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Research Articles

The Effect of Additional TiO_2 Nanofluid on Heat Transfer Rate and Thermal Resistance on Processor Cooling with Ultrasonic Vibration

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A B S T R A C T

The cooling system is very important for cooling the processor to keep it at working temperature. According to Moore's law, the processor doubles every 24 months. This has an impact on the power consumed by the processor will increase, along with increasing power, the heat emission generated will also increase. So a water cooling system is needed to overcome these problems in the future. The addition of nanofluid to the cooling medium and the provision of ultrasonic vibration treatment are expected to maximize cooling performance. The purpose of this study was to determine the effect of the addition of TiO_2 nanofluid and ultrasonic vibration on the overall heat transfer coefficient and thermal resistance, and then compare them with conditions without vibration. The method used is an experimental method with various concentrations of TiO_2 nanofluid 0.1%, 0.15%, and 0.2%. The power consumed by the processor is simulated using a heater with variations of 150W, 200W, and 250W. An ultrasonic transducer is added to the radiator to provide a vibration frequency of 40 KHz. The result of this research shows that the U value of aquadest bottom fluid with vibration increases from 2834.563579 $W/m^2.^oC$ becomes 3283.473891 $W/m^2.^oC$ or 15.84%. Nanofluid TiO_2 0,1% with vibration increased from 3419.874768 $W/m^2.^oC$ to 4109.319539 $W/m^2.^oC$ or 20.16% The effect of nanofluid concentration increased from 4029.871937 $W/m^2.^oC$ becomes 5534.745283 $W/m^2.^oC$ or 37.34% and the Rth value of aquadest base fluid with vibration decreased from 0.1588 $^oC/W$ to 0.1508 $^oC/W$ by 4.99%. Nanofluid TiO_2 0,15% with vibration decreased from 0.0895 $^oC/W$ to 0.0813 $^oC/W$ or 9.22%. The effect of nanofluid concentration decreased from 0.11275 $^oC/W$ to 0.073 $^oC/W$ or 35.25%.

1. INTRODUCTION

The cooling system is a very important system for cooling the processor to keep it at working temperature. The more sophisticated performance of the processor, the higher the power required, resulting in higher heat emissions, because the heat generated is directly proportional to the power consumed. If the heat generated exceeds the specifications, it can trigger overheating of the processor, resulting in a decrease in performance and performance until it can suffer serious damage. According to Moore's law, processors double every 24 months [1] So the implication of Moore's law is the creation of processors with high specifications from generation to generation. With high specifications, the performance of the processor will also increase. Then the power required also increases. And as the power increases, the heat emission produced will also be higher. Conventional processor cooling starting from the heatsink and heatsink fan still cannot overcome processors that have high performance and power

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[2]. So we need a cooling system that matches the power generated from the processor. Water cooling cooling system is one solution to overcome processors that have high performance.

Nanofluid is a fluid that is applied to a water cooling in cooling system, so it is expected that with better fluid properties compared to the base fluid of nanofluid, it can improve the performance of processor cooling more optimally [3]. Nanofluid has a high thermal conductivity value compared to aquadest base fluid. The nanofluid used is a mixture of titanium dioxide (TiO_2) nanoparticles with distilled water as the base fluid. Studies conducted by several researchers stated that the effect of TiO_2/water nanofluid on water blocks was studied at different flow rates. The heat transfer coefficient increased 18.91% for 0.1 vol% at a flow rate of 1 LPM compared to the water base fluid. As well as thermal resistance decreases with increasing flow rate and volume fraction of nanofluid compared to water base fluid. The maximum reduction in thermal resistance of 17.76 % occurred at a flow rate of 1.5 LPM for 0.1% vol of TiO_2 nanofluid. This significant decrease in thermal resistance, acts as a motivation for using nanofluids as electronic coolants. This indicates that nanofluids are good candidates of refrigerants for cooling electronic devices [4]. The addition of ultrasonic vibrations to the system can also provide better results to assist the process of cooling system performance, studies conducted by several researchers found that cooling systems that use ultrasonic vibrations get more optimal results than those that do not use vibration [5]. Due to the propagation of ultrasonic waves in the liquid which results in the effects of acoustic flow, acoustic cavitation, and oscillation of liquid particles that can increase the heat transfer process.

This study aims to determine the effect of the addition of TiO_2 nanofluid and ultrasonic vibration on the cooling performance of the water cooling processor which includes the overall heat transfer coefficient on the radiator and thermal resistance on the processor and water block.

2. METHODOLOGY

The type of research used is experimental research. By conducting experiments on variations in the concentration of nanofluid TiO_2 and variations in the power of the heater as well as the treatment of ultrasonic vibration, the overall heat transfer coefficient produced by the radiator and the thermal resistance between the heater and the waterblock were investigated.

2.1. Experimental Set Up

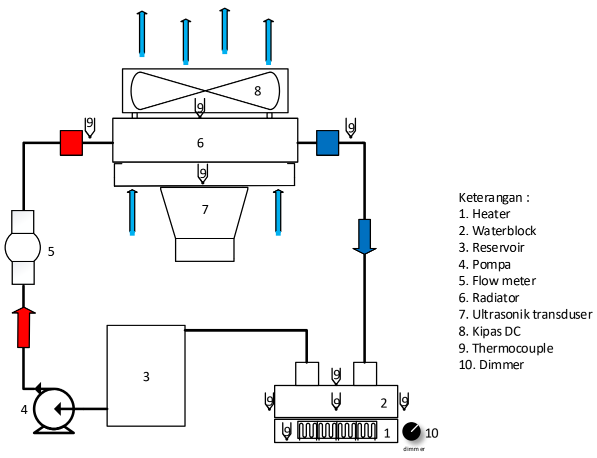

Figure 1. Experimental Set Up

The heater in the installation is assumed to be heat generated by the processor with power variations of 150 Watt, 200 Watt, 250 Watt, the power is maintained by the dimmer during data collection. The thermocouple is used to measure the temperature of the heater and water block, as well as the temperature of the fluid at the inlet and outlet of the radiator and to determine the difference in air temperature before and after passing through the radiator. On the radiator, a cooling fan is installed to help the process of releasing heat, then ultrasonic vibration is given using an ultrasonic transducer. In the simulation, the pump functions to pump the fluid flow, while a flow meter is installed to determine the flow rate. The cooling media used were aquadest base fluid and TiO_2 nanofluid with concentrations of 0.1%, 0.15%, and 0.2%.

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2.2. Method of Data Collection

The data collection process in this study was carried out experimentally. The data taken in this study are the in and out radiator fluid temperatures, the in and out temperatures of the radiator air flow and the temperature of the water block and heater. Data retrieval is when using aquadest base fluid with conditions not given vibration and given vibration, then nanofluid TiO_2 with a concentration of 0.1% ; 0.15% ; 0.2% with no vibration and vibration conditions.

The following are the steps in data collection:

1. Install the heater, pump, cooling fan and ultrasonic generator on a 220 VAC power source.
2. Enter 1 liter of aquadest base fluid in the reservoir.
3. Turn on the heater and adjust the power with a dimmer, for the first experiment it uses 150 W of power. At the same time, turn on the heater temperature gauge and water flow meter.
4. Turn on the pump and adjust the flow speed using a dimmer with a constant discharge of 3.4 LPM. At the same time turn on the cooling fan.
5. Wait until the condition is steady or stable, about 10 minutes.
6. Connect the Arduino USB from the panel box to the laptop to read the temperature value from the radiator and water block.
7. Perform data retrieval with conditions without ultrasonic vibration.
8. Cool the heater and fluid to normal temperature or room temperature.
9. Repeat the process from numbers 3 to 4, after that turn on the ultrasonic generator, for data collection with the condition treatment given vibration.
10. Repeat process number 5 to 6, after that perform data retrieval with ultrasonic vibration conditions.
11. After getting data from the base fluid with a power of 150 W. Next, take data with variations in heater power of 200 W, 250 W and replace the fluid with 0.1% TiO2 nanofluid; 0.15% ; 0.2% with no vibration and vibration conditions.

2.3. Perhitungan Sifat Termofisika Nanofluid

The thermophysical properties of nanofluids include density, viscosity, specific heat and thermal conductivity. The following is the formula and calculation of the thermophysical properties of nanofluids:

Nanofluid density equation:

$$\rho_{nf} = \varphi\rho_p + (1-\varphi)\,\rho_b \quad (1)$$

Nanofluid viscosity equation:

$$\mu_{nf} = \mu_f\,(1 + 7{,}3\,\varphi + 123\,\varphi^2) \quad (2)$$

Nanofluid specific heat equation:

$$(\rho C_p)_{nf} = (1-\varphi)\,(\rho C_p)_b + \varphi(\rho C_p)_p \quad (3)$$

Nanofluid thermal conductivity equation:

$$\frac{k_{nf}}{k_b} = \frac{k_p + 2\,k_b + 2\,(k_p - k_b)\,(1+\beta)^3\varphi}{k_p + 2k_b - (k_p - k_b)\,(1+\beta)^3\varphi} \quad (4)$$

Table 1. Thermophysical Properties TiO_2 Nanofluid

Thermophysical Properties	0%	0.1%	0.15%	0.2%
ρ (kg/m^3)	997,1	1000,3529	1001,97935	1003,6058
μ (kg/m.s)	0,0008905	0,0008971	0,0009004	0,0009039
Cp (J/kg.ºC)	4183	4179,5032	4177,7548	4176,0064
k (W/m.ºC)	0,5948	0,5962	0,5970	0,5977

2.4. Calculation of the Overall Heat Transfer Coefficient of Radiator

The overall heat transfer coefficient is an indicator of the value to determine the heat exchanger can be said to be good. The overall heat transfer coefficient value can be influenced by several factors, namely the thermophysical properties of the fluid as well as the geometry and area where the heat transfer occurs and the most significant is the fluid flow velocity is the factor that affects the largest U value [6].

Before calculating the overall heat transfer coefficient value, it is necessary to take the logarithmic average of the LMTD. The radiator is a cross flow and shell and tube multi-pass heat exchanger, to calculate the lm value, the following equation can be used [7]:

$$\Delta T_{lm} = F.\ \Delta T_{lm\ CF} \qquad (5)$$

F in the above equation acts as a correction factor that depends on the geometry of the heat exchanger and the inlet and outlet temperatures of the fluid, to find the value of $F.\ \Delta T_{lm\ CF}$ the following equation is used:

$$\Delta T_{lm\ CF} = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)} \qquad (6)$$

The correction factor F is an algebraic expression that has been developed for various cross-flow configurations in heat exchangers, and the results can be represented graphically. To determine the correction factor F, it is necessary to calculate the value of P (thermal effectiveness of the fluid on the tube side) and R (heat capacity ratio). The equation is as follows:

$$P = \frac{T_{h\ out} - T_{h\ in}}{T_{c\ in} - T_{h\ in}} \qquad (7)$$

$$R = \frac{T_{c\ in} - T_{c\ out}}{T_{h\ out} - T_{h\ in}} \qquad (8)$$

The overall heat transfer coefficient value is obtained by changing the equation of the heat transfer rate as follows:

$$\dot{Q} = U.\ A.\ \Delta T_{lm} \qquad (9)$$

So the overall heat transfer coefficient formula is as follows:

$$U = \frac{\dot{Q}_{avg}}{A.\Delta T_{lm}} \qquad (10)$$

Before performing calculations using the above equation, the required value of $\dot{Q}_{fluid}$ (heat released by the radiator) is as follows:

$$\dot{Q}_{fluid} = \dot{m}.\ C_p\ .\ (T_{h\ in} - T_{h\ out}) \qquad (11)$$

And $\dot{Q}_{air}$ (heat received by the air), the equation is as follows:

$$\dot{Q}_{air} = \dot{m}.\ C_p\ .\ (T_{c\ out} - T_{c\ in}) \qquad (12)$$

And then average between $\dot{Q}_{fluid}$ and $\dot{Q}_{air}$ as follows:

$$\dot{Q}_{avg} = \frac{\dot{Q}_{fluid} + \dot{Q}_{air}}{2} \qquad (13)$$

2.5. Perhitungan Hambatan Termal Antara Heater dan Water block

Calculation of thermal resistance on the heater and water block is by calculating the temperature difference between the heater and the water block, then divided by the power generated by the heater. To get the temperature value from the water block, that is by calculating the average temperature from each side of the water block. The equation to calculate the thermal resistance between the heater and the water block can use the following formula:

$$R_{th} = \frac{\Delta T}{Q} \qquad (14)$$

Because the heat generated by the heater is the same as the power released. Then Q = P So the equation is as follows:

$$R_{th} = \frac{\Delta T}{P} = \frac{T_{heater} - T_{wb}}{P} \qquad (15)$$

3. RESULTS AND DISCUSSION

3.1. The Effect of Addition of TiO2 Nanofluid on U Vibrating and Non Vibrating

Based on the results of experiments that have been carried out, it is found that the addition of TiO_2 nanofluid with ultrasonic vibration has an effect on the overall heat transfer coefficient in the radiator. This is because theoretically with the addition of ultrasonic vibrations there will be a phenomenon of density and strain on the particles colliding with each other so as to produce a cavitation effect on the fluid. This cavitation effect can accelerate the heat

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transfer process. In addition, ultrasonic vibrations can also produce an acoustic streaming effect where the fluid will form fluid motion in the direction of the wave propagation, so that it can affect the temperature of the fluid coming out of the radiator, which can affect the value of LMTD (Logarithmic Mean Temperature Difference). Changes in the LMTD value will affect the amount of heat released by the radiator and will affect the overall heat transfer coefficient (U).

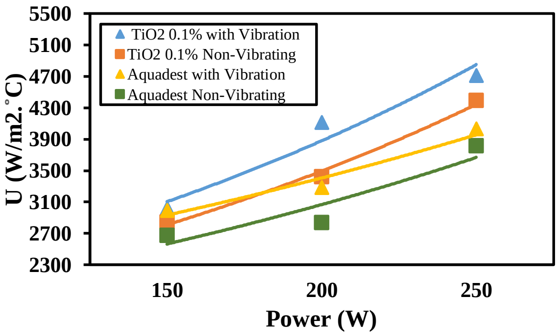

Figure 2. Effect of Aquadest and 0.1% TiO_2 Nanofluid on U Vibrating and Non Vibrating

Figure 2 above, it can be seen that the addition of nanofluid to the base fluid can affect the overall heat transfer coefficient (U) in the radiator. This is due to the superior thermophysical properties of nanofluids from base fluids, so that they can affect the value of the heat transfer coefficient. In the graph above, it can be seen that the highest overall heat transfer coefficient (U) occurs in 0.1% nanofluid using vibration, which is 4713.25201 $W/m^2.^oC$. In this condition there is an increase of 7.34% from the no-vibration condition with a value of 4390.92455 $W/m^2.^oC$. The highest increase occurred in 0.1% nanofluid at a power of 200 W without vibration, which was 3419.874768 $W/m^2.^oC$, an increase of 20.16% in conditions with vibration of 4109.319539 $W/m^2.^oC$. As for the value of the increase in the highest aquadest base fluid, which is 15.84%, it occurs at a power of 200 W, namely in conditions without vibration of 2834.563579 $W/m^2.^oC$ and conditions with vibration of 3283.473891 $W/m^2.^oC$.

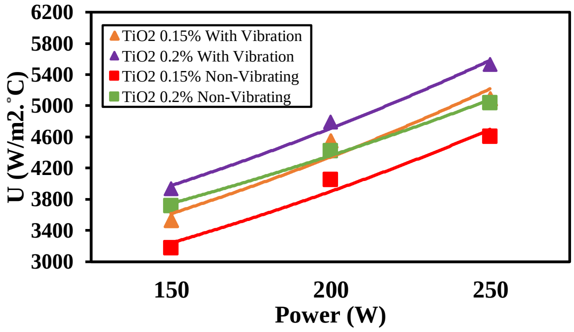

Figure 3. Effect of 0.15% and 0.2% TiO_2 Nanofluid on U Vibrating and Non Vibrating

In Figure 3 above, it can be seen that the highest overall heat transfer coefficient (U) occurs in 0.2% nanofluid using vibration, which is 5534.745283 $W/m^2.^oC$. In this condition there is an increase of 9.82% from the condition without vibration which is worth 5039.977246 $W/m^2.^oC$. The highest increase occurred in 0.15% nanofluid at a power of 150 Watt without vibration, which was 3177.120048 $W/m^2.^oC$, an increase of 11.07% in conditions with vibration of 3528.803925 $W/m^2.^oC$.

Table 2. 2-way ANOVA calculation results

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Treatment	788869.244	1	788869.2	83.5079322	0.0000	4.4939985
Concentration	5409665.29	3	1803222	190.885019	0.0000	3.2388715
Interaction	110832.813	3	36944.27	3.91083784	0.0286	3.2388715
Within	151146.215	16	9446.638			
Total	6460513.56	23				

Based on the table above, the P-value of the treatment and concentration is 0.00, which means $0.00 < 0.05$. Then H1 is accepted which means there is a significant difference between the addition of ultrasonic vibration treatment to the overall heat transfer coefficient value. And there is a significant difference between the concentration variations and the overall heat transfer coefficient value.

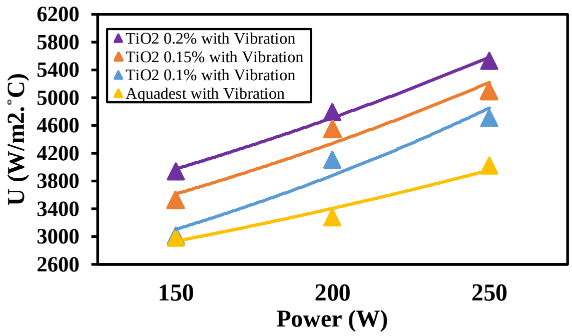

Figure 4. Effect of TiO_2 Nanofluid Concentration on U Vibrating Condition

In Figure 4 above, it can be seen the vibration conditions in the base fluid and the addition of nanofluid with concentrations of 0.1%, 0.15% and 0.2%. In base fluid and 0.2% nanofluid, the 250 Watt power has increased from 4029.871937 $W/m^2.^oC$ to 5534.745283 $W/m^2.^oC$ or 37%. The overall heat transfer coefficient (U) is obtained from the division of the Q_{avg} value by the constant convection area ($A_{convection}$) multiplied by the LMTD value. The calorific value released by the fluid Q_{fluid} is theoretically obtained from the product of the mass flow rate of the fluid (m_{fluid}), specific heat (C_p) and the difference in fluid temperature (ΔT_{fluid}). The value of mass flow rate (m_{fluid}) and fluid temperature difference (ΔT_{fluid}) is influenced by the concentration level of nanoparticles, the higher the concentration of nanoparticles, the higher the value of both is also greater. LMTD value as a divisor that can affect the overall heat transfer coefficient (U). The LMTD value will be smaller as the concentration of the nanoparticles increases through the calculation of data from the results of experiments that have been carried out. So that the output value, namely the overall heat transfer coefficient (U) will increase with increasing concentration of nanoparticles, because the value of the heat released by the fluid is getting bigger and the LMTD is getting smaller.

The value of heat released by air (Q_{air}) is theoretically obtained from the equation between the mass flow rate of air (m_{air}), specific heat of air (C_p) and the difference in air temperature (ΔT_{air}). The mass flow rate air value is influenced by air velocity (v), air mass (ρ) and the cross-sectional area of the radiator fan which is feasible to be constant. The air is influenced by the difference in the temperature of the incoming air (T_{in}) and the out going air (T_{out}). The Q_{fluid} value obtained from the mass flow (m_{fluid}) in the nanofluid is greater than that of the aquadest base fluid, the higher the concentration of the nanofluid, the greater the value of the fluid flow mass. larger than the base fluid. In addition, the change in temperature of the fluid (ΔT_{fluid}) is a factor that greatly affects the value of the heat released by the fluid (Q_{fluid}) significantly.

Table 3. 2-way ANOVA calculation results

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Power	9269124.04	2	4634562.021	188.3221	0.0000	3.4028261
Concentration	8861270.62	3	2953756.874	120.0238	0.0000	3.0087866
Interaction	440553.911	6	73425.65183	2.983598	0.0254	2.5081888
Within	590634.387	24	24609.76613			
Total	19161583	35				

Based on the table above, the P-value of power and concentration is 0.00, which means 0.00 <0.05. Then H1 is accepted, which means that there is a significant difference between the power variations and the overall heat transfer coefficient value. And there is a significant difference between the concentration variations and the overall heat transfer coefficient value.

3.2. *Effect of Addition of TiO2 Nanofluid on Rth Vibrating and Without Vibrating*

Based on the results of experiments that have been carried out, it is found that the addition of TiO_2 nanofluid with ultrasonic vibration has an influence on the value of the thermal resistance between the heater and the water block. This is due to the influence of ultrasonic vibration on the radiator which produces a large overall heat transfer coefficient value, so that the temperature of the fluid coming out of the radiator has a low temperature, so when the fluid flows into the water block, it can cooled the heat from the heater better. The following is a graph of the effect of ultrasonic vibration on the value of thermal resistance in the base fluid and 0.1% TiO_2 nanofluid.

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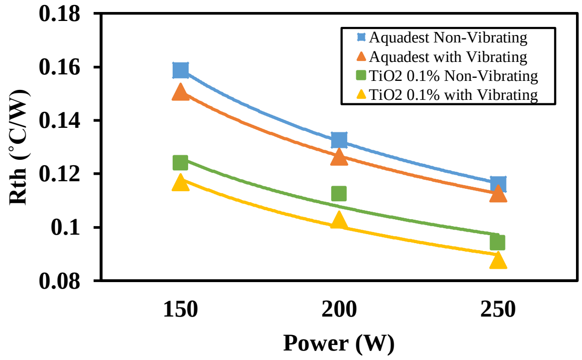

Figure 5. Effect of Aquadest and 0.1% TiO_2 Nanofluid on Rth Vibrating and Non Vibrating

Figure 5 shows that the smallest thermal resistance value at 0.1% concentration of TiO_2 nanofluid with additional vibration at 250 Watt power is 0.0880 °C/W. In this condition, the Rth value decreased by 6.63% from the 0.1% concentration without vibration, which was 0.0943 °C/W. While the value of the largest thermal resistance in the base fluid without using vibration at 150 Watt power is 0.1588 °C/W.

Theoretically the value of thermal resistance (Rth) is influenced by the difference in temperature from the heater and water block then divided by the power consumed by the heater. The effect of the mass concentration of TiO_2 nanoparticles also affects the value of thermal resistance, due to the thermophysical properties which include density, specific heat, viscosity and thermal conductivity of TiO_2 nanofluids which are better than the base fluid, so adding mass of nanoparticles to the base fluid with a certain concentration can change thermophysical properties of the base fluid. The addition of ultrasonic vibrations to the radiator can dissipate fluid heat better so that the fluid flowing into the water block has a lower temperature and can lower the temperature of the heater better, so that the temperature difference between the heater and the water block can be smaller.

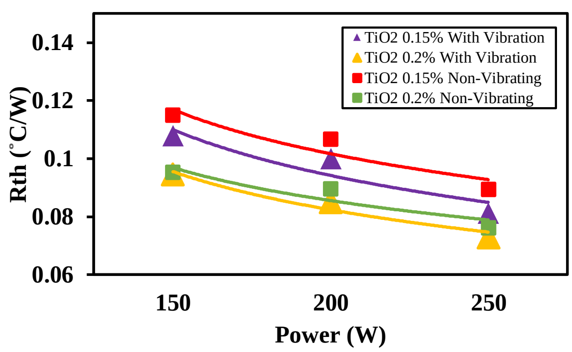

Figure 6. Effect of 0.15 and 0.2% TiO_2 Nanofluid on Rth Vibrating and Non Vibrating

Figure 6 shows that the smallest thermal resistance value in TiO_2 nanofluid at a concentration of 0.2% with the addition of vibration at 250 Watt of 0.0730 °C/W, a decrease of 4.26% from a concentration of 0.2% without using vibration is 0.0763 °C/W. While the greatest thermal resistance value at 0.1% concentration of TiO_2 nanofluid without using vibration at 150 Watt power is 0.1242 °C/W.

Table 4. 2-way ANOVA calculation results

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Treatment	0.000193745	1	0.000193745	169.372181	0.0000	4.49399848
Concentration	0.005526345	3	0.001842115	1610.38101	0.0000	3.23887152
Interaction	1.80678E-05	3	6.02262E-06	5.26498407	0.0102	3.23887152
Within	1.83024E-05	16	1.1439E-06			
Total	0.00575646	23				

Based on the table above, the P-value of the treatment and concentration is 0.00, which means 0.00 < 0.05. Then H1 is accepted, which means there is a significant difference between the addition of ultrasonic vibration to the thermal resistance value. And there is a significant difference between the concentration variations on the value of the thermal resistance.

The value of thermal resistance (Rth) is obtained by dividing the temperature difference between the heater and the water block by the power generated by the heater. Because the heat generated by the heater is directly proportional to the power consumed by the heater. The addition of nanoparticles to aquadest bottom fluid can affect the value of thermal resistance (Rth), the greater the concentration added, the smaller the thermal resistance value. The following is a graph of the effect of the addition of TiO_2 nanofluid on the condition of the radiator being given ultrasonic vibration

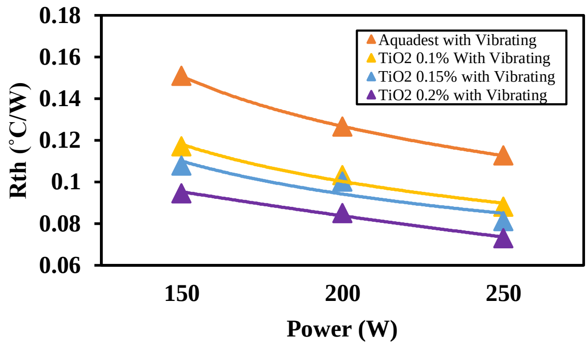

Figure 7. Effect of TiO_2 Nanofluid Concentration on Rth Vibrating Condition

In Figure 7 above, it can be seen the vibrating conditions in the base fluid and the addition of nanofluid with concentrations of 0.1%, 0.15% and 0.2%. In base fluid and 0.2% nanofluid with 250 Watt power, the thermal resistance value (Rth) decreased from 0.1163 ºC/W to 0.0730 ºC/W or 37%. The value of the thermal resistance is influenced by the temperature of the heater and water block. A small temperature difference between the heater and the water block can reduce the value of the thermal resistance.

Table 5. 2-way ANOVA calculation results

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Power	0.00480142	2	0.0024007	1148.119905	0.0000	3.4028261
Concentration	0.01040437	3	0.0034681	1658.603519	0.0000	3.0087866
Interaction	0.00040689	6	6.781E-05	32.43165701	0.0000	2.5081888
Within	5.0184E-05	24	2.091E-06			
Total	0.01566286	35				

Based on the table above, the P-value of power and concentration is 0.00, which means $0.00 < 0.05$. Then H1 is accepted, which means there is a significant difference between the power variation and the thermal resistance value. And there is a significant difference between the concentration variations on the value of the thermal resistance.

In electronic cooling systems, the value of thermal resistance is a very calculated value, because this value is an indicator of a cooling system that can be said to be good or bad. Other factors such as the addition of TIM (Thermal Interface Material) such as thermal paste can overcome the high value of thermal resistance. This is because the addition of a thermal interface material can fill the gap between the heater surface and the water block. So that by adding thermal paste on the surface of the heater and water block the empty gap can be filled and the heat from the heater can be absorbed by the water block. The high thermal conductivity value of the thermal paste can also make the heat absorption better, so that the heat generated by the heater is absorbed by the water block better.

4. CONCLUSION

Based on the results of the research that has been done, the following conclusions can be drawn:

1. The overall heat transfer coefficient (U) of the radiator increases as the concentration of TiO_2 nanofluid increases. and with the addition of ultrasonic vibration with a power of 24 Watt the overall heat transfer coefficient (U) has increased from the condition without being given a vibration. In aquadest base fluid without vibration power of 250 W, the U value of 3814.914609 W/m^2.ºC increases to 4029.871937 W/m^2.ºC or 5.63%. The largest increase occurred in 0.1% concentration of TiO_2 nanofluid without vibration with a power of 250 W, the U value of 3419.874768 W/m^2.ºC increased to 4109.319539 W/m^2.ºC under vibration conditions, or 20.16%.

2. The value of the thermal resistance (Rth) between the heater and the water block decreased as the concentration of TiO_2 nanofluid increased. And with the addition of ultrasonic vibration, the value of thermal resistance (Rth) has decreased from the no-vibration condition. In aquadest base fluid without vibration, the value of Rth is 0.1163 ºC/W decreased to 0.1128 ºC/W or 3.01%. The biggest decrease occurred in 0.15% TiO_2 nanofluid with a power of 250 W, namely the non-vibrating condition with a value of 0.0895 ºC/W decreased to 0.0813 ºC/W in the vibrating condition, or 9.22%

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NOMENCLATURE

φ = Concentration of nanoparticles (%)
ρ_{nf} = Density of nanofluid (kg/m^3)
ρ_p = Density of nanoparticles (kg/m^3)
ρ_b = Density of base fluid (kg/m^3)
μ_{nf} = Viscosity of nanofluid (kg/m.s)
μ_f = Viscosity of the base fluid (kg/m.s)
$(\rho C_p)_{nf}$ = Specific heat of nanofluid (J/kg.°C)
$(\rho C_p)_b$ = Specific heat of base fluid (J/kg.°C)
$(\rho C_p)_p$ = Specific heat of nanoparticles (J/kg.°C)
k_{nf} = Thermal conductivity of nanofluid (W/m.°C)
k_b = Thermal conductivity of the base fluid (W/m.°C)
k_p = Thermal conductivity of nanoparticles (W/m.°C)
β = Ratio of nano layer thickness (h)
U = Overall heat transfer coefficient (W/m^2. °C)
F = Correction factor (0-1)
ΔT_{lm} = LMTD (°C)
$\dot{Q}$ = Heat transfer rate (W)
$\dot{m}_{fluid}$ = Mass flow rate of fluid (kg/s)
$\dot{m}_{air}$ = mass flow rate of air (kg/s)
$C_{p\ fluid}$ = Specific heat of fluid (kJ/kg. °C)
$C_{p\ air}$ = Specific heat of air (kJ/kg. °C)
$T_{h\ in}$ = Hot fluid inlet temperature (°C)
$T_{h\ out}$ = Hot fluid outlet temperature (°C)
$T_{c\ in}$ = Air inlet temperature (cold) (°C)
$T_{c\ out}$ = Air outlet temperature (cold) (°C)
A = Radiator tube surface area (m^2)
R_{th} = Thermal resistance (°C/W)
ΔT = Temperature difference (°C)
P = Heater power (W)