Design of Cooling System on Brushless DC Motor to Improve Heat Transfers Efficiency

Safril
Department of Automotive Engineering Technology, Politeknik STMI Jakarta

Mustofa
Department of Automotive Engineering Technology, Politeknik STMI Jakarta

Zen, Muhamad
Department of Automotive Industrial Engineering, Politeknik STMI Jakarta

Sumasto, Fredy
Department of Automotive Industrial Engineering, Politeknik STMI Jakarta

他

https://doi.org/10.5109/4794206

出版情報：Evergreen. 9 (2), pp.584-593, 2022-06. 九州大学グリーンテクノロジー研究教育センター
バージョン：

Design of Cooling System on Brushless DC Motor to Improve Heat Transfers Efficiency

Safril[1*], Mustofa[1], Muhamad Zen[2], Fredy Sumasto[2], Mohammad Wirandi[1]
[1]Department of Automotive Engineering Technology, Politeknik STMI Jakarta, Republic of Indonesia
[2]Department of Automotive Industrial Engineering, Politeknik STMI Jakarta, Republic of Indonesia
*Corresponding Author's email: safril@kemenperin.go.id

(Received February 11, 2022; Revised June 20, 2022; accepted June 20, 2022).

Abstract: Electric vehicles generally use a Brushless DC (Direct Current) motor as the main motor of the vehicle. Brushless DC Motor is not an instrument with a perfect level of efficiency. Brushless DC motors can still overheat at certain times, thus damaging the insulating material of the motor. Damaged motorcycles are obtained when the vehicle continues to operate over long distances and for long periods. In these conditions, the motor efficiency will drop significantly. This paper proposes designing a cooling system on a Brushless DC casing by applying a hollow fin that is continuously flowing with water. A Brushless DC motor casing design is simulated using software to determine the actual conditions of water circulation that occur in the design. Furthermore, this study uses an empirical and comparative approach to evaluate the efficiency of a cooling system. The results showed that the design of a hollow fin cooling system with water media tended to experience an efficiency of 43.410% and an increase in the average efficiency of the previous study of 17.348%.

Keywords: Brushless DC Motor; Cooling System; Design and Optimization; Heat Transfer Enhancement

1. Introduction

Energy efficiency is becoming more popular as global environmental protection is improved. In a situation like this, the electric motorbike is a mainstay to replace fossil resources in the automotive industry[1,2], and Indonesia is one of the competitors in the massive development of electric vehicles[3]. Currently, many electric vehicle manufacturers rely on the primary driving device, namely the electric motor [4]. The electric motor is part of a government project to reduce fossil fuels [5,6]. The use of electric motors can reduce air pollution, which positively impacts globally [7–9]. Electric motors are generally capable of producing power as the prime mover but can also be used as a producer of electrical energy [10,11]. Based on the demand for electric motors, which is estimated to increase every year, a series of planning in the form of cost estimates is required [12], design planning according to environmental requirements [13], and planning the life of the electric motor [14].

A drive with better performance efficiency with high torque rotation and a motor rotation speed that can be controlled easily will be very much needed as the main driving force for electric vehicles to fulfill the automotive market, especially in Indonesia. Electric motors that are commonly used are direct current (DC) motors and induction motors. DC motors have high efficiency with high maintenance costs. In contrast, induction motors have low maintenance costs with low efficiency and heat easily [15]. Usually, induction motors are widely used by industry because of their simplicity in construction [16]. Although brushless DC (BLDC) electric motors are often used in electric vehicles.

The daily use of an electric motor is a BLDC motor which has several advantages. These advantages include: without the use of a brush/brush, a barely audible motor sound, and compact maintenance [17,18], and regular maintenance aimed at maximizing the performance of the BLDC motor [19]. The BLDC motor is also a type of synchronous motor with minimal slip on the induction motor. In a BLDC motor, the magnetic field generated by the rotor rotates at the same frequency [20], in addition to these advantages, electric motors are also inseparable from the dangers of overuse, such as the use of BLDC in electric vehicles when used continuously and when they have a vehicle load that exceeds the usage limit of a BLDC motor. These things will have an impact on increasing heat at the motor temperature of the BLDC so that there will be a decrease in the quality of performance on the BLDC motor, which is due to vibrations caused by vehicle shocks [21], so that the insulation of the motor dynamo windings is damaged which can burn in its worst condition [22].

The need for a motor that has a more efficient performance with high torque rotation and has a controllable motor rotation speed [23], Excessive power factor values can result in a waste of current, so a control system is needed [24,25], utilization of control systems will reduce maintenance costs with accurate detection [26], and can increase motor torque. Whereas in a vehicle with a constant speed controller, motor phase current, motor torque increases with increasing temperature [27].

A motor has a bad heat dissipation condition due to several factors such as the installation space, work environment, and a high increase in operating temperature, and obstacles to increasing power density and torque density. BLDC motors have two types of rotors based on the location of the rotors, namely the inner rotor and the outer rotor. Increasing motor efficiency is the most influential thing and must be considered in BLDC electric motors. Efficiency is always related to heat transfer and performance on BLDC motors [28], so that the better the heat transfer efficiency, the better the cooling system [29–31]. One of the benchmarks of efficiency in a BLDC motor is heat transfer to the motor caused by the load received by the motor and the use of maximum speed, so it is one of the crucial factors in an electric motor design [32].

The type of BLDC motor material also has a significant effect on the cooling process of the BLDC motor, where the type of material will affect heat transfer and accelerate cooling [33,34]. Copper in electric motors has an insulating material. When there is damage, it will result in excessive heat dissipation so that symptoms of overheating in the BLDC motor and a decrease in motor efficiency in terms of age can occur quickly [35]. The speed control system also significantly reduces heat due to an unstable speed pattern that causes excess energy [36].

Some studies refer to reducing excessive heat in BLDC motors, including using a cooling fan [37]. However, the researcher can still be developed by utilizing water media as a cooling BLDC motor. A cooling system with water media is not the primary basis, especially in this study, accompanied by the design development on the BLDC motor casing. The output of this study aims to minimize the impact of excess heat on the BLDC motor by applying the design and simulation method to a series of cooling fins that are designed to be hollow as water flow in the BLDC motor casing design and also discuss the type of material used in the BLDC motor casing in this study.

2. Literature Review

This study was conducted based on gap research based on several previous studies. In several studies, in previous studies, the cooling system on BLDC motors still applies a system that focuses on cooling media such as water, air, fluid, and oil. Vu & Hwang (2013) [38] conducted a study where at 35,805 meters per second, the average temperature of the fins decreased from 80.356 to 69.437 ^{O}C. If converted in Celsius, the heat reduction in the BLDC motor using numerical analysis methods was 10,919 degrees. Celsius. Research is not only on motor coil but on the motor casing is also needed; if the temperature reaches 50 degrees Celsius, the circulation of the cooling system fluid causes the casing temperature to drop 24 ^{O}C in one second and return to an ambient temperature of 23.2 ^{O}C [39]. In increasing optimal cooling, an appropriate method is needed; the application of the thermodynamic method has a significant effect in reducing excess heat by 25.0 degrees Celsius [40].

Permana (2016) [41] suggests the effect of cooling air, liquid fluid, and a combination of air-liquid cooling on a 10 KW BLDC motor aims to determine the temperature distribution that occurs from a BLDC motor using the Solidworks Flow simulation application. Heat in a BLDC Motor that is not disposed of properly can cause Overheat by applying a numerical approach to Computational Fluid Dynamic (CFD)[42]. The winding temperature at Axial BLDC at 100 km/hour is 105 ^{O}C ± 6.93% with a magnetic temperature of 57.8 ^{O}C ± 6.93% [43].

Based on research conducted by Koren et al. (2018) [44] emphasizes the analysis of BLDC motor drive systems at high temperatures by building mathematical models of fuzzy-PID control systems, waveforms, time-domain simulation, and frequency. The results showed that the performance of the double close-loop simple control system deteriorated with increasing temperature. When the vehicle is stationary until it reaches constant speed, the control current, motor phase current, and motor torque decrease with temperature. The Urban Assault (UADC) driving cycle was evaluated under various conditions to obtain a cooling efficiency value of 40.3% [45]. Water cooling media and fans have a positive effect on cooling the BLDC motor. The oil cooling method has an excellent cooling effect on the stator core and works longer at rated conditions; the effect of cooling on windings with a temperature of 130.3 degrees Celsius gives an efficiency of 30.6% [46]. Typical motors have poor heat dissipation conditions and are limited by installation space, working environment, and increased high operating temperature and resistance to increase power density and torque density. The development of the cooling system aims to reduce heat on the outside and inside of the BLDC motor. Development can also be done by designing fans and water as cooling systems [47], liquid cooling systems can also increase efficiency by 33% [48]. Heat transfer depends on the relative orientation of the heated cavity and the magnetic field lines. The convection heat transfer in direct current motors affects the rate of shrinkage of the magnetic field cavity when the surface is hot [49].

Material selection affects the rate of temperature change[50,51] and resistance to heat in the BLDC motor casing. Material 6061-T6 is a type of aluminum material from the cast made in the form of billets. The billet is a metal that has a round or square cross-section which is made by casting because the 6061-T6 material is considered homogeneous. The percentages of the chemical composition of aluminum 6061-T6 are: Si 0.649%; Fe 0.677%; Cu 0.248%; Mn 0.112%; Mg 0.929%; Zn 0.119%; Ti 0.181%; Cr 0.101%; Pb 0.007%; Al 97.135% and the mechanical properties of the material 6061-T6, namely: Tensile Strength (σu) 310 Mpa; Yield

Strength (σys) 276 Mpa; Modulus of Elasticity Shear (E) 68.9 Gpa; Strenght (T) 207 Mpa; Poison Ratio (v) 0.33 and; Elongation (δ) 12% [52]. Referring to the results of the literature review, which can see in Table 1 that it is found that there is a research gap for a more optimal cooling system, namely by designing a hollow fin so that water can flow as a cooling medium. The design of the BLDC motor fin is simulated using the 6061-T6 material, thus providing positive results in accelerating heat transfer and heat dissipation compared to the design in previous studies.

Table 1. A previous study of the cooling system in BLDC

Researchers	Electric Motor Type	Cooling System	Software	Method	Findings
Vu & Hwang, 2013 [38]	BLDC	Cooling Air	Computational Fluid Dynamics	Numerical Method	At a speed of 35,805 meters per second, the average temperature on the fins decreases from80.356 to 69.437 ^{O}C.
Abdul Karim & Mohd Yusoff, 2014 [40]	Electric Motor	Cooling System	CATIA	Thermodynamic analysis	Electric motor liquid cooling at an operational temperature of 65 ^{O}C to 40 ^{O}C
Paine & Sentis, 2015 [39]	Electric Motor	Air-Cooled and Liquid-Cooled	-	Experimental Analysis	on the motor case, the temperature reaches 50 degrees Celsius, the circulation of the cooling system fluid (fluid) causes the casing temperature to drop by 24 ^{O}C in one second and return to the ambient temperature of 23.2 ^{O}C
Permana, 2016 [41]	BLDC	Air and Liquid Water	Solidworks	Modeling	The cooling system applies water cooling and liquid cooling resulting in the highest 85.83 ^{O}C and the lowest of 57.01 ^{O}C.
Mukhlisin et al., 2018 [43]	Axial BLDC	Thermal Camera FLIR T420	Computational Fluid Dynamics	Simulation	At 5000 RPM, the winding temperature is 105 ^{O}C ± 6.93 percent, and the magnetic temperature is 57.8 ^{O}C ± 6.93 percent.
Koren et al., 2018 [44]	Electric Motor Standard	Air Cooling	Computational Fluid Dynamics	Modeling Fluid Flow	Based on concept 3.1 reduced the temperature of the magnets by almost 40%, and the loss value was still smaller.
Huang et al., 2019 [45]	Electric Motor	Hybrid Cooling System	Finite Element Analysis	Numerical Method	The hybrid cooling system offers that the liquid removes 40.3% of heat at 25 ^{O}C ambient temperature.
Uta Nugraha et al., 2019 [47]	Brushless DC	Water and Fan	Ansys Maxwell	Design and Simulation	The main housing has a temperature of 75 ^{O}C. The average decrease temperature was 65 ^{O}C while using water and a fan.
Guo & Zhang, 2019 [46]	Permanent Magnet	Air Cooling	ANSYS	Simulation	at winding temperature, 130.3 ^{O}C result of system efficiency is 30.6%.
Tarsius et al., 2020 [48]	BLDC	Liquid Cooling	MAXWELL	Numerical Method	The use of liquid cooling can increase efficiency by up to 33%.

Researchers	Electric Motor Type	Cooling System	Software	Method	Findings
Choi et al., 2020 [49]	BLDC	Air Cooling	-	Experimental Study	The temperatures at points A and B for 30 L/min were 26.5 and 25.1 ^{O}C, respectively. The temperatures were 21.2 ^{O}C and 18.5 ^{O}C for 50 L/min at points A and B.

3. Research Method

In the early stages, that carried out this research by designing the BLDC motor casing, where this casing is the central part of the BLDC motor cooling system. The casing fins are designed to be hollow for cooling water flow. The method used in this research is the simulation and analysis method to determine the cooling calculations on the BLDC motor casing with water cooling media.

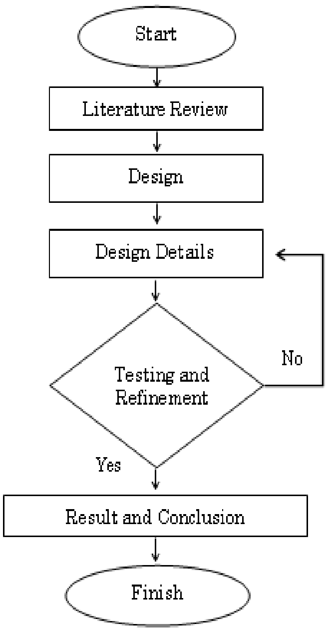


Fig. 1: Flowchart of methodology

Fig 1. shows the flowchart of the writing method in the cooling system research on the BLDC motor. This research begins with collecting data based on literature review journals to get gaps used as ideas in developing cooling efficiency in BLDC motors. The development of the ideas obtained is compiled in a design draft which is further developed down to the level of design detail. The design details are final, then testing and refinement are carried out using the simulation method in each detail section of the BLDC motor casing design. In the testing simulation, if the test results show a malfunction or design failure that cannot be meshed, then a refinement is carried out to the design stage where that will carry out the design details and if the test simulation results are appropriate and the results are obtained, a conclusion is made. Writing conclusions is the final stage and is declared complete. In determining the heat transfer in the BLDC motor, the method used is the mathematical method; one can see the calculation results of the mathematical method in Table 2. The calculation results show different speeds starting from 1000 RPM, 1500 RPM, 2000 RPM, 2500 RPM, 3000 RPM, 3500 RPM, and 4000 RPM; the calculation results of the Current Phase thermal energy output at 1000 RPM are 32,890 A, Core loss of 42.8890 watts and Winding Loss of 115.3790 watts while the heat generation for the core value is 58110.29725 W/ m^3 and for winding 119173.86700 W/m^3.

The current Phase output of heat energy at 1500 RPM is 33,920 A, Core loss 62.7920 watts and Winding Loss 156.1120 watts, for heat generation for core values is 128662.10549 W/m^3 and for Winding 239463.39657 W/m^3. The current Phase output of 2000 RPM speed energy is 36,370 A, Core loss 82.8370 watts and Winding Loss 198.4070 watts, for heat generation for core values is 230692.69819 W/m^3 and for Winding 404030.16596 W/m^3.

The current Phase output of heat energy at a speed of 2500 RPM is 37.530 A, Core loss 102.7530 watts and Winding Loss 239.2830 watts, for heat generation for core values is 360911.32529 W/m^3 and for Winding 607187.92020 W/m^3. The current Phase output of heat energy at 3000 RPM is 38,690 A, Core loss 122.6690 watts and Winding Loss 280.1590 watts, for heat generation for core values is 521643.85915 W/m^3 and for Winding 851316.50677 W/m^3.

The current Phase output of heat energy at 3500 RPM is 41.010 A, Core loss 142.7010 watts and Winding Loss 322.3110 watts, for heat generation for core values is 720470.37851 W/m^3 and for Winding 1141306.65501 W/m^3. At a speed of 4000 RPM, the calculation of the current phase energy output of heat is 45,650 A, for the core loss is 16.9650 watts and for winding 367.0150 watts, while the heat generation at the core is 972956.61330 W/m^3 and winding 1484814.44149 W/m^3. The results obtained on the change in the parameters for each RPM look very significant, so it is necessary to improve the existing system design.

Table 2. Calculation of heat generation

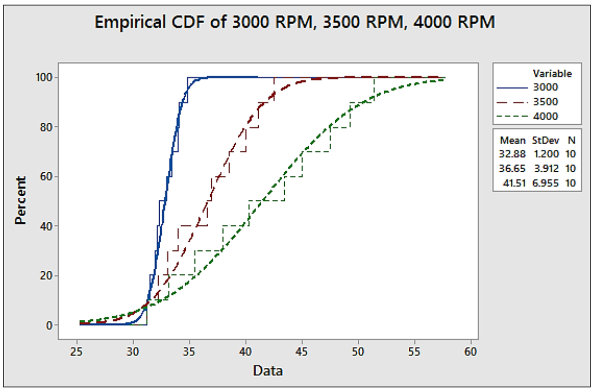
Speed Specification			Internal Parameter		Calculation Energy Output			Heat Generation	
Rpm	**m/s**	**km/jam**	**Watts**	**Celcius / Minutes**	**Current Phase (A)**	**Core loss (watt)**	**Winding loss (watt)**	**Core (W/m^3)**	**Winding (W/m^3)**
1000	10.7905	38.8457	105.8186	3.3432	32.890	42.8890	115.3790	58110.29725	119173.86700
1500	16.1857	58.2686	158.7274	5.0148	33.920	62.7920	156.1120	128662.10549	239463.39657
2000	21.5810	77.6914	211.6373	6.6864	36.370	82.8370	198.4070	230692.69819	404030.16596
2500	26.9762	97.1143	264.5461	8.3580	37.530	102.7530	239.2830	360911.32529	607187.92020
3000	32.3714	116.5371	317.4549	10.0296	38.690	122.6690	280.1590	521643.85915	851316.50677
3500	37.7667	135.9600	370.3648	11.7012	41.010	142.7010	322.3110	720470.37851	1141306.65501
4000	43.1619	155.3829	423.2736	13.3728	45.650	162.9650	367.0150	972956.61330	1484814.44149

4. Result and Discussion

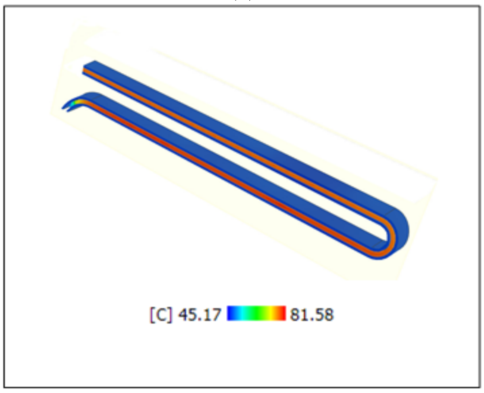
Based on the parameters collected from mathematical calculations, an output indicator is obtained in the form of hot air through the BLDC motor fins. It is necessary to make an idea for the casing design to reduce the temperature of the motor. Previously, the casing design, which was designed to be hollow on the fin, was carried out. Then the simulation was carried out under constant speed conditions with a range of 3000 RPM, 3500 RPM, and 4000 RPM, while the type of material used is aluminum 6061-T6. Aluminum 6061-T6 has advantages such as good formability, relatively high tensile strength, corrosion resistance, and light metal. For the initial simulation stage, an experiment was carried out by applying the simulation method to the BLDC motor design. The initial stage is data meshing to determine the meshing model specifications of the BLDC motor fin elements. This stage is a determination to get the detailed parts and characteristics of the BLDC motor casing.

In Fig 2.(a), the simulation results are displayed at a constant and gradual speed ranging from 3000 RPM, 3500 RPM, and 4000 RPM. The simulation results can be shown at a speed of 3000 RPM, the lowest hot spot of 31.25 ^{O}C and the highest heat of 34.81 ^{O}C. The simulation results at 3500 RPM, the highest heat of 42.56 ^{O}C. The simulation at 4000 RPM the highest is 51.44 ^{O}C. Things that need to be known for the temperature tolerance allowed on the motor depend on the insulation where each insulation class is different, or it can be said that the dimensions and thickness of the motor stator also affect the temperature increase. The cooling system is inseparable from the fins as a heat transfer medium with the convection heat transfer method, which can be seen through simulation software. The simulation is aimed at the hollow fin, which functions as a water-cooling medium.

Fig 2(b) shows the simulation results by convection under specific heat conditions. Convection Value on the lattice is 82.84 W/(m^2 C) maximum condition cooling system between 45-130 ^{O}C. The simulation results by convection produce cooling using water media 47.16 W/(m^2 C). Simulation of water flows in the fin cavity of the BLDC motor casing and the flow of 2500 mm, with the simulation results in graphical form. The study results are based on simulations that show several flow results that have a good or bad impact on the cooling system design of the BLDC motor. Flow turbulence intensity is one factor that affects the quality of cooling on the BLDC motor casing. The very irregular motion of particles in a water flow in the casing fin cavity is challenging to predict motion.



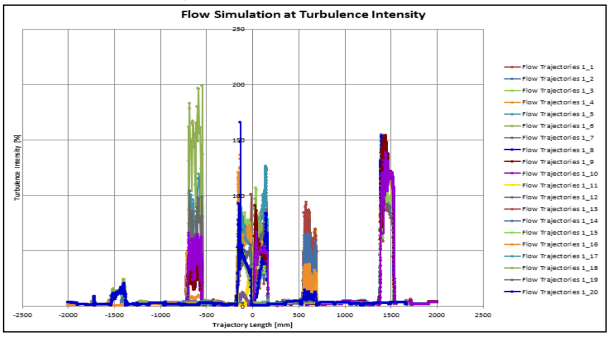
(a)



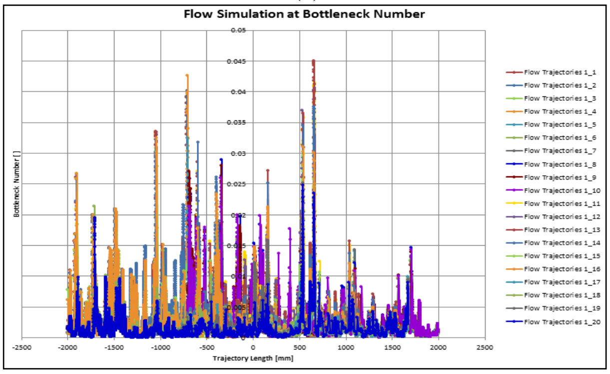
(b)

Fig. 2: (a) Result Empirical on 3000 RPM, 3500 RPM and,4000 RPM and, (b) Result simulation on Lattice

The level of turbulence fluctuation in the flow causes the intensity of turbulence to impact heat absorption. The higher the turbulence intensity value, the greater the velocity fluctuation. The intensity of the turbulence simulation shown in Fig 3(a) is obtained at the idle speed trajectory of the water circulation in the casing fin cavity functioning correctly, with relative heat and at the trajectory length of -547.3300108 mm, the temperature on the casing occurs at the highest level of turbulence of 198.9811646% and the trajectory length of 1425.900193 mm level. The percentage of turbulence began to subside with a percentage of 152.6531639%. At this level, the cooling system in the BLDC motor casing is relatively stable. The bottleneck of water flow makes the simulation on the bottleneck number of BLDC motor design, on the sides of the flow obstruction can be seen in the trajectory line at the highest level of 654.9594685 mm with the achievement of a bottleneck number of 0.044673935 and returning to stability at a trajectory length of 1038.499659 mm with a bottleneck number of 0.01575084 this result can be seen in Fig 3(b).



(a)

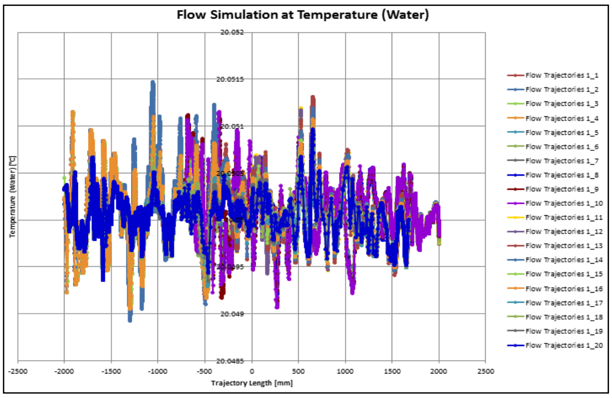


(b)

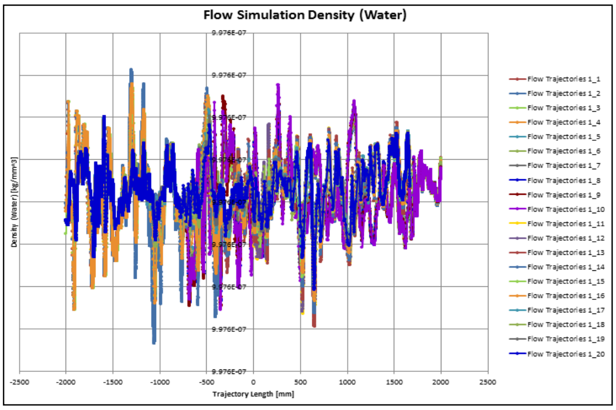
Fig. 3: (a) Flow simulation at Turbulence Intensity and, (b) Flow Simulation at Bottleneck Number

Fig 4(a) shows the water temperature in the casing fin cavity with temperature specifications in hot conditions reaching 20.05107451 ^{O}C at a trajectory length of -1056.753358, and heat can be muted or returned to stability at a trajectory length of 1501.169566 mm with a water temperature of 20.0497077 ^{O}C. Density simulation is shown in Fig 4.(b), where the resulting trajectory length 1301.106113 mm density water is 9.97562E-07 [kg/mm^3].

Based on the simulation there is a reduction efficiency in the hot water temperature (20.0497077 ^{O}C/ 20.05107451 ^{O}C) * 100% = 0.99993%. The cooling system on a BLDC motor with Water media is discussed in detail on the transfer of water from one side to another using a simulation method in software. The simulation is carried out on the cooling system design on the BLDC motor, which can be seen in Fig 5., showing the overall simulation of the water transfer process; you can see the red indicator shows the condition of hot water, while the blue color shows the condition of cold water. In the cooling system simulation, the role is water, but the type of material is very influential in giving a positive effect on the cooling system.



(a)



(b)

Fig. 4: (a) Flow simulation at Temperature (Water), (b) Flow simulation at Density (Water)

Table 3. shows that the results of the overall research simulation simultaneously result in 3-speed phases, namely: 3000 RPM, 3500 RPM, and 4000 RPM, and the grid conditions at the highest speed (4000 RPM) for each speed produce different cooling estimates at a speed of 3000 RPM with an average value of heat generated of 32.880 ^{O}C, with the condition of the water experiencing a cooling acceleration of 6.592% and the estimated cooling of the BLDC motor casing by convection using 6061-T6 material obtained 0.697%. At 3500 RPM, the average calorific value of the casing is 40,500 ^{O}C, and the cooling acceleration is 8,120%, while the 6061-T6 lattice

condition material experiences heat transfer with an acceleration of 0.859%. At a speed of 4000 RPM with an average calorific value on the BLDC casing 49.105 OC, cooling is accelerated with 9.845% water media. On the cooling grid, conditions are accelerated and can reduce the heat temperature to a percentage level of 1.041%. The simulation of the highest velocity conditions on the average heat grating is 63.375 OC, cooling is accelerated with 12.706% water media. In the lattice, conditions accelerate cooling and reduce heat temperatures to a percentage level of 1.344%.

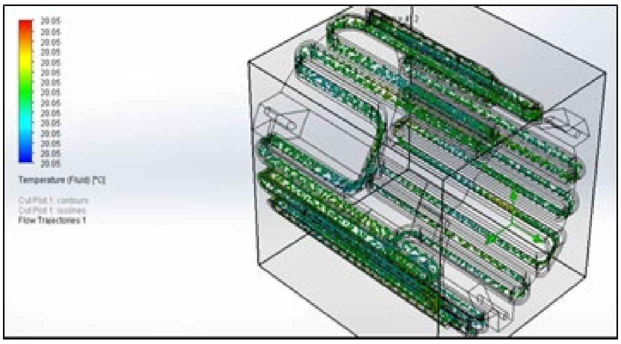


Fig. 5: Result simulation water flow

Based on Table 4, the results of the cooling system efficiency on the BLDC motor casing are shown. The resulting efficiency is 43.410% and an increase in efficiency compared to the previous literature review, the result is an increase in efficiency of 32.491% compared to Vu & Hwang, (2013) [38]; an increase of 18.410% compared to Abdul Karim & Mohd Yusoff, (2014) [40]; 42.610% increase in efficiency compared to Paine & Sentis, (2015) [39]; 14.590% increase in efficiency compared to research Permana, (2016) [41]; The results of the comparison of efficiency -3.790% to the research Mukhlisin et al., (2018) [43], are negative because in the study they simulated at a speed of 5000 RPM while in this study the parameters were only 4000 RPM An increase in efficiency of 33.410% compared to Uta Nugraha et al., (2019) [47]; an increase in efficiency of 40.710% compared to Choi et al., (2020) [53]; 3.410% efficiency results against comparison Koren et al., (2018) [44]; 3.110% efficiency results against comparison Huang et al., (2019) [45]; 12.810% increase in efficiency compared to research Guo & Zhang, (2019) [46] and; 10.410% increase in efficiency compared to studies Tarsisius et al., (2020) [48]. Thus the results of the study experienced an increase in the average efficiency of the previous study of 17.348%.

Table 3. Calculation of heat generation

Condition	**Current Phase (A)**	**Core loss (watt)**	**Winding loss (watt)**	**Lower Heat**	**Upper Heat (^{O}C)**	**Average Range (^{O}C)**	**Result Water Condition (%)**	**Result Convection Lattice Condition (%)**
3000 RPM	38.69	122.669	280.159	31.250	34.510	32.880	6.592	0.697
3500 RPM	41.01	142.701	322.311	38.44	42.560	40.500	8.120	0.859
4000 RPM	45.65	162.965	367.015	46.77	51.440	49.105	9.845	1.041
Lattice Condition	45.65	162.965	367.015	45.17	88.580	63.370	12.706	1.344
Average Condition	42.75	147.825	334.125	40.408	52.523	46.465	9.316	0.985

Table 4. The results of the comparison value efficiency analysis

Literature	**Lower Heat (^{O}C)**	**Upper Heat (^{O}C)**	**Efficiency (%)**	**Increased efficiency (%)**
Vu & Hwang, 2013 [38]	69.44	80.36	10.919	32.491
Abdul Karim & Mohd Yusoff, 2014 [40]	40	65	25.000	18.410
Paine & Sentis, 2015 [39]	23.2	24	0.800	42.610
Permana, 2016 [41]	57.01	85.83	28.820	14.590
Mukhlisin et al., 2018 [43]	57.8	105	47.200	-3.790
Uta Nugraha et al., 2019 [47]	65	75	10.000	33.410
Choi et al., 2020 [49]	18.5	21.2	2.700	40.710
Koren et al., 2018 [44]	-	-	40.000	3.410

Huang et al., 2019 [45]	-	-	40.300	3.110
Guo & Zhang, 2019 [46]	-	-	30.600	12.810
Tarsius et al., 2020 [48]	-	-	33.000	10.410

5. Conclusion

This research applies the design and simulation method to the BLDC motor casing, which is designed with a hole in the casing fin, and the material used is aluminum 6061-T6. In determining the calculated value of the material testing, mathematical calculation methods and material meshes are used. Research and simulations were carried out at speeds of 3000 RPM, 3500 RPM, and 4000 RPM. From the results of each simulation, the value of heat transfer is effective and relatively fast in cooling the BLDC motor elements with water media. The simulation results show an efficiency level of 43.410%, which results from an increase in efficiency compared to previous studies to provide the latest information from this study. The highest efficiency was 42.61% compared to Paine & Sentis (2015) [32]. Thus the average percentage of the cooling system with water media is 9.316%, and the average heat absorption value with the 6061-T6 material is 0.985%.

The comparative value efficiency analysis results are the final step in determining the novelty of this study, where from the comparison results, the average efficiency increase is 17.348%. According to that result, the design of the hollow fin cooling system with water media tended to experience an efficiency of 43.410% and an increase in the average efficiency of the previous study. This shows that the design of a cooling system with a hollow fin is considered feasible.

References

1) J.S. Park, B.-G. Gu, J.-H. Choi, and I.-S. Jung, "Development of bldc motor drive for automotive water pump systems," *J. Int. Counc. Electr. Eng.*, **1** (*4*) 395–399 (2011). doi:10.5370/jicee.2011.1.4.395.
2) M.C. Jena, S.K. Mishra, and H.S. Moharana, "Experimental investigation on energy saving potential in ahu of an air-conditioning system with bldc fan," *J. Inst. Eng. Ser. C*, **101** (*6*) 1083–1091 (2020). doi:10.1007/s40032-020-00602-6.
3) A. Habibie, M. Hisjam, W. Sutopo, and M. Nizam, "Sustainability evaluation of internal combustion engine motorcycle to electric motorcycle conversion," *Evergreen*, **8** (*2*) 469–476 (2021). doi:10.5109/4480731.
4) A.A. Ghoni, H. Suryoatmojo, and M. Ashari, "Desain dan analisis variabel air gap pada motor axial flux brushless dc berbasis 3d finite element method untuk aplikasi kendaraan listrik," *J. Tek. Its*, **4** (*2*) 26–30 (2015).
5) I. Prastyaningrum, and P. Ardi, "Project based learning for brush less dc motor," *Pros. SNFA (Seminar Nas. Fis. Dan Apl.*, **5** 112–118 (2020). doi:10.20961/prosidingsnfa.v5i0.46591.
6) S. Sawant, R.M.R. Ahsan Shah, M. Rahman, A.R. Abd Aziz, S. Smith, and A. Jumahat, "System modelling of an electric two-wheeled vehicle for energy management optimization study," *Evergreen*, **8** (*3*) 642–650 (2021). doi:10.5109/4491656.
7) A. Joseph Godfrey, and V. Sankaranarayanan, "A new electric braking system with energy regeneration for a bldc motor driven electric vehicle," *Eng. Sci. Technol. an Int. J.*, **21** (*4*) 704–713 (2018). doi:10.1016/j.jestch.2018.05.003.
8) H. Koide, T. Seiichi, K. Tamura, W. Jung, H. Nakayama, S. Matsuda, and K. Moroga, "Possibility of cooperation for a low carbon society:comparison of the fukuoka and busan metropolitan cities," *J. Nov. Carbon Resour. Sci.*, **2** 21–35 (2010).
9) Syafrudin, M.A. Budihardjo, N. Yuliastuti, and B.S. Ramadan, "Assessment of greenhouse gases emission from integrated solid waste management in semarang city, central java, indonesia," *Evergreen*, **8** (*1*) 23–35 (2021). doi:10.5109/4372257.
10) R. Nisha, and K. Gnana Sheela, "Review of pv fed water pumping systems using bldc motor," *Mater. Today Proc.*, **24** 1874–1881 (2019). doi:10.1016/j.matpr.2020.03.612.
11) M. Bansal, A. Agarwal, M. Pant, and H. Kumar, "Challenges and opportunities in energy transformation during covid-19," *Evergreen*, **8** (*2*) 255–261 (2021). doi:10.5109/4480701.
12) F. Sumasto, F. Imansuri, M. Agus, Safril, and M. Wirandi, "Sustainable development impact of implementing electric taxis in jakarta: a cost-benefit analysis," *IOP Conf. Ser. Mater. Sci. Eng.*, **885** 012027 (2020). doi:10.1088/1757-899x/885/1/012027.
13) Safril, T.A. Gunawan, A.I. Ramadhan, Sukarman, I.B. Rahardja, and Khoirudin, "Design and simulation analysis on airless tires to off-road vehicles," *J. Crit. Rev.*, **7** (*13*) 938–945 (2020). doi:10.31838/jcr.07.13.158.
14) M. García, P. Ponce, L.A. Soriano, A. Molina, B. MacCleery, and D. Romero, "Lifetime improved in power electronics for bldc drives using fuzzy logic and pso," *IFAC-PapersOnLine*, **52** (*13*) 2372–2377 (2019). doi:10.1016/j.ifacol.2019.11.561.
15) K.S. Gowthaman, S. Palaniyappan, L.H.T. Raj, and A.T.S. Subramanian, "Temperature detection and control in multiple dc motors," *Mater. Today Proc.*, **45** (*xxxx*) 2202–2206 (2021). doi:10.1016/j.matpr.2020.10.114.

16) M. Khelifa, M. Mordjaoui, and A. Medoued, "An inverse problem methodology for design and optimization of an interior permanent magnetic bldc motor," *Int. J. Hydrogen Energy*, **42** (*28*) 17733–17740 (2017). doi:10.1016/j.ijhydene.2017.02.017.
17) M.M. Kamal, L. Mathew, and S. Chatterji, "Speed control of brushless dc motor using intelligent controllers," *SCES 2014 Inspiring Eng. Syst. Glob. Sustain.*, **119** (*16*) 3955–3961 (2014). doi:10.1109/SCES.2014.6880121.
18) Đ. Lekić, and S. Vukosavić, "Split ratio optimization of high torque density pm bldc machines considering copper loss density limitation and stator slot leakage," *Int. J. Electr. Power Energy Syst.*, **100** (*February*) 231–239 (2018). doi:10.1016/j.ijepes.2018.02.029.
19) M.F. Azizi, G.D. Kalandro, and H. Widyono, "Rancang bangun motor bldc axial flux menggunakan dua kawat email pada lilitan kumparan stator," *J. Arus Elektro Indones.*, 52–57 (n.d.).
20) M.A. Faisol, G. Kiswanto, and R.A.S. Danardono, "Rancangan sistem traksi motor bldc (brushless direct current) pada sistem konversi kendaraan hibrid bahan bakar bakar gas (bbg)-listrik dtm ui," 1–20 (2013).
21) K. Alameh, G. Hoblos, and G. Barakat, "Statistical vibration-based fault diagnosis approach applied to brushless dc motors," *IFAC-PapersOnLine*, **51** (*24*) 338–345 (2018). doi:10.1016/j.ifacol.2018.09.599.
22) M. Wirandi, Safril, F. Sumasto, M. Agus, and F. Imansuri, "BLDC motor design by applying the control of direct current and analysis of loading mechanism soft starting," *IOP Conf. Ser. Mater. Sci. Eng.*, **885** 012005 (2020). doi:10.1088/1757-899x/885/1/012005.
23) R. Salehi Arashloo, M. Salehifar, L. Romeral, and V. Sala, "A robust predictive current controller for healthy and open-circuit faulty conditions of five-phase bldc drives applicable for wind generators and electric vehicles," *Energy Convers. Manag.*, **92** 437–447 (2015). doi:10.1016/j.enconman.2014.12.075.
24) H. Wang, "Design and implementation of brushless dc motor drive and control system," *Procedia Eng.*, **29** 2219–2224 (2012). doi:10.1016/j.proeng.2012.01.291.
25) R. Gambhir, and A.K. Jha, "Brushless dc motor : construction and applications," *Int. J. Eng. Sci.*, **2** (*5*) 72–77 (2013).
26) M. Arun Noyal Doss, V. Kalyanasundaram, V. Ganapathy, and K. Karthik, "A cost effective speed control method for bldc motor drive," *Int. J. Control Theory Appl.*, **9** (*Specialissue33*) 1–10 (2016).
27) I. Garniwa, B. Dipantara, M. V. Nugroho, B. Sudiarto, and N. Noorfatima, "Analysis of the effect of the motor temperature to brushless direct current motor performance on karling electric vehicle," *J. Phys. Conf. Ser.*, **1376** (*1*) (2019). doi:10.1088/1742-6596/1376/1/012024.
28) Z. Fu, J. Liu, and Z. Xing, "Performance analysis of dual-redundancy brushless dc motor," *Energy Reports*, **6** 829–833 (2020). doi:10.1016/j.egyr.2020.11.125.
29) C. Abeykoon, "Compact heat exchangers – design and optimization with cfd," *Int. J. Heat Mass Transf.*, **146** 118766 (2020). doi:10.1016/j.ijheatmasstransfer.2019.118766.
30) Y. Aiman, M. Firdaus, M.N. Musa, and S. Syahrullail, "The effectiveness of jet impingement cooling system on various flat plate surface," *Evergreen*, **8** (*1*) 187–192 (2021). doi:10.5109/4372277.
31) N. Hasbullah, F. Al Zahrah Mohd Saat, F.S. Anuar, D. Johari, and M.F. Sukri, "Temperature and velocity changes across tube banks in one-directional and bi-directional flow conditions," *Evergreen*, **8** (*2*) 428–437 (2021). doi:10.5109/4480725.
32) E.S. Sehgal, E.T. Kaul, and E.A. Malik, "Performance of bldc motor using simulink for torque and speed analysis," *Int. J. Engeneering Technol.*, **2** (*7*) 819–822 (2013).
33) S.M. Ali, and A. Chakraborty, "Performance study of adsorption cooling cycle for automotive air-conditioning," *Evergreen*, **2** (*1*) 12–22 (2015). doi:10.5109/1500423.
34) F. Jerai, T. Miyazaki, B.B. Saha, and S. Koyama, "Overview of adsorption cooling system based on activated carbon - alcohol pair," *Evergreen*, **2** (*1*) 30–40 (2015). doi:10.5109/1500425.
35) J. Kuria, and P. Hwang, "Investigation of thermal performance of electric vehicle bldc motor," *Int. J. Mech. Eng.*, **1** (*1*) 2277–7059 (2012).
36) N.R. Arsya, H. Suryoatmojo, and S. Anam, "Desain kontrol kecepatan motor brushless dc berbasis power factor correction (pfc) menggunakan single ended primary inductance converter (sepic)," *J. Tek. ITS Vol.*, **5** (*2*) (2016).
37) J. Hur, B.K. Lee, C.Y. Won, and B.H. Lee, "Development of high-efficiency 42v cooling fan motor for hybrid electric vehicle applications," *2006 IEEE Veh. Power Propuls. Conf. VPPC 2006*, 3–8 (2006). doi:10.1109/VPPC.2006.364307.
38) D.T. Vu, and P. Hwang, "New cooling system design of bldc motor for electric vehicle using computation fluid dynamics modeling," *J. Korean Soc. Tribol. Lubr. Eng.*, **29** (*5*) 318–323 (2013). doi:10.9725/kstle.2013.29.5.318.
39) N. Paine, and L. Sentis, "Design and comparative analysis of a retrofitted liquid cooling system for high-power actuators," *Actuators*, **4** (*3*) 182–202 (2015). doi:10.3390/act4030182.
40) Z.A. Abdul Karim, and A.H. Mohd Yusoff, "Cooling system for electric motor of an electric vehicle propulsion," *Adv. Mater. Res.*, **903** 209–214 (2014). doi:10.4028/www.scientific.net/AMR.903.209.
41) R.B. Permana, "Simulasi pengaruh pendinginan udara, fluida cair, dan kombinasi pendinginan udara-

fluida cair pada motor bldc 10 kwliquid coolingmenggunakan aplikasi solidsworks flow simulation," 2016.

42) C. Li, and K. Ito, "Performance evaluation of wind decontamination system by computational fluid dynamics," *Evergreen*, **1** (*2*) 12–17 (2014). doi:10.5109/1495158.

43) A. Mukhlisin, Prabowo, and M.N. Yuniarto, "Study numerical and experimental a cooling of axial brushless direct current (bldc) motor for electric scooter," *AIP Conf. Proc.*, **1983** (2018). doi:10.1063/1.5046231.

44) M. Koren, Z. Petró, V. Szente, J. Dorogi, and G.G. Balázs, "Development of air-cooling concepts for electric motor used in electric aircrafts," *Conf. Model. Fluid Flow (CMFF '18)*, (2018).

45) J. Huang, S. Shoai Naini, R. Miller, D. Rizzo, K. Sebeck, S. Shurin, and J. Wagner, "A hybrid electric vehicle motor cooling system-design, model, and control," *IEEE Trans. Veh. Technol.*, **68** (*5*) 4467–4478 (2019). doi:10.1109/TVT.2019.2902135.

46) F. Guo, and C. Zhang, "Oil-cooling method of the permanent magnet synchronous motor for electric vehicle," *Energies*, **14** (*15*) 1–11 (2019). doi:10.3390/en12152984.

47) Y. Uta Nugraha, A. Cahyadi, J. Raharjo, M. Nur Yuniarto, and A. Wikarta, "Design and performance analysis of brushless dc motor cooling system for low-cost manufacturing process," *IOP Conf. Ser. Mater. Sci. Eng.*, **694** (*1*) 0–7 (2019). doi:10.1088/1757-899X/694/1/012007.

48) K. Tarsisius, Marsono, and S. Sayuti, "Liquid cooling model of axial bldc motor," *J. Multidiscip. Eng. Sci. Stud.*, **6** (*11*) 3569–3573 (2020). http://jmess.org/.

49) J. Choi, J.H. Lee, Y.G. Jung, and H. Park, "Enhanced efficiency of the brushless direct current motor by introducing air flow for cooling," *Heat Mass Transf. Und Stoffuebertragung*, **56** (*6*) 1825–1831 (2020). doi:10.1007/s00231-020-02827-8.

50) K. Uddin, I.I. El-Sharkawy, T. Miyazaki, B.B. Saha, and S. Koyama, "Thermodynamic analysis of adsorption cooling cycle using ethanol-surface treated maxsorb iii pairs," *Evergreen*, **1** (*1*) 25–31 (2014). doi:10.5109/1440973.

51) S. Supriadi, N. Putra, B. Ariantara, and I. Indhiarto, "Fabrication of a lotus-type porous material to be applied in heat pipe wick," *Evergreen*, **8** (*4*) 855–860 (2021). doi:10.5109/4742132.

52) Husaini & Zuhaimi, "Perilaku retak aluminium paduan a6061-t6 pada pembebanan mixed mode," *J. Tek. Mesin*, **8** (*1*) 26–32 (2006). doi:10.9744/jtm.8.1.pp.26-32.

53) M. Nayak, H.N. Manjunath, and M. Madhusudhan, "Performance studies on automated solar powered air cooler/ air heater," *Int. J. Sci. Technol. Res.*, **9** (*1*) 3480–3483 (2020).