower temperatures in the internal components of a computer due to increased convective heat transfer. Thanks to this contribution, it was decided to simulate all configurations at maximum fan speed to maximize the thermal efficiency of the equipment in an environment with maximum thermal demand.

In the literature, [10] explains the importance of the impedance of a system, which is the resistance faced by the airflow to pass through a system, thus allowing the actual air flow rate and static pressure to be determined. However, no systematic metric has been established in the literature for calculating the total flow impedance of an enclosure, including shape, obstacles, actual air paths and thermal connection between components. This limits the ability to compare configurations quantitatively and scientifically. For this reason, a prototype model was developed to obtain the impedance curve of the cabinet. A proposal explored little in the literature. This curve allows for the calculation of the real operating point of the system utilizing the intersection with the characteristic curve of the fans, which is a useful tool for thermal design on a physical basis, which opens possibilities for future work.

3. Background

In [11], a heat transfer analysis with heat-generating components by swapping the locations of two fans on the side for airflow inside a desktop computer. The components added inside the cabinet were the motherboard, processor, three RAMs, five adapter cards, a hard disk, a Zip drive, a floppy disk drive, and a DVD drive. The simulations were performed in PHOENICS and took the k-ε turbulence model. At the end of the simulations, they obtained a configuration with a higher Nusselt number in the different regions of the cabinet.

Likewise, they demonstrated that the higher the Reynolds number, the higher the Nusselt number, thus improving heat transfer. With these results, they conclude that the higher the turbulence of the fluid, the better the heat transfer between the components and the air.

Subsequently, [5] shows a CFD modeling for the forced cooling of a computer cabinet in which three different model heat sinks for the processor were tested, using Ansys Icepak software for preprocessing and FLUENT for the solution and post-processing. The simulated equipment contained a 70W processor, graphics card, motherboard, RAM, power supply, adapter cards, CD, DVD and floppy disk drives. They conclude that the cabinet grids are simplified as detailed grids would make the simulation more difficult, and an unnecessarily refined mesh distorts the stability of the model, causing longer computation times. A zero-equation turbulence model can analyse fluids and heat transfer inside a computer cabinet. On the other hand, radiation effects can be ignored due to forced convection and low-temperature differences inside the equipment. [12] shows CFD analysis of thermal regions and flow fields inside a desktop personal computer with 80 W and 130 W multi-core processors, respectively, using the FLUENT package and the k-ε turbulence model. The main objectives of those simulations were to determine the airflow patterns and the maximum operating temperature of the components in the computer system and to investigate the effect of different parameters on the heat dissipation of the processor. Among the results were velocity vectors in a section parallel to the motherboard. The airflow pattern with a straight vertical finned heatsink indicated strong flow through the heat sink and over the memory cards but weak in areas away from the motherboard. In addition, the CPU temperature has a non-linear variation concerning its respective fan speed. Likewise, the ambient air temperature and air intake area considerably affect the CPU temperature.

According to [13], waste heat given off by computer chips must be removed to avoid the reduction in processor clock speed or temporary or permanent failures. For their part, [14] highlights the importance of thermal management due to the high-power density presented by the nanotechnology approach to electronic devices since increased heat generation translates into decreased productivity and eventual failure. This paper proposes a practical and theoretical approach by addressing the impact of fan positioning on the heat dissipation of computer components by analyzing a case by CFD using SOLIDWORKS Flow Simulation.

4. Computational Fluid Dynamics (CFD)

4.1. Constitutive Equations

The Navier-Stokes equations describe the motion of a real fluid produced by viscous forces, the force of pressure and gravity in general, i.e., the flow of an incompressible fluid with constant viscosity. Mathematical turbulence models are used to calculate turbulent eddies' increased intensity and diffusion. The selection of the turbulence model in a CFD simulation is important because the consistency of the fluctuations produced in the fluid will depend on the model chosen. For the present work, the $k-\varepsilon$ model was used in its modified version by Lam and Bremhorst, which describes laminar, turbulent and transient flows of homogeneous fluids and consists of the following turbulence conservation laws:

$$\frac{\partial \rho k}{\partial t}+\frac{\partial \rho k u_i}{\partial x_i}=\frac{\partial}{\partial x_i}+\left(\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right)+\tau_{ij}^{R}\frac{\partial u_i}{\partial x_j}-\rho\varepsilon+\mu_t P_B \tag{1}$$

$$\frac{\partial \rho \varepsilon}{\partial t}+\frac{\partial \rho \varepsilon u_i}{\partial x_i}=\frac{\partial}{\partial x_i}+\left(\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right)+C_{\varepsilon 1}\frac{\varepsilon}{k}\left(f_1\tau_{ij}^{R}\frac{\partial u_i}{\partial x_j}+C_B\mu_t P_B\right)-f_2 C_{\varepsilon 2}\frac{\rho\varepsilon^2}{k} \tag{2}$$

These equations incorporate the effects of low Reynolds numbers in the decomposition of isotropic turbulence. In turn, they utilize the critical and turbulence Reynolds numbers by reducing the turbulent viscosity and turbulence energy while increasing the turbulence dissipation when the critical Reynolds number is significantly decreased.

4.2. The k-epsilon Model

The k-ε model is a turbulence model widely used in three-dimensional flows with complex boundary conditions, being one of the most used tools for CFD analysis of ventilation and heat transfer in closed systems. Its application in this study for the performance of axial fans and computer cabinets is justified based on the literature. In this regard, [3] used a combined Multiple Reference Frame (MRF) models with a k-ε turbulence model to represent the real behavior of axial fans in electronic contexts. Unlike simplified models, this combination enabled the generation of physically coherent predictive results. The pressure-flow rate (P-Q) curves obtained through the MRF model were compared with experimentally measured curves for a real axial fan, yielding a relative error between predicted and measured pressure within 5%. This validates the accuracy of the combined MRF + k-ε model, thereby ensuring its effectiveness for ventilation studies in computer cases where the interaction between flow, geometry, and impedance is significant.

Similarly, in the study [7], a simulation and optimization of the "Big Sur" server cooling system from Open Compute was conducted, where the k-ε model was used due to its effectiveness in simulating internal turbulent flows, such as those present in server enclosures with multiple heat-generating components. This model enabled accurate temperature distribution and airflow path prediction, which is crucial for identifying recirculation zones and potential overheating areas. Finally, [15] used the k-ε model to analyze the aerodynamic behavior of low-pressure axial fans.

Their study involved RANS (Reynolds-Averaged Navier–Stokes) simulations using various turbulence models, including Spalart–Allmaras (SA) and Shear Stress Transport (SST). Numerical results were compared with experimental data from a fan with a hub-to-tip ratio of 0.14. The CFD simulations predicted the total pressure with a relative deviation of approximately 3.3% compared to experimental data at the point of maximum efficiency. The simulated total-to-static efficiency showed a relative deviation of around 3.4% from experimental measurements at the same operating point.

5. Materials and Methods

The XPG VALOR AIR case was chosen for the analysis because this model was available physically, facilitating the design and taking of measurements. In addition, the design that predominates in the market is the one that follows this case: an ATX format case that is placed vertically with an inlet to place up to three fans in the front, a rear slot for a fan and a top slot to install up to two fans. Figure 1 shows the model of the designed cabinet:

Fig. 1 Comparison between the real model and the model used for the simulations of the XPG VALOR AIR case

Fig. 2 Assembly used for simulations with the XPG VALOR AIR case

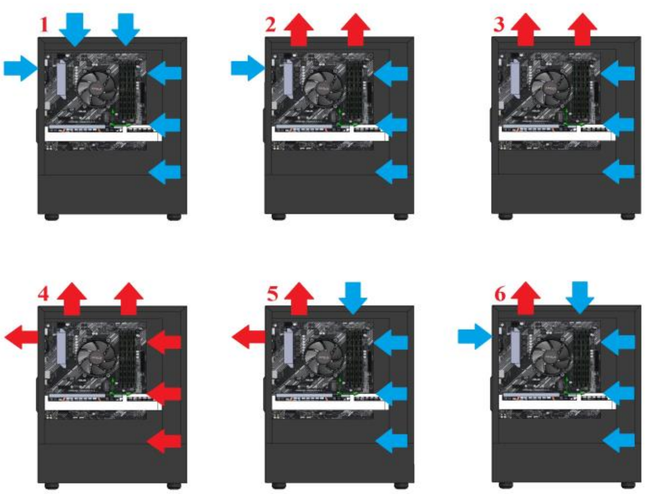

Fig. 3 Configurations used in the simulations with six fans in the XPG VALOR AIR case

The simulated equipment would have the following components: CPU: AMD Ryzen 5 5600G, Motherboard: Asus PRIME A520M-A II/CSM, GPU: GeForce RTX 3060 VISION OC 12G, RAM: 4 x 8GB DDR4 modules, PSU: Gigabyte GP-P650B ATX, Storage: 2 x 500GB SSD, Case Fans: ROG STRIX XF 120. The fans simulated in the unit were represented by simplified parts where the characteristic curves would be simulated. Once all the internal components were designed, the fan configurations to be simulated were defined. Figure 2 shows the equipment to be simulated:

Prior to the simulations, fan configurations were defined for the case in question; in this way, control would be kept comparing the results obtained along the different configurations; it should be clarified that for this case, six configurations were defined using six fans based on those used by [16] and eight own configurations using three fans. Figures 3 and 4 show the previously defined configurations:

Since two sets of simulations were performed with six and three fans, the <NumConf> tag would represent the configuration used, and the <NumVent> tag would represent the number of fans in the simulation. Table 1 shows the parameters used in the simulations:

Fig. 4 Configurations used in the simulations with three fans in the XPG VALOR AIR case

Table 1. Configuration of projects

Flow Simulation Project	
Project name	CONF<NumConf>VENT<NumVent>
Configuration	Use current
Unit system	SI, units of angular velocity: RPM
Type of analysis	Internal Exclude cavities without flow conditions
Physical characteristics	Heat conduction in solids
Fluid	Gas / Air
Default solid	Alloys / Steel (Mild)
Wall conditions	Default conditions
Initial conditions	Default conditions Turbulence parameters: Turbulence energy and dissipation

To define the heat rates of the motherboard components, the maximum nominal values of the market were used to simulate equipment operating under demanding conditions with zero efficiency. Table 2 shows all the defined heat sources used in the simulations:

A level 4 automatic global mesh with advanced channel refinement enabled was considered. Local meshes were placed on the processor heat sink and in the region covered by the RAMs. Figure 5 shows a close-up of the area meshing around the CPU heatsink and RAM.

Figure 6 shows a close-up of the mesh defined in the midplane of the assembly. It is crucial to perform a correct meshing since the quality of the results obtained will depend on it. Inside the assembly are areas with thin slots, such as the fins of the CPU heatsink and the GPU cooling system. These two components are of great importance in a computer. The correct simulation will allow these components to behave as similarly as possible to reality, resulting in an analysis of the thermal management of the equipment with a high degree of reliability.

Table 2. Heat sources used in the projects

Computer Components	Total Heat Generation Rate
Processor	65 W
Power Supply Unit	4 W
Motherboard Inductors	10 W
Motherboard transistors (MOSFETs)	22 W
RAM chips	4 W
Motherboard chipset	6 W
Graphics processing chip (GPU)	170 W
Graphics memory (VRAM)	32 W
GPU Inductors	9 W
GPU transistors (MOSFETs)	15 W

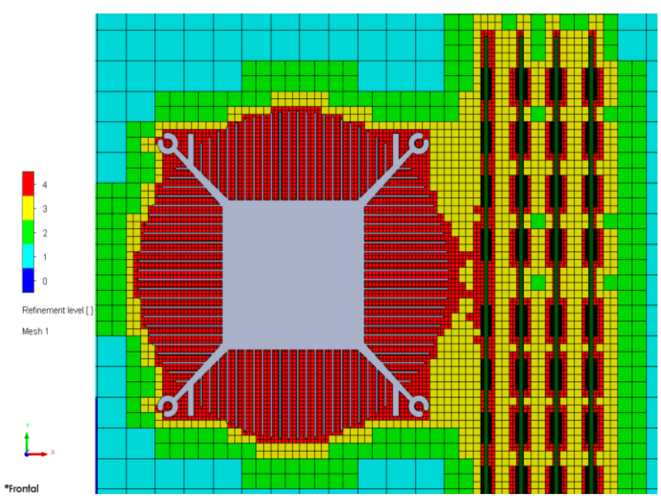

Fig. 5 Fluid mesh in the upper region of the case

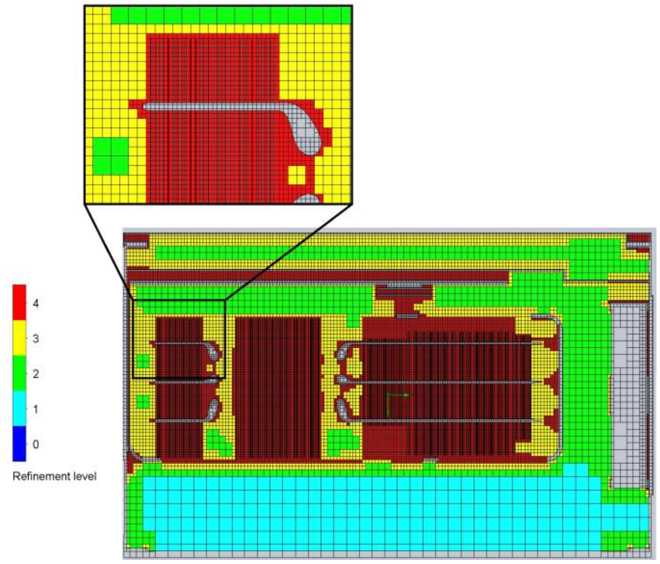

Fig. 6 Fluid mesh in the middle plane of the case graphics card

6. Results and Discussion

6.1. Impedance Curve

The impedance curve was plotted for the fan configurations that yielded the lowest overall component temperatures, i.e. CONF3VENT6 and CONF8VENT3. All the results of this section can be found in the tables in Appendix 1. It should be clarified that this calculation was done theoretically, knowing the concepts of the impedance curve applied in a system; however, a computer cabinet is a much more complicated ventilation system since it not only has different air inlets and outlets but also contains fans that enter and expel the air in the system, as well as internal fans that redirect the air trajectory inside the cabinet.

Since the literary sources that addressed the calculation of the impedance curve of a system showed insufficient information on the methodology for calculating the impedance curve in a system of the same complexity as a computer cabinet, a methodology was developed to calculate the impedance curve based on the theoretical principles of impedance, i.e., the resistance to airflow shown in the static pressure differences in the air inlets and outlets. First, the proportionality of the inlet and outlet flow rates was obtained for each of the fans for both configurations. For this purpose, the flow rates of the inlet fans of each configuration were added, which would define the total inlet flow rate of the system; subsequently, the percentage of the total flow rate entering or ejecting each fan from the cabinet was calculated. Tables 5 and 6 show the calculation of the percentages of total flow rates considered in the configurations. Then, three flow rates were selected to plot the impedance curve, which would be 0.02 m^3/s, 0.04 m^3/s, y 0.06 m^3/s. Once these total inlet flow rates were obtained, the flow rates that would enter or be expelled by the fans were calculated according to the percentages previously calculated. Tables 7 and 8 show each fan's total simulated flow rates in the selected configurations.

After this, the static pressures of the inlet and outlet fans were added so that the pressure difference could be calculated to plot the impedance curve of both systems. In the case of CONF8VENT3, the outlet static pressures were taken as atmospheric pressure, i.e. 101325 Pa. Tables 9 and 10 show the final calculation of the values used to plot the impedance curves for both configurations. To obtain the system's operating point, an intersection between the system curve and a characteristic curve is required. In this case, a characteristic curve representing the three ROG STRIX XF120 fans installed in parallel was considered; for this, the characteristic curve was calculated as proposed by [17]. Figure 7 shows the intersections of the possible impedance curves of the CONF3VENT6 and CONF8VENT3 configurations and compares the characteristic curves of a single ROG fan and three ROG fans installed in parallel.

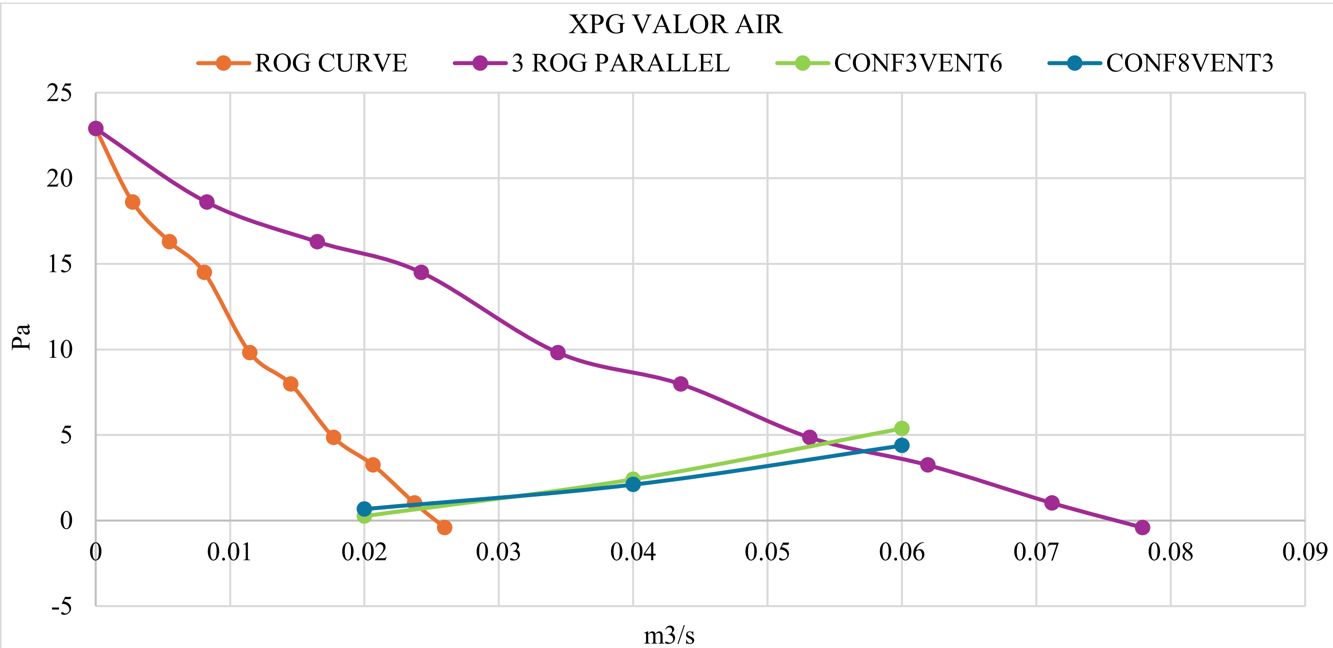

Fig. 7 Intersection of impedance curve and cabinet characteristic curve

According to [10], the CONF8VENT3 configuration shows a slightly lower impedance than CONF3VENT6 but maintains a similar behavior and performance in component cooling.

Since no standardized methodology was found to corroborate the accuracy of the results, they allow the flow resistance to heat dissipation in a desktop computer to be related, thus establishing a basis for future work and experimental validation.

6.2. Results of the Configurations in the Case

After running the simulations in this case, i.e., the six-fan and three-fan combinations, the component temperatures and air temperature contours in the case planes were compared. Tables 3 and 4 present the most relevant results for the conclusions of this paper:

Figures 8 and 9 show the behavior of the air trajectories and their temperature contours. Figure 8 contains the outlines of CONF3VENT6 (top) and CONF4VENT6 (bottom), while Figure 9 contains the outlines of CONF4VENT3 (top) and CONF8VENT3 (bottom). The planes chosen for all configurations were the following: the elevation plane of the assembly, a plane 18.25 mm from the backplane and the lateral plane. A plane close to the motherboard was selected to observe the behavior of the air in an area with more obstacles. In addition, the size of the vectors shown on the planes is a function of air velocity. These settings were maintained for all configurations.

Table 3. Values obtained in the case with six case fans

Average Temperatures	Unit	CONF3 VENT6	CONF4 VENT6
CPU	[°C]	53.115	56.541
PSU	[°C]	23.325	26.453
MB INDUC	[°C]	73.432	84.672
MB MOSFET	[°C]	87.673	98.308
RAM 1	[°C]	72.152	71.808
RAM 2	[°C]	116.492	94.164
RAM 3	[°C]	112.736	93.288
RAM 4	[°C]	71.989	96.340
GPU	[°C]	80.204	81.309
VRAM	[°C]	43.752	44.820
PCB GPU	[°C]	41.326	40.581
INDUC GPU	[°C]	57.159	56.554
MOSFET GPU	[°C]	86.872	86.041

Table 4. Values obtained in the case with three case fans

Average Temperatures	Unit	CONF4 VENT3	CONF8 VENT3
CPU	[°C]	64.762	53.728
PSU	[°C]	39.344	23.657
MB INDUC	[°C]	86.284	73.797
MB MOSFET	[°C]	102.162	87.785
RAM 1	[°C]	71.883	72.193
RAM 2	[°C]	79.557	107.308
RAM 3	[°C]	85.488	109.148
RAM 4	[°C]	73.336	71.767
GPU	[°C]	90.079	79.419
VRAM	[°C]	53.825	43.015
PCB GPU	[°C]	50.495	40.409
INDUC GPU	[°C]	65.316	55.963
MOSFET GPU	[°C]	95.098	85.695

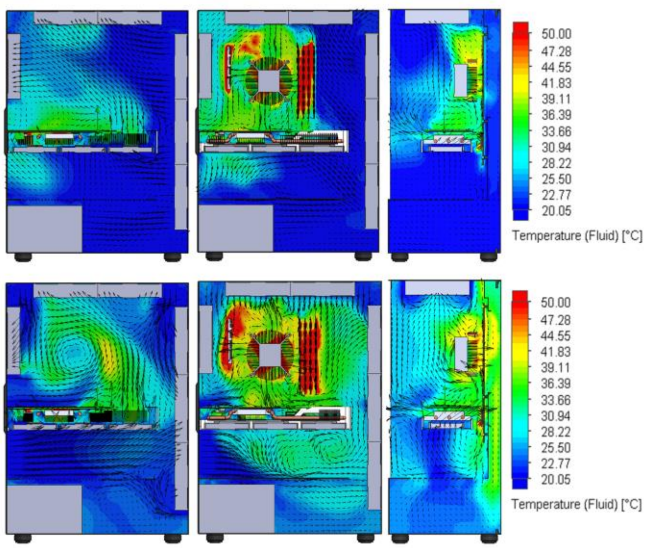

Fig. 8 Air temperature contours with six case fans

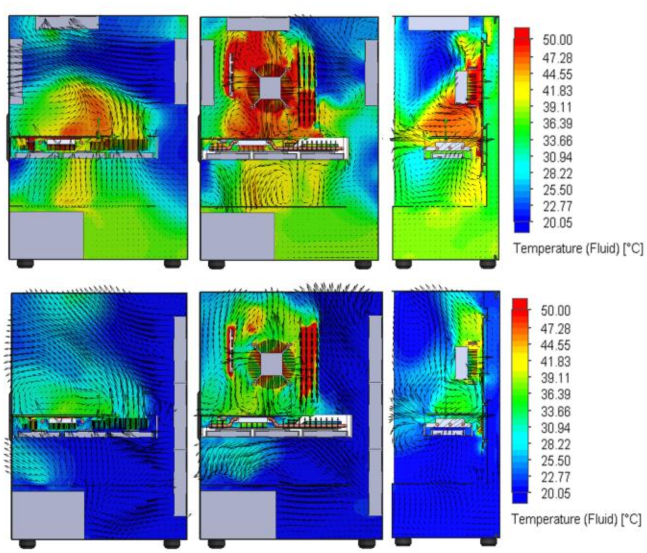

Fig. 9 Air temperature contours with three case fans

It is very noticeable how the air temperature rises in the space between the RAMs, as in all configurations, high temperatures predominate in the region between the processor and the RAMs, consistent with the quantitative data. It is very noticeable how configuration number 4 with 3 and 6 fans shows high-temperature contours.

6.3. Correlation of Results

The last analysis of results was based on the calculation of the correlation matrix, thus obtaining the relationship between various variables of the data sets obtained in the simulations of the cases. The values obtained in the eight simulations with three fans and six simulations with six fans were taken as a sample to create the case matrix.

Figure 10 shows the relationship between the average temperatures of the components, obtaining a high positive relationship between the temperature of the power supply and the temperatures of the components of the graphics card because the graphics card fans draw air from the lower region of the case where the power supply is also located Similarly, the power supply shows high positive relationships with the processor and VRM.

This correlation highlights the importance of maintaining the cooling system, as the relationships show a high impact on the power supply with the most important components in a computer.

Positive relationships are also obtained between the graphics card and the processor temperatures; this highlights the importance of maintaining proper heat dissipation of both the processor and the graphics card, which are essential components for a computer.

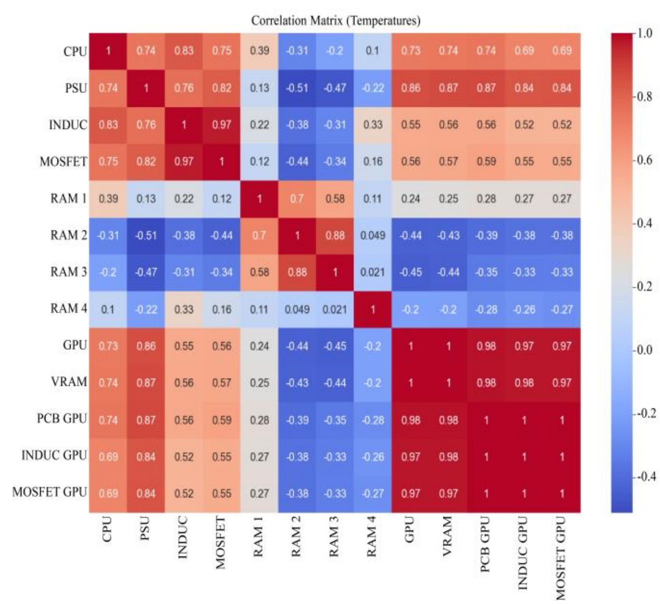

Fig. 10 Correlation matrix of the temperatures of all computer components

6.4. Results Validation

Finally, the four configurations shown were implemented through physical tests by replicating the simulated conditions in a real environment. The configurations were selected this way to provide a frame of reference for validating the accuracy of the results against each other. The case was tested without the front panel and the dust filter on the top. The latter is important to consider, as these filters hinder the fans' airflow in physical tests. This condition was not accounted for in the simulations due to the required mesh resolution.

3DMark software was used in its free version, which included the Steel Nomad simulation in version 1.0. In addition to this software, the HWMonitor program, version 1.55.0, was used to monitor the temperatures in the motherboard, processor, and graphics card sensors. This program records the system's maximum, minimum and current values from the moment it is executed until it is closed. The following figures show the scores (in 3DMark) of each configuration as well as the temperatures of the equipment at the end of the stress test.

Figures 11 and 12 show that the configurations with six fans prove to be efficient; however, with three fans, this is not the case, as in Figure 13, the CONFIG8VENT3 obtains significantly better results than the CONFIG4VENT3 shown in Figure 14, with the latter being the worst performer in both absolute test values and simulations for most components.

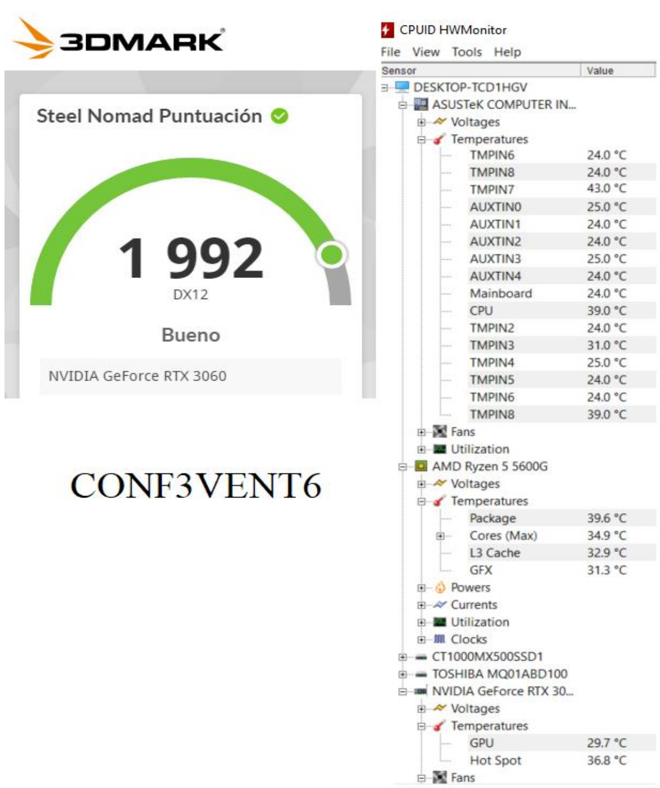

Fig. 11 Results obtained in the performance test with the CONF3VENT6 configuration

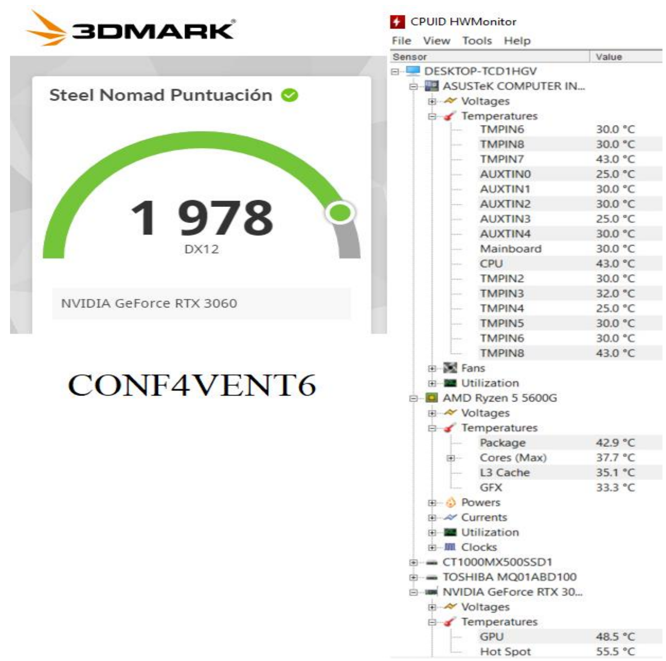

Fig. 12 Results obtained in the performance test with the CONF4VENT6 configuration

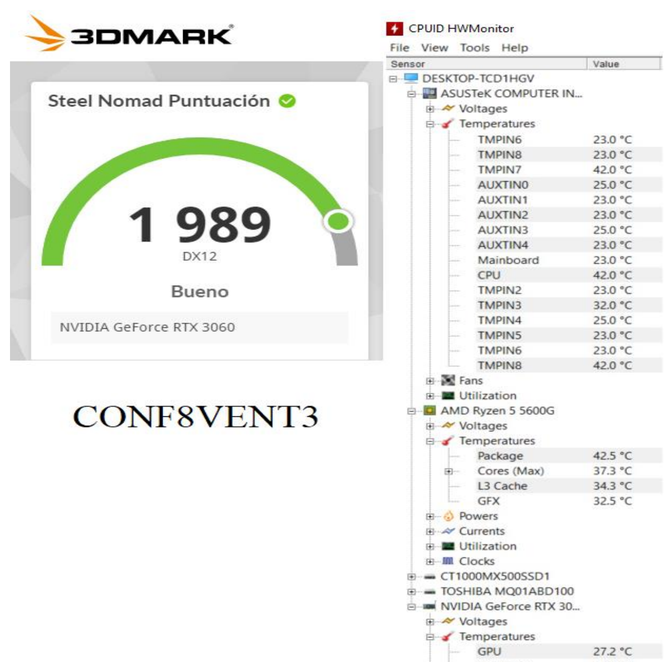

Fig. 13 Results obtained in the performance test with the CONF8VENT3 configuration

The temperatures obtained from the motherboard, processor and graphics card sensors are shown. However, the exact locations of the sensors shown are unknown, so these values should be interpreted with caution, particularly those of the motherboard, as its larger size results in many more temperatures with unknown locations. In addition to this, the software does not allow us to obtain the RAM temperature, and no way to monitor them was found.

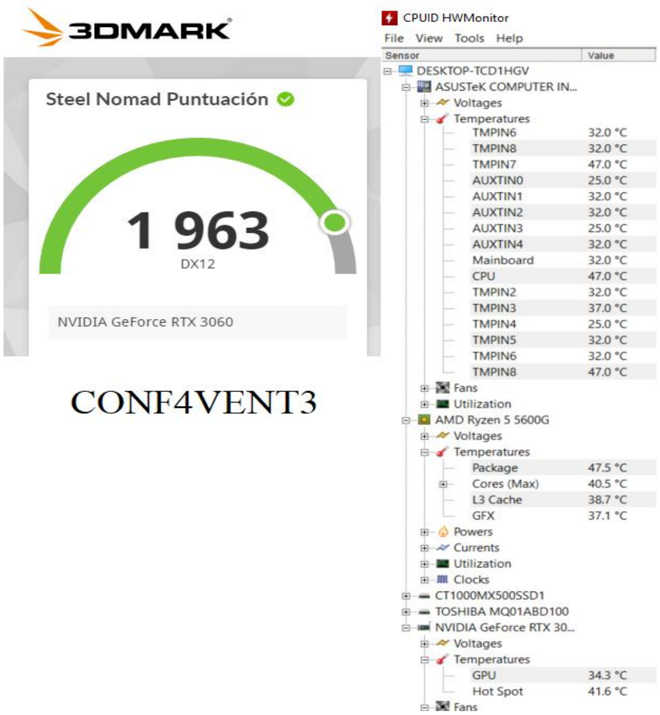

Fig. 14 Results obtained in the performance test with the CONF4VENT3 configuration

Figures 12 and 14 show that the CONFIG4VENT6 and CONFIG4VENT3 configurations obtain the least efficient results of the set tested. However, the configuration with six fans installed in the case obtains slightly better results than the configuration with only three fans, demonstrating that even a fully negative pressure configuration with six fans keeps the components in an allowable temperature range without sacrificing much in terms of performance and stability of the equipment.

7. Conclusion

The results obtained in the tests do not show temperatures that put the components at risk; however, they provide an initial understanding of the components' performance under high workloads for extended periods. Therefore, the CONF4VENT6 and CONF4VENT3 configurations are unsuitable for demanding and prolonged use. Despite obtaining high temperatures in components such as RAM memories, these values highlight the importance of maintaining a correct airflow and the difficulty that these components present due to the orientation they have with respect to the air inlet. The heat dissipation capacity of the XPG VALOR AIR case stands out, as it achieved the lowest temperatures in 90% of the components. The form factor of the first enclosure demonstrated high thermal efficiency even with few fans installed. In contrast, the second enclosure design, being larger, requires a greater number of fans to dissipate the same amount of heat as the first enclosure. According to [8], higher fan speeds and increased airflow significantly reduce component temperatures. Furthermore, he states that if the user's graphics card operates below the manufacturer's thermal throttling threshold, fan speed can be reduced without concerns about premature failure or excessive noise.

This was demonstrated in tests performed with the 3D Mark software in this study, where no temperatures were reached that would trigger thermal throttling of the components. Thus, the component fans do not need to operate at maximum speed under typical usage conditions. Thermal throttling was avoided since all simulations were performed using SOLIDWORKS Flow Simulation. Implementing the simulated configurations poses a risk of thermal throttling, which could affect result interpretation and equipment operation. Throttling reduces component performance and energy consumption, leading to non-representative results, while prolonged exposure to improper conditions may cause irreparable damage.

In a practical sense and with easy access for the public, the information shared regarding the arrangement of computer case fans is usually general. It focuses on positive, negative, or neutral pressure configurations without delving into the variables affected by the number and placement of fans. One example is [16], which attempts to demonstrate which fan configuration yields the best temperatures in a desktop computer. However, the author does not clarify the behavior or models of the fans used. This information is crucial, as fans can be either fixed-speed or variable-speed and failing to configure these speeds results in an unstable scenario that increases the complexity of the analysis, thereby making the results less reliable. That is why the present study aimed to obtain stable and reliable quantitative results by ensuring all fans were identical and physically operating at their maximum speed. As a result, the temperatures reported reflect the lowest possible values achievable with each configuration.

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Appendix 1

Table 5. Percentages of total flow rates with CONF3VENT6 configuration

	Front Fan 1	Front Fan 2	Front Fan 3	Top Fan 1	Top Fan 2	Back Fan	Inlet Flow
	0.02597604	0.0226906	0.02247422	0.0165926	0.0170623	0.0169708	0.071140894
Percentage	36.514%	31.895%	31.591%	23.324%	23.984%	23.855%	

Table 6. Percentages of total flow rates with CONF8VENT3 configuration

	Front Fan 1	Front Fan 2	Front Fan 3	Inlet flow
	0.025049836	0.021803659	0.021389894	0.068243389
Percentage	36.707%	31.950%	31.344%	

Table 7. Simulated flow rates for calculating the impedance curve of the CONF3VENT6 configuration

	Air Intake			Air Outlet		
Total flow	**Front Fan 1**	**Front Fan 2**	**Front Fan 3**	**Back Fan**	**Top Fan 1**	**Top Fan 2**
0.02	0.007302704	0.006379068	0.006318228	0.004771044	0.004664714	0.00479678
0.04	0.014605408	0.012758136	0.012636456	0.009542087	0.009329428	0.00959356
0.06	0.021908111	0.019137204	0.018954685	0.014313131	0.013994141	0.014390339

Table 8. Simulated flow rates for calculating the impedance curve of the CONF8VENT3 configuration

	Air Intake		
Total Flow	**Front Fan 1**	**Front Fan 2**	**Front Fan 3**
0.02	0.007341322	0.00638997	0.006268708
0.04	0.014682645	0.012779939	0.012537416
0.06	0.022023967	0.019169909	0.018806124

Table 9. Values used to plot the impedance curve of the CONF3VENT6 configuration

Total Flow	0.02	0.04	0.06
Static Pres. In	303976.33	303977.85	303979.04
Static Pres. Out	303976.07	303975.44	303973.66
Difference	0.26	2.41	5.38

Table 10. Values used to plot the impedance curve of the COONF8VENT3 configuration

Total Flow	0.02	0.04	0.06
Static Pres. In	303975.67	303977.1	303979.38
Static Pres. Out	303975	303975	303975
Difference	0.67	2.1	4.38