Numerical study optimation design of CPU cooling system analysis using CFD method

Fajar Dwi Yudanto [a,1], Rochmad Novian Inderanata [a,2,*], Arif Bintoro Johan [a,3], Setuju [a,4]

[a] Department of Mechanical Engineering Vocational Education, Universitas Sarjanawiyata Tamansiswa, Indonesia
[1] yudanfajar@gmail.com; [2] rninderanata@ustjogja.ac.id; [3] abeje_janoko@yahoo.com; [4] setuju@ustjogja.ac.id
* corresponding author

ARTICLE INFO

Article history
Received September 20, 2023
Revised October 20, 2023
Accepted November 03, 2023
Available online November 11, 2023

Keywords
Design optimation
Numerical study
Computational fluid dynamic
Taguchi
Engineering materials

ABSTRACT

Electronic devices such as integrated circuits and computer microprocessors are made of various components that generate high heat (increased temperature and thermal fluctuations cause thermal stress), which is the main cause of failure of electronic devices, thus requiring cooling. Component placement is frequently utilized to improve the CPU room conditions to keep it cool. This research numerically investigates desktop PC processors and heatsink configurations for mechanical engineering vocational learning. The kind of metal material, number of fans, and fan arrangement were all tested at three levels. The computer components in this research are the CPU, heatsink, fan, and processor—a 65-watt Thermal Design Power (TDP) CPU with a constant air intake speed of 5 m/s. The criteria investigated include metal type (steel, aluminum, and copper), cooling design (horizontal, vertical, and mixed), and fan count (2-4-8). The methods used in this research are the Computational Fluid Dynamics (CFD) method and the Taguchi method to examine fluid flow characteristics and temperature. Numerical results show the maximum temperature is 123 °C in the vertical, eight-fan, and steel configurations. Minimum temperature 39.22 °C in mixed configuration, eight fans, and copper. These findings reveal that the kind of metal material, number of fans, and fan arrangement all impact the CPU cooler and heatsink configuration. However, the Taguchi method can provide a more detailed understanding of configuration.

1. Introduction

In this era, computers are the main tool used by humans for productivity, both in industry and education. A computer or personal computer is a tool that is really needed by all groups, including universities, offices, schools, designers, YouTubers, and even gamers [1]. Normal jobs use computers. Offices will use computers for office work. Universities and schools such as Tamansiswa also have and use computers for vocational learning, engineering design, engineering drawing, and simulations. Basic knowledge, technical skills, and positive work attitudes are formed from quality learning [2], of course, in this case, vocational learning uses computers with technical drawing, engineering design, and simulation software. Students in the digital era are required to develop various skills and intelligence, especially in operating technology and producing applied work that can be utilized in society 5.0 by integrating technology in learning so that they can train curiosity about technology, skills in using technology, literacy skills, solving problems, technical skills quickly, creativity in creating technological products, and critical thinking skills regarding product ethics and aesthetics [3].

However, computers also have limitations in their use. If used excessively, the computer will quickly become damaged [4]. Electronic devices such as integrated circuits and computer microprocessors are made of various components that generate high heat (increased temperature and thermal fluctuations cause thermal stress), which is the main cause of failure of electronic devices, thus requiring cooling [5]–[9]. Many factors are involved in this damage, including human error or excessive use and the environment (conditions of the environment and surroundings). Many factors are involved in damage to the environment, such as short circuits, age, overload, and overheating. The environment, especially overheating, may be very sensitive to the use of cooling, so this research will discuss CPU cooling so that the computer is not easily damaged. In addition, lowering the CPU temperature can improve computer performance, so CPU cooling is very important [10]. The consequences of overheating have spurred researchers to develop cooling models to increase the efficiency and performance of the chip or processor itself [11]. In research by [11], they developed a radiator cooler with a vertical CPU. Using the experimental method, researchers wanted to see the effect of liquid filling rate, heating power, and wind speed on two vertical pipe radiators and compared them with aluminum fin computer CPU radiators. The results show that when the radiator works stably, the optimal filling ratio is 25%, and the lowest thermal resistance is only 0.1 C/W; the average temperature of the heat source increases with increasing heating power and decreases with wind speed. Compared with current aluminum fin radiators, vertical radiators have superior heat dissipation performance, temperature uniformity, and stability. For example, under the heating power of 80 W, the average heat source temperature is 66°C, and the average temperature deviation of the heat source is 3.16°C, compared with the aluminum fin radiator, down by 17.3°C and 0.61°C, each.

This research [12] examined the cooling of electronic CPU enclosures used for telecommunications radar systems using the CFD method. The results you want to take are cooling or thermal performance measurements. Redesign using a copper shelf with a thickness of 3 mm and a vapor chamber (VC) pipe found that the operating temperature was within the specified temperature limits. The use of VC can reduce the enclosure temperature by an average of 5.4°C. This study also shows that cooling via finned plates can reduce temperatures at the expense of increasing fan energy consumption.

In the 2018 study by [13], they examined the cooling method for Desktop CPUs using the CFD method. Cooling focuses more on the use of varied heatsinks. Based on the results of this research, modifying the heatsink can reduce heat more effectively. The addition of fins makes the resulting heat transfer even better. So, the use of this model is very suitable for initial validation. An example of cooling using a heat sink in this research is shown in Fig. 1.

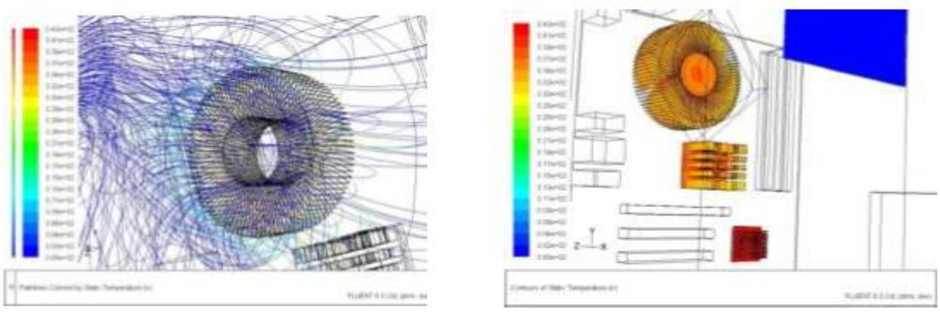


Fig. 1. CFD analysis results using a heatsink [11]

Furthermore, research from [14] examined CFD modeling of an environmentally friendly cooling system using nanofluid and passive fin heat transfer techniques. The method used in this research is the use of 3D CFD software to study the effect of nanofluid and fins on CPU heat management [14], [15]. Apart from fin design, the influence of heat sink materials (fins and beams) made of silver, nickel, and copper, and variations in nanoparticle volume fraction on CPU cooling [16], [17]. This research focuses on pressure changes or (pressure changes, pumping power, convection heat transfer coefficient, and fin thermal efficiency. Based on the results, the heat transfer of sinusoidal spiral fins is more efficient than winding fins [18]. Then silver is the material that is better at absorbing heat than nickel and copper. Based on the research that has been carried out, the current researcher wants to combine several methods in previous research using liquid cooling, PCM, and water (air) in the first-factor variable, the number of enclosure fan cooling, and the form of cooling in the form of vertical, horizontal, and mixed. Based on these three factors and three levels, the most optimal use for cooling the enclosure will be obtained.

This research focuses on cooling, such as CPU fans. Apart from the cooling aspect, component placement can often be used to optimize the condition of the CPU room to keep it cool [19]. Apart from optimizing the placement of components and cooling systems, research conducted by [20], [21] varied the heat sink by adding fins. Based on the results obtained, the heat transfer of sinusoidal spiral fins is more efficient than winding fins. Then silver is a material that is better at absorbing heat than nickel and copper. This research uses the Computational Fluid Dynamic (CFD) method. Computational Fluid Dynamics is a numerical fluid computing method, so it is suitable as a tool for simulating designs [20], [22], [23]. By using CFD, researchers do not need to carry out experimental trials. CFD is also commonly used by researchers to test their designs so they can minimize existing costs. Apart from that, CFD can also minimize errors that exist from actual conditions by validating with experimental research. So, CFD research is a wise choice.

2. Method

The method used in this research is the Computational Fluid Dynamics (CFD) method. CPU Cooling System simulation using Computational Fluid Dynamics uses several steps in the process, including (1) study of literature related to CPU Cooling Systems and developments in the world today. Literature studies can be carried out by looking for CFD simulation journals on CPU design, cooling materials, and component layout in the CPU enclosure; (2) modeling with a simple form that can represent the CPU enclosure model; (3) meshing/discretization to be calculated by Computational Fluid Dynamics using commercial fluid computing software; (4) setting boundary conditions, cell zone conditions, material settings, operating conditions, and so on for the simulation process; (5) collecting qualitative data in the form of images, and quantitative data in the form of graphs to validate; (6) simulation with an error limit of <10%; (7) varying the design to investigate the optimal point of fluid characteristics and temperature using the Taguchi/2k Factorial method.

2.1. Computational Fluid Dynamics (CFD)

The CFD method solves problems in fluid flow (without heat transfer) using two basic flow equations, namely mass conservation and the momentum equation in fluid flow. The mass conservation equation solved in CFD is as follows in (1).

$$\nabla \rho \vec{V} + \frac{\partial \rho}{\partial t} = 0 \quad (1)$$

For incompressible fluids, there is no change in density either with changes in space or changes in time, so the equation, as in (2) and (3).

$$\nabla.\overrightarrow{V} = 0 \tag{2}$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{3}$$

In conservation of time, this indicates that in a closed volume control. The amount of flowing mass at each position will remain constant. The momentum equation for fluid flow can be shown in the equation below, as in (4), (5), and (6).

$$\rho\left(\frac{\partial u}{\partial x} + u\,\frac{\partial v}{\partial y} + w\,\frac{\partial w}{\partial z}\right) = \rho.g - \frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x} + u\,\frac{\partial^2 u}{\partial y} + w\,\frac{\partial^2 u}{\partial z}\right) \tag{4}$$

$$\rho\left(\frac{\partial u}{\partial x} + u\,\frac{\partial v}{\partial y} + w\,\frac{\partial w}{\partial z}\right) = \rho.g - \frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 v}{\partial x} + u\,\frac{\partial^2 v}{\partial y} + w\,\frac{\partial^2 v}{\partial z}\right) \tag{5}$$

$$\rho\left(\frac{\partial u}{\partial x} + u\,\frac{\partial v}{\partial y} + w\,\frac{\partial w}{\partial z}\right) = \rho.g - \frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 w}{\partial x} + u\,\frac{\partial^2 w}{\partial y} + w\,\frac{\partial^2 w}{\partial z}\right) \tag{6}$$

The equation above is the Navier-Stokes equation. This equation is a form of numerical equation because it is impossible to form an equation that explains the force caused by contact between the surface of a fluid and the surface of a solid object analytically. This equation shows the internal forces acting on a fluid flow that have a direction to the plane (normal force) and also forces that have a direction tangential to the plane (shear force). The above equation is valid for incompressible viscous flow conditions.

2.2. CPU (Central Processing Unit)

This research uses a CPU casing design on the market, with the processor placed in the right casing along with a heatsink. Apart from that, boundary conditions use inlet-velocity inlet, outlet-pressure outlet, and walls on each casing wall. The processor is modeled using a solid cell zone condition, which can generate heat, and the heatsink is attached to the processor part. The mesh in this simulation uses a polyhedral with 482000 nodes. Mesh selection is based on grid independence by making five variations in the number of meshes. It was found that the error in the 4th variation was a relatively small error. The model and mesh images are shown in Fig. 2.

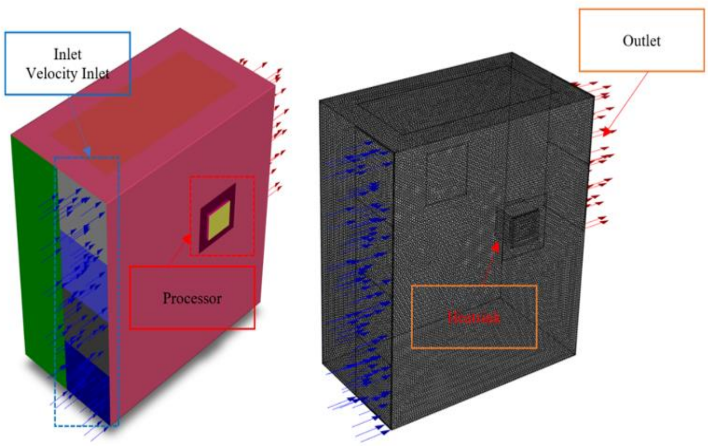


Fig. 2. CPU casing model, Boundary Condition, and Mesh

In this study, the steady k-ε Realizable enhancing wall treatment model was used. This is expected to get a good Y+ area so that the viscous sublayer area can be better captured by the simulation [24], [25]. The energy equation is activated to obtain convection and conduction heat transfer in the CPU. In the material section, the fluid material uses air, while the heatsink and processor section will be varied using several materials, namely Steel (Fe), Aluminum (Al), and Copper (Cu).

In the cell zone, the solid processor activates the source term of the market heat generation processor, namely thermal design power (TDP) 65Watt, or if converted to heat generation, it becomes 2.6x106 Watt/m3 from volume processor [25]. Then, the boundary condition inlet uses an inlet velocity of 5 m/s with a hydraulic diameter of 125 mm and a turbulent intensity of 5%. The outlet section uses an outlet pressure of 0 gauge or 1 atm. In the solution method section, COUPLED and second order are all used in the settings to get high accuracy [25].

The residual scale uses 104 in all options except energy, which uses 106. After that, initialization is carried out using hybrid initialization because it has several inlet areas. The iteration process varies from 1000-2000 iterations per simulation.

2.3. Experimental Design

An experimental design was used in this research. The aim of using an experimental design is to find out the optimal point and what factors influence it with taguchi method [26], [27]. This optimization uses three factors, and each has three levels, so the number of variations in this simulation is 27. These factors and levels are shown in Table 1. The temperature response that will be reviewed in this research is the temperature response at the heat sink and processor.

Table 1. Experimental Design

No	Experimental Design			
	Variable	*Level 1*	*Level 2*	*Level 3*
1	Quantity of Coolant	2 Cooling	4 Cooling	8 Cooling
2	Heatsink Material	Steel (Fe)	Aluminium (Al)	Copper (Cu)
3	Fan Configuration	Horizontal	Vertical [12], [13]	Mixture

3. Results and Discussion

3.1. Design Optimization Analysis

Design optimization was carried out using the Taguchi 3-factor 3-level method. This factor includes the number of coolers, material, and fan placement, while the levels include two coolers, four coolers, eight coolers, ferrous material, aluminum, copper, horizontal, vertical, and mixed fan placement. With this design optimization configuration, 27 configuration options are obtained, which are simulated using CFD.

Based on the CFD simulation results, the temperature values in the processor and sink are obtained as a temperature response. These data will later be processed using design optimization, as shown in Table 2.

Table 2. Design Optimization Data

No	Variabel & Level			Respon Temperatur Processor (Celcius)	Respon Temperatur Sink (Celcius)	Meab2	Mean3
	Coolant Amount	*Material*	*Fan Placement*				
1	2	Fe	Horizontal	73.012714	50.203115	73.013	50.203
2	2	Fe	Vertical	102.08601	79.207344	102.09	79.207
3	2	Fe	Mixture	105.67708	81.078246	105.68	81.078
4	2	Al	Horizontal	51.257989	49.134008	51.258	49.134
5	2	Al	Vertical	75.500936	73.472319	75.501	73.472
6	2	Al	Mixture	82.357277	80.196857	82.357	80.197
7	2	Cu	Horizontal	50.1971	49.079848	50.197	49.08
8	2	Cu	Vertical	74.210784	73.14661	74.211	73.147
9	2	Cu	Mixture	81.280577	80.147932	81.281	80.148
10	4	Fe	Horizontal	69.742289	47.354245	69.742	47.354
11	4	Fe	Vertical	111.88498	87.45461	111.88	87.455
12	4	Fe	Mixture	66.490562	44.711186	66.491	44.711
13	4	Al	Horizontal	48.743864	46.620309	48.744	46.62
14	4	Al	Vertical	83.000123	80.881139	83	80.881
15	4	Al	Mixture	46.270174	44.168903	46.27	44.169
16	4	Cu	Horizontal	47.698611	46.580393	47.699	46.58
17	4	Cu	Vertical	81.512712	80.402575	81.513	80.403
18	4	Cu	Mixture	45.247081	44.139395	45.247	44.139
19	8	Fe	Horizontal	62.571761	41.319239	62.572	41.319
20	8	Fe	Vertical	122.13166	98.778798	90.626	89.563
21	8	Fe	Mixture	60.349753	39.732457	60.35	39.732
22	8	Al	Horizontal	42.912735	40.765554	42.913	40.766
23	8	Al	Vertical	92.190895	90.163074	92.191	90.163
24	8	Al	Mixture	41.335893	39.217808	41.336	39.218
25	8	Cu	Horizontal	41.867869	40.732534	41.868	40.733
26	8	Cu	Vertical	90.778362	89.56347	122.13	98.779
27	8	Cu	Mixture	40.304964	39.183754	40.305	39.184

Based on the results of the Taguchi method data on the temperature response in the processor and sink, it was found that fan placement was the factor that had the most influence on the temperature in the processor and sink. This can be seen in the response for the means table on the processor and sink. The other influencing factor, namely the material factor, is the second influence, and the number of coolers is the last factor for the processor temperature response. Meanwhile, in response to means in the sink show as Fig. 3, the material factor is the last influence, and the second influence is the quantity of coolant.

Response Table for Means

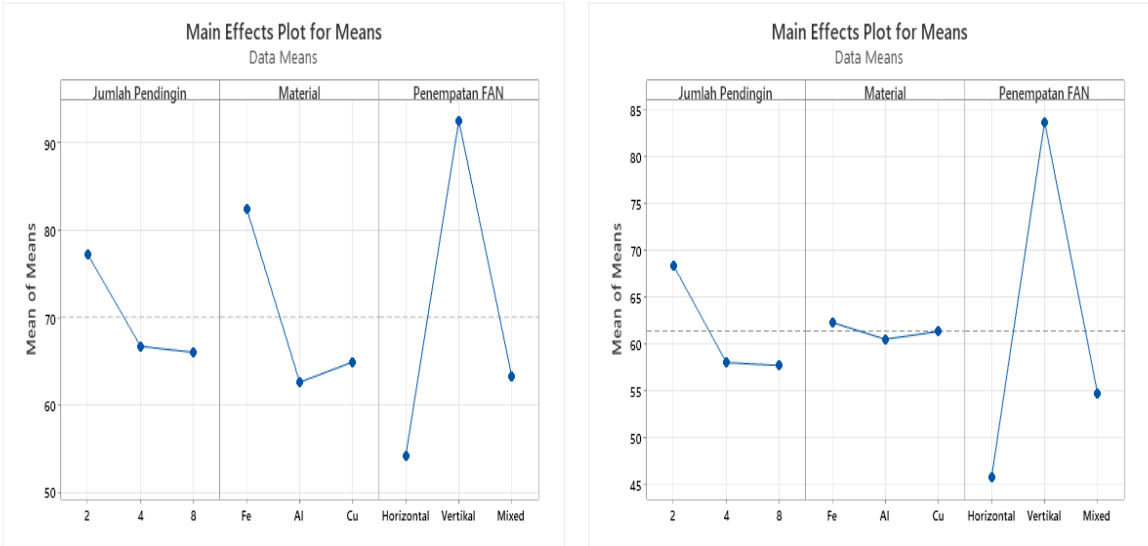
Level	Jumlah Pendingin	Material	Penempatan FAN
1	77,29	82,49	54,22
2	66,73	62,62	92,57
3	66,03	64,94	63,26
Delta	11,25	19,87	38,35
Rank	3	2	1

Response Table for Means

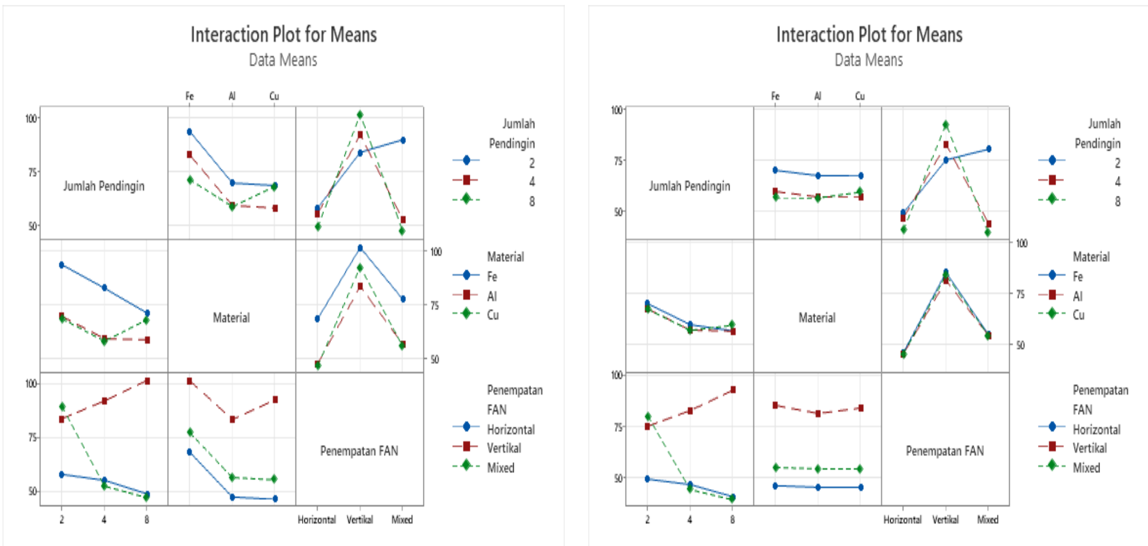
Level	Jumlah Pendingin	Material	Penempatan FAN
1	68,41	62,29	45,75
2	58,03	60,51	83,67
3	57,72	61,35	54,73
Delta	10,69	1,78	37,92
Rank	2	3	1

Fig. 3. Response for Means (a) Processor, (b) Heat

As seen in Fig. 4, the average value obtained on the processor is 70°C. In terms of the number of coolers, a good level factor is to use 4 and 8 coolers or level 2 and level 3. Steel or iron materials cannot reduce the temperature significantly, so the best is aluminum. Regarding the fan placement factor, vertical fan placement does not affect the cooling in the processor, while horizontal and mixed have a very big influence.



(a) (a)



(b) (b)

Fig. 4. Main effect plot for means processor temperature response (a), sink temperature response(b)

Based on Fig. 4, the average value obtained for the sink temperature is 61°C. Regarding the number of coolers, the number of coolers two is not recommended because it is still above the average value. Meanwhile, the number of coolers 4 and 8 is the choice because it is below the average value but not significant. The vertical cooling configuration factor is still not recommended for use because it cannot cool both the sink and the processor. Apart from that, based on the results of interactions between factors, it was found that the number of coolers and fan placement had an interaction, meaning there was a relationship between the factors.

3.2. ANOVA analysis

Based on ANOVA results on the temperature response of the processor, material and fan configuration are factors that influence cooling. Meanwhile, the amount of coolant does not have a significant effect because the Pvalue > α (5%). Apart from that, the interaction between cooling factors and fan configuration remains the most influential interaction between factors in processor cooling. Analysis of variance show as Fig. 5.

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Pendingin	2	715.6	4.91%	715.6	357.82	3.75	0.071
Material	2	2125.6	14.57%	2125.6	1062.81	11.13	0.005
Fan	2	7234.8	49.59%	7234.8	3617.38	37.87	0.000
Pendingin*Material	4	471.8	3.23%	471.8	117.95	1.23	0.369
Pendingin*Fan	4	3091.2	21.19%	3091.2	772.79	8.09	0.006
Material*Fan	4	185.5	1.27%	185.5	46.37	0.49	0.747
Error	8	764.1	5.24%	764.1	95.51		
Total	26	14588.5	100.00%				

(a)

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Pendingin	2	665.9	6.18%	665.90	332.95	49.19	0.000
Material	2	14.2	0.13%	14.24	7.12	1.05	0.393
Fan	2	7068.7	65.59%	7068.74	3534.37	522.13	0.000
Pendingin*Material	4	29.8	0.28%	29.77	7.44	1.10	0.419
Pendingin*Fan	4	2933.1	27.21%	2933.10	733.27	108.33	0.000
Material*Fan	4	11.6	0.11%	11.65	2.91	0.43	0.784
Error	8	54.2	0.50%	54.15	6.77		
Total	26	10777.6	100.00%				

(b)

Fig. 5. Analysis of Variance (a) Processor, (b) Heat

Based on the ANOVA results on the temperature response of the heatsink, the material is a factor that does not have a significant effect. This is seen from the value 1- Pvalue > α (5%); the P-value of the material is 0.393 or 39%, so it does not have a significant effect, while the number of coolers and fan placement has a very significant effect because Pvalue > α (5%). Apart from that, the interaction between factors, namely the cooling fan, is a factor that interacts and has a significant effect on cooling.

3.3. Heat Transfer Analysis and Fluid Mechanics

Based on the material properties data in Table 3, the thermal conductivity (k) value of copper is the highest, while the specific heat (Cp) value of aluminum is the highest. This will later affect the heat transfer that occurs in the processor and heat sink.

Table 3. Material Properties [18]–[20]

Material	Thermal Conductivity (W/m.K)	Spesific Heat (J/kg.°C)
Steel	45	466
Aluminum	237	897
Copper	398	387

Based on the results of the temperature profile in the sink, we can see that the temperature using each material will be different show as Fig. 6, especially when using steel material. Steel material has a smaller thermal conductivity than others, so the cooling propagation speed is less than steel and copper materials. This is in line with the conduction formula, namely Q = -kAdT/dx, because conduction is the transfer of heat through a solid medium, and thermal conductivity greatly influences the speed of heat propagation in each material. This results in the selection of materials for the processor and sink being very necessary. The use of steel material in processors and sinks is not recommended because steel material, apart from being heavy, also has low thermal conductivity.

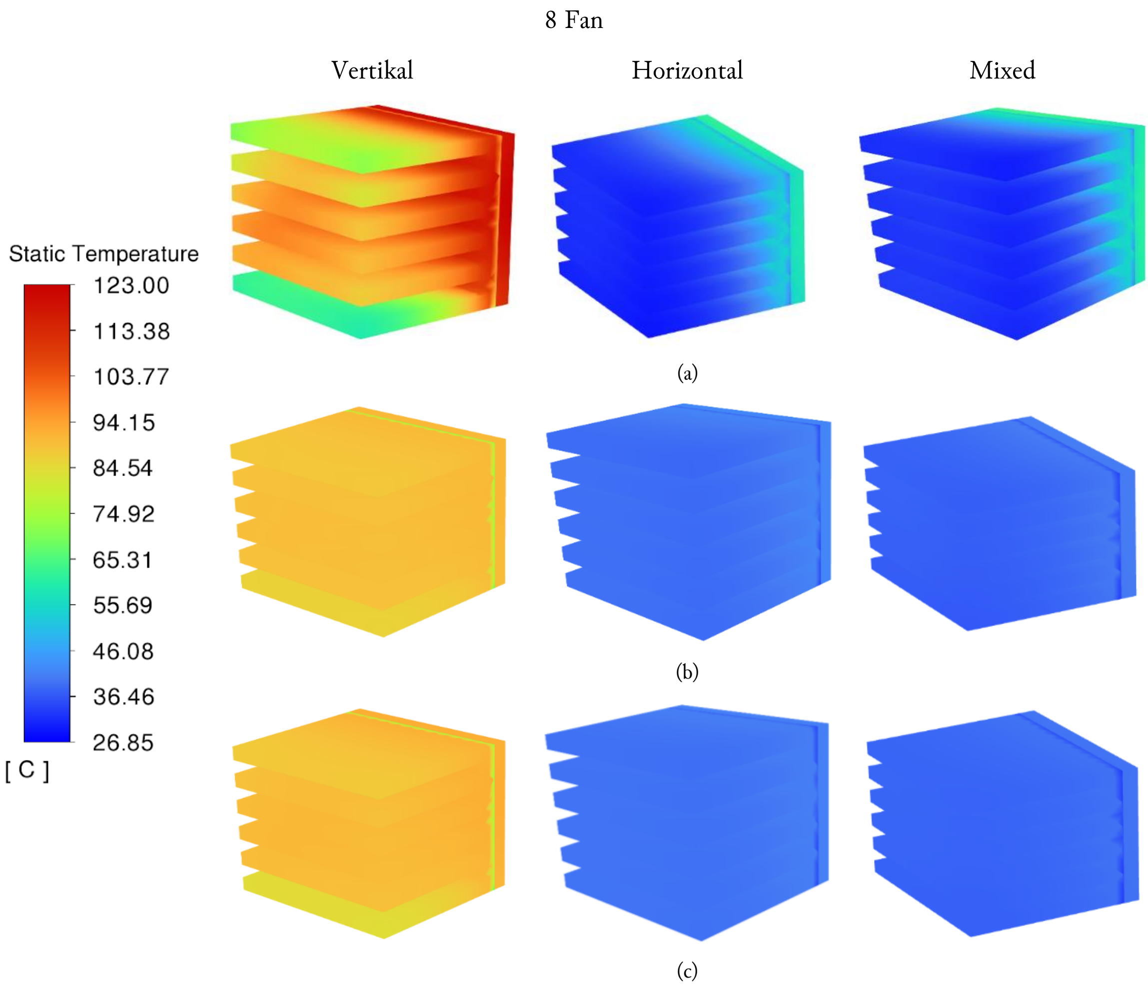


Fig. 6. Static temperature contours of Processor and Heat Sink (a) Steel, (b) Aluminum, (c) Copper

Apart from that, based on the specific heat value (Cp), steel has a specific heat value in the middle between aluminum and copper. With the smallest thermal conductivity value and specific heat value in the middle, cooling of the heatsink material is faster by convection. However, because the heat propagation is slow, the resulting heat sink contour using steel material becomes cold at the fin tip, and the heatsink body and CPU become hot. Temperature Contour show as Fig. 7.

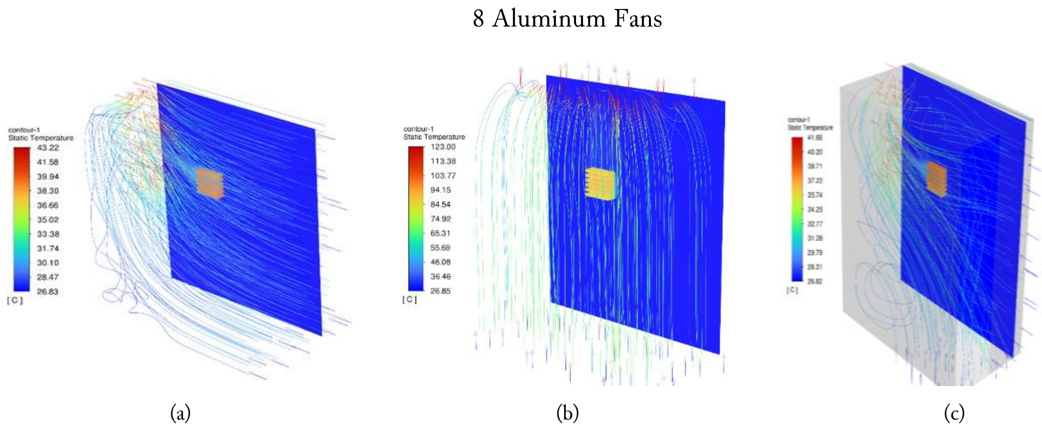


Fig. 7. Temperature Contour with Pathline Velocity on 8 Aluminum Fan design variations (a) Horizontal, (b) Vertical, (c) Mixture

The temperature profiles of the vertical, horizontal, and mixed fan designs differ. Fig. 6 depicts this temperature profile. The temperature scale runs from blue to red, with red being hotter than blue. This scale is also supported by temperatures ranging from 26.85°C to 123°C. This scale's use is standardized in order to detect qualitative variations. According to Fig. 6, vertical cooling is still red to orange, or estimated at 84°C-122.13°C. Meanwhile, the temperature contours are not significantly different when horizontal or mixed. The flat and diverse forms have low sink and processor outlines in light blue, implying an expected temperature range of 36.46°C-46.08°C. In Fig. 4, you can see that mixed still has a lower average temperature than horizontal. In the mixed fan configuration, the average temperature reaches 39.22°C, while the horizontal has an average temperature of 40.77°C. These findings demonstrate that a mixed arrangement with more than four fans can be explored. If it is fewer than four, a horizontal arrangement might be used. Meanwhile, vertical fan arrangement is not advised since it cannot cool as well as mixed or horizontal fan configurations. Velocity contour show as Fig. 8

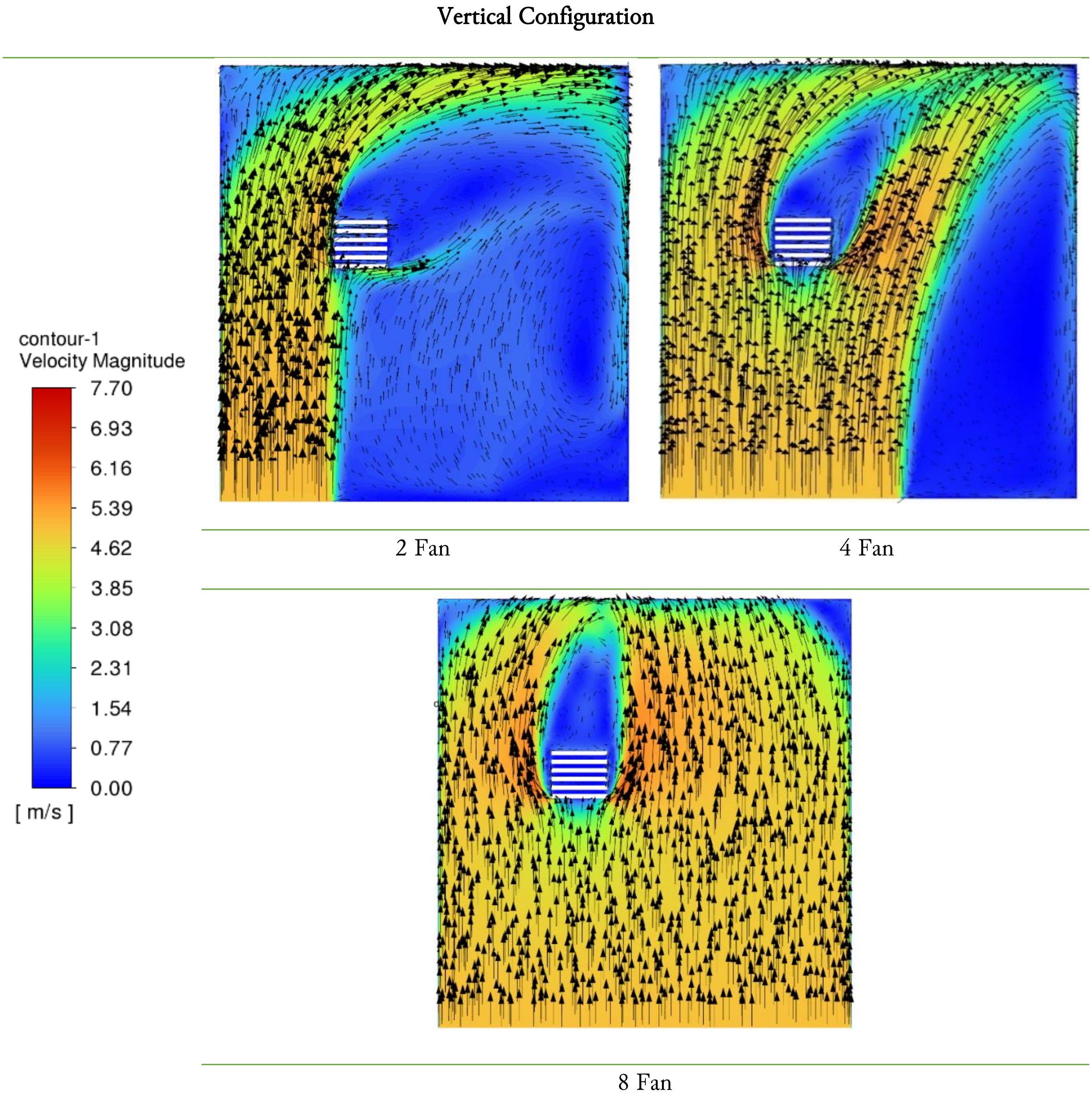


Fig. 8. Velocity Contour with vector velocity on vertical configuration (a) 2 Fan, (b) 4 Fan, and (3) 8 Fan

The following are the results of the configuration of 8 Vertical Fans on one material. Based on the contour results of these 8 vertical fans, it was found that at fan number factor 2 there was turbulence in several areas near the heatsink, whereas at fan numbers 4 and 8 the wake or vortex area was no longer visible. This shows that the greater the turbulence, the more effective it is in circulation, as stated by [28]. Based on these results, researchers in the future will research further into the shape of the heatsink fins to speed up cooling as well as better fluid mechanics. Fins that accommodate vertical and horizontal side configurations. This will increase the heat transfer that occurs in the heatsink and heat will be wasted more quickly.

Based on fluid mechanics, the vertical configuration cannot cool because a lot of backflow occurs in the heatsink. In real conditions, this configuration is only for fan exit or minus pressure, so the pressure from the inlet to the outlet is greater because the pressure at the boundary is smaller than atmospheric pressure. In horizontal and mixed configurations the temperature can be reduced more, because in this configuration it can create more turbulence so that the temperature can be reduced more significantly.

The fan placement configuration in this research also has factors that need to be considered in future research. This configuration is a fin shape configuration. The fin shape in this study uses a horizontal heatsink only, so fluid flow will affect the fin based on its shape. The shape of the fin that can allow vertical and horizontal flow is the fin that is most relevant for further research.

4. Conclusion

CFD is used to analyze heat transfer that occurs in the processor and heatsink using the Taguchi method. Based on analysis and discussion, it was found that the highest temperature of the processor and heatsink was 122.13o C & 98.78o C respectively using material steel. The lowest temperature on the processor and heatsink is 40.3o C & 39.18o C using the 8 Mixed Copper Fan configuration. Factors that really influence cooling on the processor and heatsink are the number of coolers and fan configuration. The best material for cooling processor and heatsink is to use copper rather than aluminum. However, copper has a higher price than aluminum. So, with the ANOVA results which show that material has no significant effect, aluminum is the best choice to use, and steel material is not recommended for use for both components

Acknowledgment

The authors would like to deliver their sincere gratitude to the Institute for Research and Community Service, Universitas Sarjanawiyata Tamansiswa for all the facilities provided to support this research.

Declarations

Author contribution. FDY and RNI conceived and designed experiments, performed simulations, analyzed and interpreted data, wrote the paper. All authors read and approved the final paper.
Funding statement. This research was supported by the Research and Community Services, Universitas Sarjanawiyata Tamansiswa under Grant No. 001/UST/LP2M/PDUUST/VI/2023.
Conflict of interest. The authors declare no conflict of interest
Conflict of interest. The authors declare no conflict of interest.
Additional information. No additional information is available for this paper.

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