



ANALYSIS ON THERMAL AND HYDRAULIC PERFORMANCE OF CPU COOLER UNDER DIFFERENT WORKING CONDITIONS

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Anahtar Kelimeler

CPU cooler, micro cooling, hydraulic performance

Öz

Like other computer hardware components, the central processing unit (CPU) generates heat during operation and requires effective cooling to maintain optimal performance. One of the most efficient methods for cooling a CPU is the use of a liquid-based cooling system. This system typically consists of three main components: a fluid block that makes direct contact with the CPU, a pump, and a heat exchanger, which includes a fan and a radiator. The coolant circulates through the system via connecting pipes. In this study, a CPU cooler's thermal and hydraulic performance was analyzed under various operating conditions. Water was used as the working fluid (coolant) in the system. A 100 W thermoelectric heater was employed to simulate the thermal load and determine the system's cooling capacity. The volumetric flow rates of the coolant were set to 1, 2, 3, and 4 L/min, respectively. It was observed that the heat transfer between the CPU surface and the cooler decreased with increasing fluid velocity. The fluid pressure was higher at the inlet of the cooler and decreased along the flow path, depending on both the geometry of the flow channels and the flow rate of the coolant. For effective heat dissipation in CPU cooling systems, it is crucial to maintain the coolant flow rate and velocity within an optimal range.

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doi : 10.46399/muhendismakina.1693839

FARKLI ÇALIŞMA KOŞULLARI ALTINDA CPU SOĞUTUCUSUNUN TERMAL VE HİDROLİK PERFORMANSININ ANALİZİ

Keywords

*İşlemci Soğutucusu, Mikro
Soğutma, Hidrolik Performans*

Abstract

Diğer bilgisayar donanım bileşenlerinde olduğu gibi, merkezi işlem birimi (CPU) de çalışırken ısı üretir ve maksimum performansla çalışabilmesi için etkili bir şekilde soğutulması gerekir. CPU'yu soğutmanın en etkili yöntemlerinden biri sıvı bazlı bir soğutma sistemi kullanmaktır. Bu sistem genellikle üç ana bileşenden oluşur: CPU ile doğrudan temas halinde olan bir sıvı bloğu, bir pompa ve fan ile radyatörden oluşan bir ısı değiştirici. Soğutucu akışkan bu sistemde borular aracılığıyla dolaşır. Bu çalışmada, bir CPU soğutucusunun termal ve hidrolik performansı farklı çalışma koşulları altında analiz edilmiştir. Soğutucu akışkan olarak sistemde su kullanılmıştır. Soğutma kapasitesinin belirlenebilmesi amacıyla 100 W'lık bir termoelektrik ısıtıcı kullanılmıştır. Sıvının hacimsel debileri sırasıyla 1, 2, 3 ve 4 L/dk olarak ayarlanmıştır. Akışkan hızı arttıkça CPU yüzeyi ile soğutucu arasındaki ısı transferinin azaldığı gözlemlenmiştir. Farklı hacimsel debilerde, akışkan basıncı soğutucu girişinde daha yüksek olmuş; bu basınç, hem CPU soğutucusunun akış kanalı geometrisine hem de akışkan debisine bağlı olarak sistem boyunca azalmıştır. CPU soğutma sistemlerinde etkili bir ısı transferi sağlanabilmesi için soğutucu akışkanın debisinin ve hızının uygun bir aralıkta tutulması gerekmektedir.

Araştırma Makalesi

Başvuru Tarihi : 08.05.2025

Kabul Tarihi : 21.07.2025

Research Article

Submission Date : 08.05.2025

Accepted Date : 21.07.2025

1. Introduction

All electronic circuit components generate heat during operation. Among them, the central processing unit (CPU) used in personal computers tends to produce more heat due to its continuous and intensive processing workload. If not managed properly, this excessive heat can cause permanent damage to the CPU. Therefore, cooling the CPU before it reaches critical temperature levels is essential. CPU cooling involves two main steps: absorbing the heat from the CPU and then dissipating that heat into the surrounding environment. Although most modern CPUs are equipped with an automatic thermal shutdown feature as a safety precaution, active cooling systems are still necessary to ensure safe and stable operation underload. CPU coolers, also known as heatsinks, are mounted directly onto the CPU to draw heat away from it. These coolers are typically made of materials with high thermal conductivity, such as aluminum or copper, although alternative materials are also used in some applications. There are two primary methods for CPU cooling: air cooling and liquid cooling. This study focuses on the latter. In liquid (or water) cooling systems, excess heat generated by the processor is transferred to a circulating coolant (typically water). The heated water is then directed to a radiator, where it releases its heat to the surrounding air, often aided by a fan mounted on the radiator. The cooled water then returns to the CPU block to repeat the cycle. The key advantages of water-cooling systems include the higher thermal conductivity of water compared to air, and significantly lower noise levels during operation. However, these systems tend to be more costly and complex than air-cooled alternatives. In a typical water-cooling setup, a heatsink (or cold plate) is placed directly on top of the CPU to absorb the heat, which is then carried by the water through a closed-loop system to the radiator. The radiator dissipates the heat into the air with the help of one or more fans. The now-cooled water is circulated back to the CPU block to maintain continuous cooling.

Yousefi, Mousavi, Farahbakhsh, and Saghir (2013) conducted an experimental investigation into the performance of CPU coolers, focusing specifically on the effects of heat pipe inclination angle and the use of nanofluids. Their findings revealed that the inclination angle has a direct influence on the performance of the evaporator. Gorzin, Ranjbar, and Hosseini (2022) studied a novel serpentine channel design for liquid-cooled CPU systems. They examined the impact of mass flow rate and inlet temperature on the system's thermal performance. Their results indicated that modifying the channel geometry led to an 11.2% reduction in base plate temperature and a 4.2-fold increase in the Nusselt number, depending on the flow rate. Može, Nemanič, and Poredoš (2020) analyzed the performance of heat pipe-based CPU coolers and reported that the best thermal performance was achieved at a 90° orientation. Similarly, Nazari, Karami, and Ashouri (2014) compared the performance of various nanofluids in CPU cooling applications using different flow rates. They found that a refrigerant consisting of 30% ethylene glycol enhanced the heat transfer coefficient by 4%. Choi, Jeong, Yoo, and Seo (2012) developed a new CPU cooler design using computational fluid dynamics (CFD) simulations. Their results demonstrated that the proposed cooler achieved efficient thermal resistance with minimal noise output. Hu, Ge,

Dai, and Wang (2016) experimentally investigated a water-cooled thermoelectric CPU cooler, focusing on the effects of air velocity and water mass flow rate at different temperature conditions. They determined that the optimal coefficient of performance (COP) occurred at an air velocity of 0.8 m/s and a water mass flow rate of 0.042 kg/s. Sun and Liu (2017) studied the flow and heat transfer characteristics of nanofluids in a liquid-cooled CPU system. Their research showed that using Cu-water and Al₂O₃-water nanofluids significantly improved cooling performance. Additionally, they developed correlations for the heat transfer coefficient and flow resistance coefficient for low concentration nanofluids in CPU coolers. Shaik (2022) designed safety control systems for refrigeration equipment, emphasizing that such controls should be integrated into the cooling system design from the beginning. Kouremenos, Kakatsios, and Floratos (1996) performed numerical calculations on the thermodynamic behavior of an ammonia-water mixture during isentropic expansion in the vapor phase and presented the results in the form of diagrams. Finally, Sentić and Lazić (2016) conducted a comparative study on the absorption refrigeration cycle using ammonia-water solutions under two different operating conditions, while Sharma, Vaish, and Kumar (2021) explored the cooling effect of functionally graded dielectric materials based on the flexocaloric effect.

In this study, the thermal and hydraulic performance of a liquid-cooled CPU cooling system was examined experimentally under varying operational conditions. The study focuses on how changes in coolant flow affect the efficiency of heat transfer, pressure distribution across the system, and the stability of the cooling process. Water was selected as the working fluid due to its high thermal conductivity and wide availability. The research aims to better understand the interaction between fluid dynamics and thermal behavior within the system, and to provide insights that can guide the design of more efficient and reliable CPU cooling solutions. By analyzing the effects of different flow conditions, the study contributes to developing optimized the cooling systems that support the safe and effective operation of high-performance computing hardware.

2. Material And Method

Research and publication ethics were observed in this study.

2.1. Structure and Description of the Cooling System

The central processing unit (CPU), much like other components in a computer system, generates a significant amount of heat during operation due to the high frequency of data processing and the continuous execution of complex computational tasks. In order to maintain stable and efficient performance, as well as to prevent potential thermal degradation or permanent hardware damage, an effective cooling mechanism is essential. Among the various cooling strategies developed, liquid-based cooling systems have emerged as one of the most efficient and reliable techniques, especially for high-performance computing applications.

In a typical liquid cooling setup, a thermal interface material (commonly referred to as thermal paste) is first applied to the surface of the CPU's Integrated Heat

Spreader (IHS). This paste plays a critical role by filling microscopic imperfections between the metallic surfaces of the IHS and the cooling block, thereby minimizing thermal resistance and enhancing the efficiency of heat conduction.

The cooling block, also known as the baseplate or cold plate, is usually manufactured from materials with high thermal conductivity, such as copper or aluminum. This component is mounted directly onto the IHS and serves as the primary medium through which heat is transferred from the CPU to the circulating coolant. Inside the block, a network of microchannels allows the coolant to flow over a large surface area, maximizing the heat absorption capacity of the fluid (Figure 1).

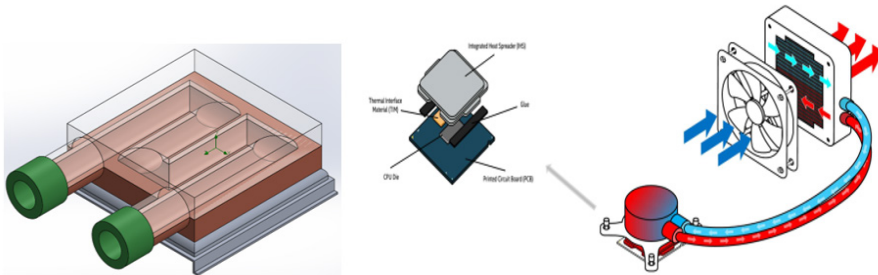


Figure 1. Water-Cooled CPU Cooler (Moze vd., 2020)

Once the coolant absorbs the heat from the CPU, it is transported via flexible, thermally insulated tubing to a radiator located elsewhere within the computer case. The radiator functions as a heat exchanger, transferring the absorbed thermal energy from the coolant to the surrounding air. This process is significantly enhanced by one or more fans mounted on the radiator, which actively push or pull air through its fins to accelerate convective heat dissipation.

After the heat is expelled, the now-cooled fluid is redirected back into the cooling block, completing the cycle. This closed-loop system ensures continuous and consistent heat removal, allowing the CPU to operate within safe thermal limits even during peak performance loads. Moreover, liquid cooling systems are often favored not only for their superior thermal efficiency but also for their reduced acoustic noise compared to conventional air-cooled systems, making them ideal for both professional workstations and enthusiast-grade personal computers.

2.2. Thermodynamic Analysis

The output power of the PTC type heater is determined as 100 W, so the heat flow is:

$$\theta = \theta_{PTC} \tag{1}$$

One of the most effective methods for evaluating the performance of a thermal system is by determining the convection heat transfer coefficient of the refriger-

ant. This coefficient serves as a key indicator of the system's ability to transfer thermal energy from a heated surface (in this case, the CPU cooler) to the coolant fluid circulating through it. A higher convection heat transfer coefficient generally signifies more effective thermal management, which is critical for maintaining the operational stability and longevity of the CPU, especially under heavy processing loads. The convection coefficient not only reflects the material and geometric properties of the cooling system components but also depends on flow characteristics such as velocity, temperature gradient, and turbulence levels of the coolant. In the context of CPU cooling, the heat transfer rate between the surface of the CPU cooler and the coolant can be calculated using the following expression (Rafati et al., 2012):

$$q = hA\Delta T_b \quad (2)$$

Where q represents the amount of heat flux generated by the heater, A is the effective surface area in contact with the CPU surface, and ΔT_b denotes the temperature difference between the CPU surface and the refrigerant. This temperature gradient acts as the driving force for thermal energy transfer from the processor to the coolant. Accurate determination of this temperature difference is crucial for evaluating the cooling system's efficiency. However, in practical scenarios, especially in closed-loop liquid cooling systems, the inlet and outlet temperatures of the refrigerant may not always be directly accessible or easy to measure with high precision.

To address this limitation, the Log Mean Temperature Difference (LMTD) method is employed (Jeng and Teng, 2013). The LMTD approach is a widely accepted technique in heat exchanger and thermal system analyses. It allows for an effective approximation of the average temperature difference between the hot and cold fluids along the heat exchanger by considering the logarithmic mean of the temperature differences at each end of the flow path. This method is particularly useful in systems with varying temperature profiles, where linear averaging would introduce significant errors. By applying the LMTD method, researchers and engineers can more accurately estimate heat transfer rates, even in systems where real-time, point-specific temperature measurements are difficult to obtain or impractical due to system complexity or measurement constraints.

$$\Delta T_b = \ln \frac{T_{\text{CPU}} - T_{\text{in}}}{T_{\text{CPU}} - T_{\text{out}}} \quad (3)$$

The amount of energy extracted from the refrigerant is:

$$q = \dot{m}c_p\Delta T \quad (4)$$

The amount of heat flux produced by the heater can be determined as:

$$q = VI \quad (5)$$

where V and I are voltage and electric current, respectively. Thus, the convection heat transfer coefficient is (Huang vd., 2010):

$$h = \frac{\dot{m}c_p(T_{in} - T_{out})}{A \ln \frac{T_{CPU} - T_{in}}{T_{CPU} - T_{out}}} \quad (6)$$

The Nusselt number is (Liu vd., 2015):

$$Nu = \frac{hD_h}{k_f} \quad (7)$$

The Reynold number is:

$$Re = \frac{ud}{\nu_f} \quad (8)$$

The pressure drop can be determined as follows:

$$\Delta P = P_{in} - P_{out} \quad (9)$$

3. Results And Discussion

The CPU cooler was evaluated under various operating conditions to understand its thermal behavior and performance efficiency. In all scenarios, water was employed as the working fluid due to its favorable thermophysical properties such as high specific heat and thermal conductivity. To simulate heat generation similar to a real CPU workload, a 100 W thermoelectric heater was used as a controlled heat source applied to the base of the cooler. The volumetric flow rates of the coolant were systematically varied and set at 1, 2, 3, and 4 liters per minute (L/min) to investigate the influence of flow rate on heat removal capability and surface temperature distribution.

The temperature profiles of both the coolant and the cooler surface were measured and analyzed under each flow condition, with the results presented in Figure 2. When the flow rate was 1 L/min (Figure 2a), the inlet temperature of the

coolant was approximately 20 °C and increased to about 22 °C at the outlet, indicating limited heat absorption capacity due to lower fluid velocity. Consequently, the surface temperatures of the CPU cooler ranged between 35 °C and 40 °C, reflecting relatively high thermal loads retained within the cooling structure. At a flow rate of 2 L/min (Figure 2b), the coolant again entered the system at 20 °C, but exited at a slightly higher temperature of 20.71 °C. The surface temperature range decreased compared to the previous case, now varying between 29 °C and 32 °C. This demonstrates an improved heat transfer efficiency due to increased coolant velocity, allowing more effective removal of heat from the cooler surface. Further increasing the flow rate to 3 L/min (Figure 2c) resulted in an outlet temperature of 20.57 °C, with the coolant entering at 20 °C. The surface temperatures in this scenario were even lower, measured between 29 °C and 30 °C. This narrow surface temperature range suggests a more stable and uniform cooling performance at moderate-to-high flow rates. At the highest tested flow rate of 4 L/min (Figure 2d), the coolant temperatures at the inlet and outlet were 20 °C and 20.5 °C, respectively. The surface temperatures further declined and ranged between 27 °C and 29 °C. This scenario demonstrated the most effective cooling performance, with the lowest overall temperature difference and surface temperature, indicating that higher flow rates enhance convective heat transfer by reducing the thermal boundary layer thickness and increasing turbulence within the cooling channels.

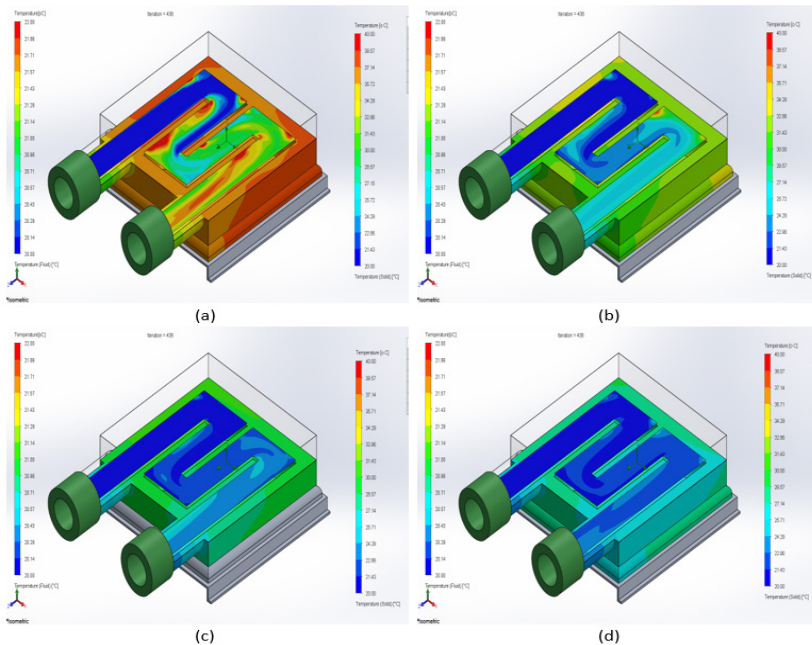


Figure 2. Fluid and surface temperature distribution in a CPU cooler for 100 W thermoelectric capacity and volumetric flow rate of a) 1 l/min, b) 2 l/min, c) 3 l/min, d) 4 l/min, respectively

Overall, the analysis revealed a clear inverse relationship between the coolant flow rate and both fluid outlet temperature and surface temperature of the CPU cooler. As the flow rate increases, the coolant has a greater capacity to absorb and transport thermal energy away from the heat source, resulting in improved thermal management of the CPU.

The overall surface temperature distributions of the CPU micro-cooler under varying coolant flow conditions were examined in detail and are illustrated in Figure 3. This analysis aimed to visualize how changes in the volumetric flow rate of the refrigerant influence both the temperature gradients within the fluid and the thermal response of the micro-cooler surface. At a flow rate of 1 L/min (Figure 3a), the inlet temperature of the coolant was measured to be in the range of 20–21 °C. As the fluid traversed the cooling microchannels, it absorbed heat from the CPU cooler surface, resulting in an outlet temperature that increased to approximately 22–24 °C. The surface temperature of the micro-cooler in this condition was relatively high, ranging from 35 °C to 37 °C, which indicates that the heat dissipation capacity at this low flow rate was limited. This is likely due to the reduced convective heat transfer and longer fluid residence time, which caused more localized heating on the cooler's surface. In the case where the flow rate was increased to 2 L/min (Figure 3b), there was a noticeable improvement in thermal performance. The inlet fluid temperature remained around 20–21 °C, but the outlet temperature rose only slightly to 21–22 °C. More importantly, the surface temperature of the micro-cooler decreased, with values ranging between 30 °C and 32 °C. This demonstrates that higher flow rates enhance the fluid's ability to remove heat more efficiently, thereby reducing the thermal load retained on the surface of the cooler. Further increasing the volumetric flow rate to 3 L/min (Figure 3c) resulted in even more favorable thermal conditions. The coolant maintained an inlet temperature of about 20 °C and exited the cooler at a slightly elevated temperature of 20–21 °C. The surface temperatures during this test scenario were found to be within a lower range, approximately between 27 °C and 30 °C. This relatively uniform and reduced surface temperature distribution suggests more effective and evenly distributed heat removal across the cooler's surface, which is indicative of improved thermal performance and stability at this higher flow rate. At the maximum tested flow rate of 4 L/min (Figure 3d), the cooling system showed the best performance. The fluid entered the micro-cooler at around 20 °C and exited at 20–21 °C, with a minimal increase in temperature, implying highly efficient heat absorption. Correspondingly, the surface temperatures of the micro-cooler were the lowest among all tested cases, recorded between 25 °C and 27 °C. This condition confirms the superior heat dissipation achieved at elevated flow rates, primarily due to the increased turbulence and enhanced convective heat transfer within the microchannel network.

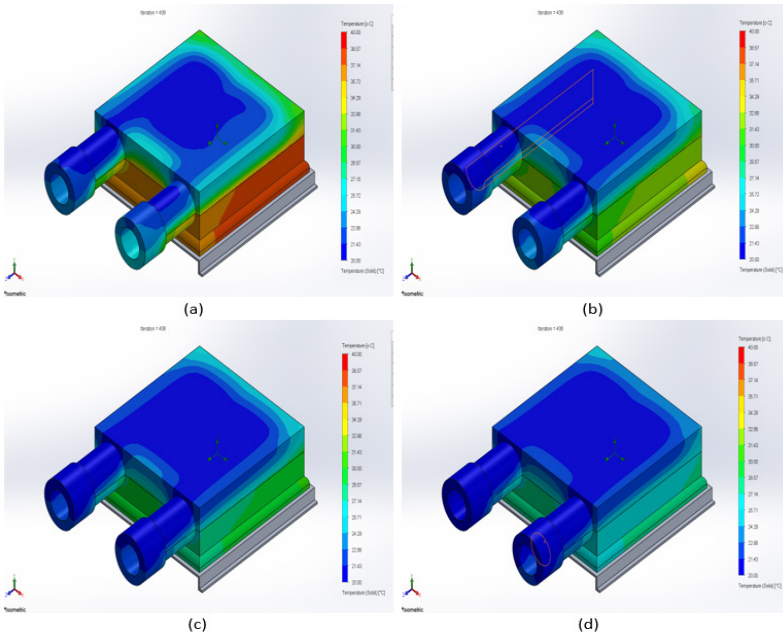


Figure 3. Total surface temperature distribution in a CPU cooler for 100 W thermoelectric capacity and volumetric flow rate of a) 1 L/min, b) 2 L/min, c) 3 L/min, d) 4 l/min, respectively

Overall, the surface temperature maps in Figure 3 clearly show that increasing the refrigerant flow rate results in lower and more uniform temperature distributions across the CPU cooler surface. This underlines the importance of optimizing coolant flow conditions in liquid-based CPU cooling systems to maintain thermal stability and prevent localized overheating, thereby ensuring reliable and efficient performance of the electronic components.

The flow pressure distributions within the CPU cooler under different volumetric flow rates, all corresponding to a thermal input of 100 W from a thermoelectric heater, have been systematically analyzed and are presented in Figure 4. These distributions provide insight into the behavior of the working fluid (water) as it circulates through the microchannel structures of the CPU cooler. Understanding the pressure profiles is critical for assessing the hydraulic performance of the cooling system and optimizing flow dynamics for enhanced heat dissipation. At a refrigerant flow rate of 1 L/min (Figure 4a), the fluid pressure at the micro-cooler inlet is approximately 103,698 Pa. As the fluid moves through the internal flow paths, it experiences a pressure drop, reaching atmospheric pressure (101,325 Pa) at the outlet. This pressure loss is primarily due to flow resistance caused by narrow channels and surface friction within the micro-cooler. The relatively low inlet pressure and moderate pressure drop suggest that the system

operates under minimal hydraulic load at this flow rate. As the flow rate increases to 2 L/min (Figure 4b), the fluid enters the CPU cooler at a pressure ranging from 103,698 Pa to 104,489 Pa and exits again at 101,325 Pa. This increase in inlet pressure reflects the higher dynamic resistance the fluid encounters due to the increased velocity. However, the outlet pressure remains constant, indicating a consistent reference pressure at the outlet boundary, typically open to the atmosphere or a low-pressure reservoir. Further increasing the volumetric flow rate to 3 L/min (Figure 4c) results in a notable rise in the inlet pressure, now ranging between 106,071 Pa and 107,653 Pa. The pressure gradient across the micro-cooler becomes steeper, signifying increased flow resistance within the internal channels. This pressure differential must be overcome by the system's pump, and it demonstrates the growing hydraulic demand of the system at higher flow rates. At the maximum tested flow rate of 4 L/min (Figure 4d), the inlet pressure reaches its highest observed values, ranging from 110,026 Pa to 110,817 Pa. Despite this increase, the outlet pressure remains at 101,325 Pa, reinforcing the fact that the cooler outlet is maintained at atmospheric conditions. The significant rise in inlet pressure with increasing flow rate is a direct consequence of both the non-linear characteristics of fluid flow in confined geometries and the turbulent or transitional flow regime likely initiated at higher velocities.

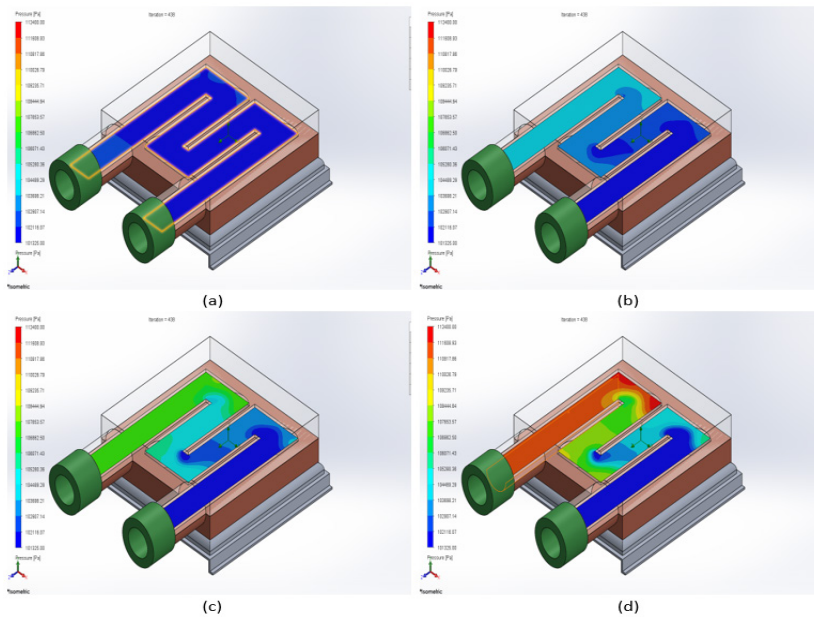


Figure 4. Flow pressure distribution in a CPU cooler for 100 W thermoelectric capacity and volumetric flow rate of a) 1 L/min, b) 2 L/min, c) 3 L/min, d) 4 L/min, respectively

Overall, the pressure analysis reveals two consistent trends. First, while the outlet pressure is held constant across all operational scenarios (typically due to open discharge conditions) the inlet pressure increases with volumetric flow rate. Second, this pressure increase is governed not only by the amount of fluid flow but also by the complex internal geometry of the micro-cooler, which introduces flow resistance through channel size, shape, and surface roughness. These observations underline the importance of designing a balance between thermal and hydraulic performance, as excessively high inlet pressures may place additional mechanical load on the pump and system components, potentially affecting the long-term reliability of the cooling system. Therefore, optimizing the CPU cooler requires careful consideration of both thermal and hydraulic factors to ensure efficient cooling without introducing excessive pressure stress within the system.

The velocity distributions of the coolant within the CPU cooler under varying volumetric flow rates were comprehensively analyzed, and the results are illustrated in Figure 5. These distributions are essential for understanding the internal flow behavior of the system, which directly influences the heat transfer performance. By examining the variation in flow velocity across the microchannels of the CPU cooler, insights can be gained into how effectively the coolant interacts with the heated surfaces. At a refrigerant volumetric flow rate of 1 L/min (Figure 5a), the coolant enters the CPU cooler with a velocity of approximately 0.3 m/s. As the fluid progresses through the microchannel structure, the velocity gradually increases due to channel geometry and potential narrowing of the flow path, reaching around 0.6 m/s at the outlet. This relatively moderate flow rate allows for sufficient residence time of the fluid over the CPU surface, promoting effective thermal energy absorption and transfer. When the flow rate is increased to 2 L/min (Figure 5b), the inlet velocity rises to approximately 0.7 m/s, while the outlet velocity varies between 0.1 m/s and 1.2 m/s. This broader range at the outlet may result from local flow instabilities or non-uniform channel distribution, potentially leading to zones of both laminar and slightly turbulent flow. The variability in outlet velocity indicates the presence of complex flow dynamics, possibly influenced by channel intersections or directional changes within the cooler. At a higher flow rate of 3 L/min (Figure 5c), the fluid enters the micro-cooler at a velocity of about 1.8 m/s, and the velocity increases further to approximately 2.2 m/s toward the outlet, with average values hovering around 2 m/s. This flow regime may begin to approach transition from laminar to turbulent, depending on the Reynolds number and channel dimensions. While higher velocities contribute to faster heat transport away from the CPU surface, they may also reduce the contact time between the coolant and the heated walls, diminishing the effectiveness of convective heat transfer. At the maximum tested flow rate of 4 L/min (Figure 5d), the fluid velocity is around 2 m/s at the inlet and increases slightly to about 2.3 m/s at the outlet. Although this scenario ensures rapid coolant circulation and potentially lower overall system temperatures, the reduced thermal interaction time due to high velocity may prevent the fluid from fully absorbing the thermal load generated by the CPU. Importantly, the analysis reveals a trade-off between flow velocity and heat transfer efficiency. While increasing the flow rate enhances the capacity for heat removal due to higher mass flow, it

simultaneously reduces the dwell time of the coolant in contact with the heated surface, which may impede efficient thermal exchange. At very high velocities, the boundary layer between the coolant and the cooler surface becomes thinner, which might initially improve heat transfer rates; however, if the coolant exits the cooler too quickly, the energy absorption remains incomplete.

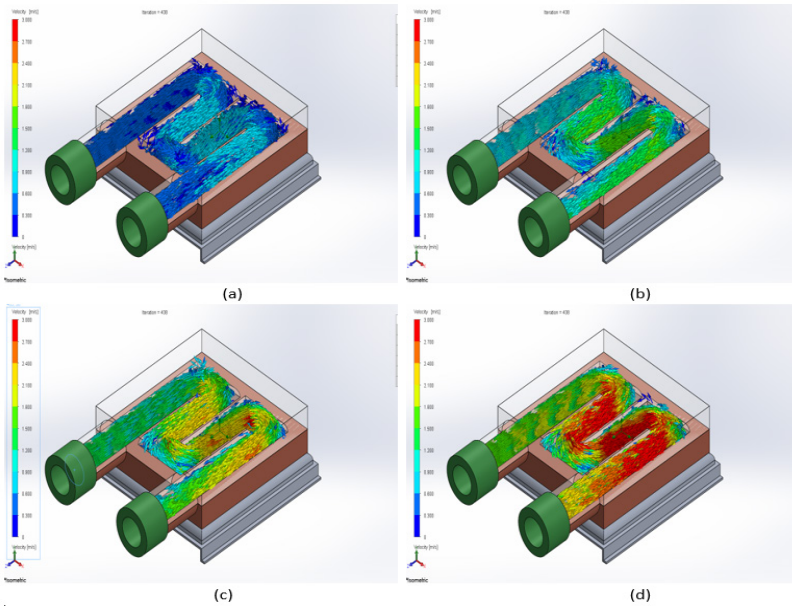


Figure 5. Flow velocity distribution in a CPU cooler for 100 W thermoelectric capacity and volumetric flow rate of a) 1 L/min, b) 2 L/min, c) 3 L/min, d) 4 L/min, respectively

Therefore, to ensure optimal cooling performance, it is essential to identify an optimal flow rate and velocity range that balances high thermal conductivity with sufficient contact time. Excessively low flow rates may result in local overheating due to inadequate heat transport, while excessively high rates may underutilize the coolant’s thermal capacity. Fine-tuning these parameters is crucial for designing CPU cooling systems that maintain reliable, efficient, and stable thermal management, especially under variable computational loads.

4. Conclusion

The thermal and hydraulic performance of the CPU cooler was thoroughly examined under varying operating conditions, with water employed as the working fluid. A 100 W thermoelectric heater was utilized to simulate the heat load generated by the CPU during operation. In this analysis, the coolant’s volumetric flow rate was systematically adjusted to 1, 2, 3, and 4 liters per minute to evaluate the influence of flow rate on the cooling effectiveness and overall system behavior.

Volumetric flow rate is one of the key parameters influencing convective heat transfer in liquid cooling systems. A lower flow rate can result in insufficient heat removal due to prolonged fluid residence time and limited mass transport of thermal energy, whereas a higher flow rate generally enhances convective heat transfer by accelerating the removal of absorbed heat from the CPU surface. However, the relationship between flow rate and cooling efficiency is not strictly linear, and optimizing this parameter is essential to achieving a balance between thermal performance and energy consumption.

The analysis showed that at the lowest flow rate of 1 l/min, both the coolant and the surface temperatures of the CPU cooler were significantly higher compared to other flow rate scenarios. This indicates insufficient thermal transport, leading to local temperature rises and reduced cooling effectiveness. As the flow rate was increased to 2, 3, and 4 l/min, a notable improvement in thermal performance was observed. The surface and outlet fluid temperatures decreased accordingly, confirming that higher flow rates contribute to more efficient heat dissipation from the CPU to the coolant.

Nonetheless, increasing the volumetric flow rate comes with trade-offs. A higher flow rate demands greater pump capacity, leading to increased energy consumption, system noise, and potential mechanical stress on the cooling loop components. Moreover, excessive flow may lead to reduced contact time between the coolant and the heated surfaces, which could limit heat transfer efficiency in certain cooler geometries. Therefore, determining the optimal flow rate is crucial for ensuring a balance between performance and power consumption.

Another important factor influencing the performance of the cooler is the internal flow channel geometry. Microchannel designs, fin arrangements, and the overall layout significantly affect flow distribution, pressure drop, and heat transfer efficiency. Narrower or more complex geometries may promote enhanced heat transfer through increased surface area and turbulence but can also introduce higher pressure losses and increase the load on the pump.

Looking ahead, nanofluids (which are suspensions of thermally conductive nanoparticles in a base fluid) offer promising enhancements for next-generation cooling technologies. Their superior thermal conductivity compared to pure water can improve heat transfer performance, potentially enabling higher power densities and more compact system designs. However, the incorporation of nanofluids introduces additional challenges, such as increased system cost, long-term stability concerns, possible clogging in microchannels, and the need for specialized pumps and materials compatible with nanoparticle suspensions.

In conclusion, this study emphasizes the importance of carefully selecting coolant flow rates and considering system design constraints when optimizing CPU cooling solutions. While higher flow rates improve thermal management, they must be weighed against the associated energy and mechanical costs. Furthermore, future research exploring alternative fluids like nanofluids may yield advanced

solutions for high-performance computing systems, provided that economic and practical implementation challenges are adequately addressed.

Author Contributions

Conceptualization, methodology, validation, and manuscript-review and editing were performed jointly by Bayram KILIÇ and Emre ARABACI. Fieldwork and supervision were carried out by Bayram KILIÇ and Osman İPEK. Research, data curation, visualization, and the manuscript-original draft were performed by all authors. All authors have read and legally accepted the final version of the article published in the journal.

Acknowledgement

No financial support was received from any institution or organization for this study. Bu çalışmada araştırma ve yayın etiğine uyulmuştur.

Conflict Of Interest

The authors declare no conflict of interest.

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