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Thermal Mapping and Heat Transfer Analysis of an Induction Motor of an Electric Vehicle Using Nanofluids as a Cooling Medium

Gaurav Kumar Pandey [1], Siddharth Sriram Sikha [1], Abhineet Thakur [1], Sai Sravan Yarlagadda [1], Sai Santosh Thatikonda [1], Bibin Baiju suja [1], Arkadiusz Mystkowski [2,*], Egidijus Dragašius [3] and Edison Gundabattini [4,*]

1 School of Mechanical Engineering, Vellore Institute of Technology (VIT), Vellore 632 014, India; abhineet.thakur2019@vitstudent.ac.in (A.T.); yarlagaddasai.sravan2019@vitstudent.ac.in (S.S.Y.); saisantosh.thatikonda2019@vitstudent.ac.in (S.S.T.); bibin.bs@vit.ac.in (B.B.s.)
2 Faculty of Electrical Engineering, Bialystok University of Technology, Wiejska 45D, 15351 Bialystok, Poland
3 Faculty of Mechanical Engineering and Design, Kaunas University of Technology, Studentų Str. 56–326, 44249 Kaunas, Lithuania; egidijus.dragasius@ktu.lt
4 Department of Thermal and Energy Engineering, School of Mechanical Engineering, Vellore Institute of Technology (VIT), Vellore 632 014, India
* Correspondence: a.mystkowski@pb.edu.pl (A.M.); edison.g@vit.ac.in (E.G.)

Abstract: The driving motor is one of the most crucial components of an electric vehicle (EV). The most commonly used type of motor in EVs is the induction motor. These motors generate heat during operation due to the flow of electrical current through the motor's coils, as well as friction and other factors. For long-run and high efficiency of the motor, cooling becomes more important. This article utilized ANSYS Motor-CAD to map the temperature signature of an induction motor and investigated the thermal efficiency of using nanofluids as a cooling medium. The thermal conductivity of nanofluids has been found to be superior to that of more conventional cooling fluids such as air and water. This research explores the effect of using Al_2O_3, ZnO, and CuO concentrations in nanofluids (water as a base fluid) on the thermal efficacy and performance of motor. According to the findings, using nanofluids may considerably increase the efficiency of the motor, thereby lowering temperature rise and boosting system effectiveness. Based on the simulation analysis using ANSYS Motor-CAD, the results demonstrate that the utilization of CuO nanofluid as a cooling medium in the induction motor led to a reduction of 10% in the temperature of the motor housing. The maximum reduction in the temperature was found up to 10% when nanofluids were used, which confirms CuO as an excellent option of nanofluids for use as motor cooling and other applications where effective heat transmission is crucial.

Keywords: high temperature; nanofluid; electric vehicle; thermal efficacy; heat transfer; overheating; thermal mapping

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1. Introduction

The popularity of electric vehicles around the globe is increasing gradually. Electric vehicles help in reducing carbon footprints as they are less polluting than the conventional petrol or diesel-operated vehicles. Electric vehicles also help in reducing our dependence on exhausting fossil fuels. EVs operate at an efficiency of about 60% which is much greater than the petrol or diesel cars which have an efficiency between 17% and 21%.

1.1. Induction Motor in Context of Electric Vehicle

Induction motors are the devices that convert electrical energy into mechanical energy. Induction motors offer wider torque range and accurate speed control, provide recharging of battery during breaking, require low maintenance, and have high efficiency [1]. They are also smaller in size when compared with permanent magnet DC (Direct Current) motors and are less expensive, Figure 1.

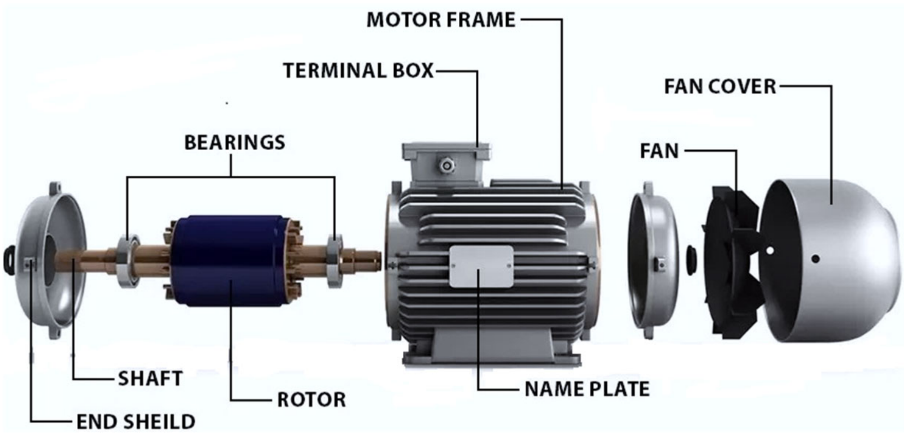

Figure 1. Front view of a typical AC Induction motor [2].

1.2. Hot Spots in Induction Motor Heat Generation

One of the main challenges faced by induction motors is thermal management. The induction motors utilized in cars require high load capacity. When these motors operate at higher speeds, they generate heat which results in an increase in losses such as copper and iron loss, thereby increasing the temperature in the rotor and stator of the motor [1]. With the increase in temperature, various parts of the induction motor could experience phase change, softening, melting, and other forms of degradation that will affect the performance of the motor. Increases in motor temperature also result in the development of thermal stress in various parts of the motor that results in cracking, material deformation, and fatigue failure. Hence, the performance and life span of the induction motor are dependent on its thermal conditions. The induction motor's temperature rises as a result of heat sources such as stator's iron losses, mechanical and windage loss, and winding joule loss [3,4]. Currently, induction motors are cooled using techniques such as air cooling, water cooling, and air–water cooling. However, these methods become less efficient with the use of improved technologies in induction motors. The heat produced inside the motor is transferred through the finned outer surface of the motor [5]. The objective of this paper is to investigate more efficient methods for cooling induction motors.

1.3. Cooling of an Induction Motor

Cooling is required in an induction motor to prevent the motor from overheating and potentially causing damage or failure. Overheating could lead to motor failure, reduced efficiency, and decreased lifespan [6]. A few methods adopted for motor cooling include air cooling, liquid cooling, and forced convection cooling. Induction motors generate heat during operation due to the flow of electrical current through the motor's coils, as well as friction and other factors.

If the motor becomes too hot, the insulation around the motor's wires could begin to break down, leading to electrical shorts and potential damage to the motor's internal components, Figure 2. Additionally, it is well known that an electric motor could suffer damage from high temperatures as high temperatures could cause the motor's bearings and other moving parts to expand, which could lead to mechanical failure [7].

The rotor, stator, shaft, housing water jacket, front-end cap, and back-end cap make up the motor. Cooling helps to dissipate the heat produced by the motor, thereby preventing it from reaching damaging temperatures. There are numerous ways to cool an induction motor, including air cooling, liquid cooling, and even passive cooling methods such as natural convection. In terms of cost and cooling uniformity, air cooling is preferable to other techniques; nonetheless, it performs the least well of the three traditional cooling techniques. In the liquid cooling scheme, as the oil flows in, the housing jacket immediately cools the heat source. Hence, liquid/oil cooling is most preferred and has the best cooling performance [8–10]. Thus, by managing the motor's temperature, cooling helps to ensure that the motor operates safely and efficiently, with minimal risk of damage or failure.

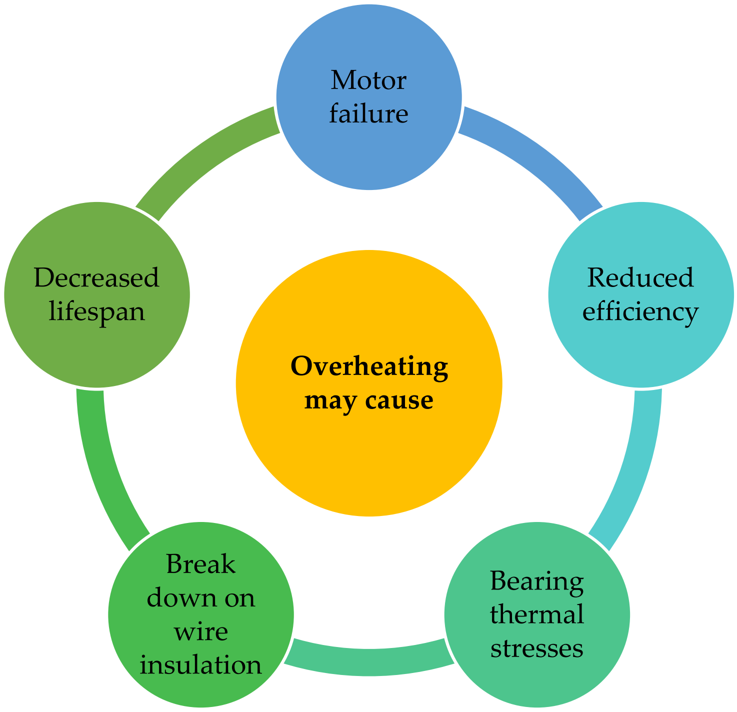

Figure 2. High temperature effect on motor parts.

There are also several factors that could affect motor cooling, including motor size, operating temperature, and the environment in which the motor is used. Designers must carefully consider these factors when selecting a cooling method for their motor [11].

1.4. Cooling Schemes

Induction motors could be cooled using various methods, each with its own set of benefits and drawbacks. The most widely used technique for cooling motors is air cooling, which involves circulating air around the motor to dissipate heat. This can be accomplished through natural convection, where heat rises and is replaced by cooler air, or forced convection, where a fan or blower is used to move air across the motor. Air-cooled motors are often less expensive and simpler to maintain than liquid-cooled motors but may be less effective in high-temperature environments [12].

Liquid cooling involves the circulation of a liquid coolant around the motor to absorb and dissipate heat. This method is typically more efficient than air cooling and is often used in high-performance applications or where space is limited [13]. However, liquid cooling systems could be more complex and require additional components such as pumps, radiators, and hoses.

Forced convection cooling involves the use of a fan or blower to circulate air around the motor at a higher velocity than natural convection. This method could be used with both air-cooled and liquid-cooled motors to increase cooling efficiency.

1.5. Nanofluids as a Coolant

The term "nanofluid" used to describe the new sort of heat dissipating fluids based on nanotechnology that have thermal features that are better in comparison to their parent fluids or traditional particle fluid suspensions [14]. In recent times, the utilization of nanofluid as a working fluid has gained popularity in enhancing equipment performance. Researchers have successfully employed nanoparticles in cooling systems due to their superior heat transfer and thermophysical properties. The study and examination of materials at a size of up to 100 nm is known as nanotechnology. Base fluids, such as water or oil, are combined with 0.05–1% concentrations or more of nanoparticles ranging in size from 10 to 100 nm.

The ability of nanofluid to conduct and convent heat is proven to have an improved heat transfer coefficient. Metallic nanofluids are frequently utilised to attain higher thermophysical characteristics—for example, viscosity, thermal diffusivity, thermal conductivity, specific heat capacity, and heat transfer coefficients. They have all the aforementioned qualities, which are superior to those of water and oil, which are regarded as base fluids [14]. Nanofluids are colloidal fluids made up of chemically stable nanoparticles that are mixed in a fluid (such as water, refrigerant, or aqueous solutions,) having 0.01% to 10% concentrations (by volume). The most often used and researched nanoparticles include metals (Au, Cu, Fe, Ag, Ti, and others) and elemental oxides (CuO, Al_2O_3, ZrO_2, FeO, SiO_2, TiO_2, and others).

In a nutshell, a 'nanofluid' is a fluid that contains suspended nanoparticles with a size typically less than 100 nm. These fluids have unique thermal properties and are being considered as potential coolants for various applications. According to studies, nanofluids have a greater thermal conductivity than conventional coolants, which could increase cooling effectiveness. The stability of these fluids and their tendency to clog or damage coolant systems are some of their potential concerns. Moreover, nanofluids may be more expensive to produce and use as coolants than conventional coolants, which may restrict their applicability [15].

Even though nanofluids could have certain benefits as coolants, further study and research are required to completely understand their characteristics and possible advantages in diverse cooling applications. This article mainly focuses on the thermal mapping and heat transfer analysis of induction motors used in electric vehicles. This paper also implements the technique for cooling the motor by nanofluids and investigates the thermal performance. The simulation study is performed using ANSYS Motor-CAD. The thermal efficiency of nanofluids with Al_2O_3, ZnO, and CuO is investigated.

2. Methodology of Analysis

2.1. Nanofluids Materials

In this analysis, water is the base fluid, and Al_2O_3, ZnO, and CuO are the nanoparticles. The volume concentration of the nanoparticles used for this study is 10%, and the temperature varies from 0 to 60 °C. The Table 1 tabulates the characteristics of nanoparticles.

Table 1. Properties of nanoparticle used.

Property	Al_2O_3	ZnO	CuO
Molecular weight (g/mol)	101.96	81.38	79.545
Size (mm)	35–45	30–40	30–50
Thermal conductivity (W/m.K)	40	49	32.9
Density (kg/m^3)	1293.139	1462.139	1527.139
Heat capacity (J/kg·K)	3739.68	3712.58	4035.18
Viscosity (kg/m.s)	2.52519×10^{-10}	1.7712×10^{-10}	1.58875×10^{-10}

2.2. Theoretical Analysis of Thermophysical Properties of Nanofluids

The thermophysical properties of nanofluids utilized in this analysis are initially investigated by theoretical model. The thermal conductivity, density, viscosity, and heat capacity are evaluated by following models.

The thermal conductivity of the nanofluids is evaluated by the Hamilton and Crosser Model [16], which is given by

$$k_{nf} = \left[\frac{k_p + (n-1)k_{bf} - (n-1)\varphi\left(k_{bf} - k_p\right)}{k_p + (n-1)k_{bf} + \varphi(k_{bf} - k_p)}\right]k_{bf} \tag{1}$$

Pak and Cho's model [17] is used to identify the density and heat capacity of the fluids.

$$\rho_{nf} = (1-\varphi)\rho_{bf} + \varphi\rho_p \tag{2}$$

$$c_{p_{nf}} = (1-\varphi)c_{p_{bf}} + \varphi c_{p_p} \tag{3}$$

The viscosity of the nanofluids is determined by Einstein's formula [18]:

$$\frac{\mu_{nf}}{\mu_{bf}} = 1 + 2.5\varphi \tag{4}$$

2.3. Numerical Analysis

2.3.1. Physics and Equations

In a single-phase induction motor heat transfer network analysis, the basic principles of heat transfer are the following:

Conductive heat transfer: The heat conduction equation, a partial differential equation, illustrates the temporal movement of heat energy in the motor. Conduction is how heat is transferred through solid objects such as the stator and rotor, and it may be stated as follows [19]:

$$\rho c\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda x\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda y\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda z\frac{\partial T}{\partial z}\right) + Q \tag{5}$$

The left-hand side of the equation represents the rate of change of thermal energy in the material, which in this case is the motor. On the right-hand side, the movement of heat energy caused by conduction is depicted, where heat flows from hotter regions to cooler ones. Fourier's law is used to relate the heat flow and the temperature gradient. The heat flux q is given by [20].

$$q = -\lambda\frac{\partial T}{\partial x} \tag{6}$$

Conductive heat transfer: Fluid motion is used to transfer heat from one location to another. Convection's equation may be written as follows [20]:

$$q = \alpha.As(T_w - T_\infty) \tag{7}$$

The formula describes the rate of heat transfer between a solid surface and a moving fluid (such as water or nanofluid) due to convection. It is derived from Newton's law of cooling, which states that the coefficient of convective heat transfer and the temperature difference between the solid surface and the moving fluid determine the rate at which heat is transferred between them [21].

Radiation is not taken into consideration in the thermal assessment of a single-phase induction motor; only conduction and convection are taken into account.

2.3.2. Simulation Procedure

The process of conducting the simulations and analysis of this work is shown in Figure 3.

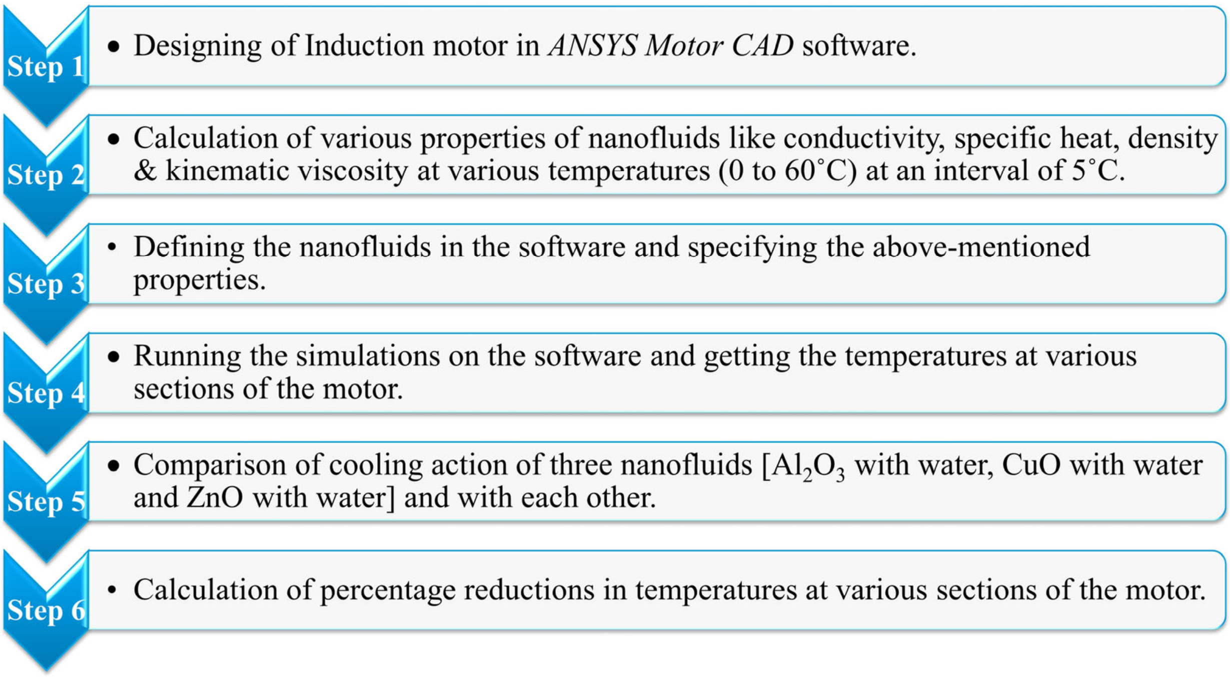

Figure 3. Flow chart of conducting the simulations and analysis.

2.3.3. Boundary Condition and Input Parameter

Tables 2–5 show motor condition, specifications of the single-phase induction motor, input parameters for thermal analysis on ANSYS, and fluid properties, respectively.

Table 2. Induction motor condition.

Section/Part of the Motor	Specific Part	Dimensions (mm)
Radial dimensions	Housing diameter	140
	Diameter of the stator lamination	130
	Diameter of the shaft	50
	Height of the shaft	95
Axial dimensions	Motor length	240
	Length of the stator lamination	50
	Length of the rotor lamination	90
	Base length	350
Stator parameters	Housing diameter	140
	Tooth width	71
Rotor parameters	Width of the rotor tooth	4
	Diameter of the Shaft	50

Table 3. Specifications of the single-phase induction motor.

Parameters	Values
Output rated power	373 W (0.5 HP)
Voltage (rated)	230V
Speed (rated)	1430 rpm
Frequency	50 Hz

Additional motor specifications: Motor type—Split capacitor (Permanent); Insulation type—Class F; Encloser Type—DPFC (Distributed Power Flow Controller; Number of Poles: 4; Number of Stator slots: 24; Number of rotor bars: 26).

Table 4. Input parameters for thermal analysis on ANSYS Motor-CAD.

Input Parameter	Input Data
Housing	Water jacket (axial)
Housing material	Aluminium (alloy 195 cast), thermal conductivity—168 W/m/C, specific heat—833 J/kg/C
Calculation type	Steady-state thermal analysis
Input power	750 W
Shaft speed	2880 rpm

Table 5. Fluid properties.

Input Parameter	Input Data
Fluid volume flow rate	1 L/min
Inlet temperature	30 °C
Parallel flow paths	1

2.3.4. Geometrical Model

The radial and axial views of the induction motor are shown in Figures 4 and 5. The geometrical model is modelled by ANSYS Motor-CAD (version: 15.1.2.1).

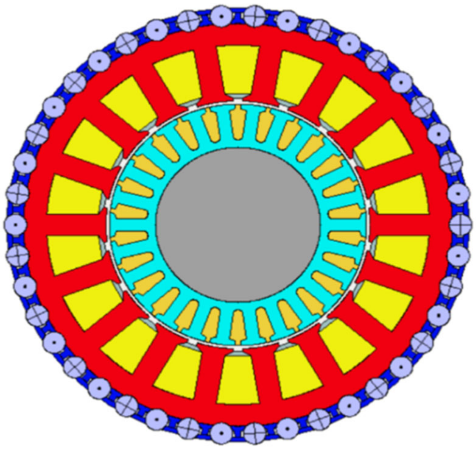

Figure 4. Radial view of analysed motor.

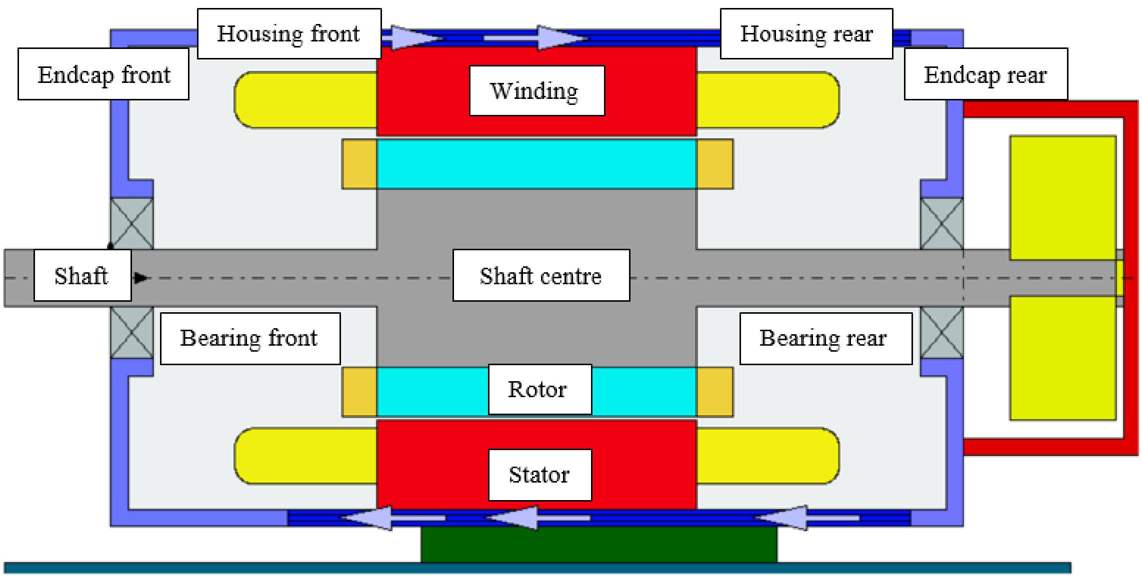

Figure 5. Axial view of analysed motor.

A specified fluid was selected as a first step from the Motor-CAD 'material database' followed by the designing of the induction motor using ANSYS Motor-CAD (version: 15.1.2.1).

2.4. Cooling Circuit Configuration

There are multiple ways that the induction motor could be cooled based on the thermal management system chosen for the motor, and the configuration of the cooling system could be very important for the proper dissipation of the heat. An air-cooled induction motor chosen in this research has radial fins which increase the surface area available for contact between the heated surface of the motor and the coolant medium, i.e., air in this case.

Compared to air cooling, liquid cooling is considered to be a much more effective technique for dissipating heat due to the use of coolants with superior thermal properties. In this case, nanofluid is used as the coolant, which needs to be circulated through the surface of the motor to absorb the heat being generated. For liquid cooling techniques, there are many configurations available, where coolant is made to pass through various sections of the motors.

In this case, a housing water jacket configuration is employed, where the coolant is circulated through various ducts in the outer surface of the motor. In the current design, 42 channels are integrated in the motor through which the coolant shall be moved and pass through using a pump [22]. Thermal analysis is performed in order to efficiently dispel heat out of the motor, minimizing the possibility of overheating (within the safe limits of operation) and increasing the motor's lifespan [23,24]. Since it is known that heat transfer takes place by conduction and convection inside the motor, heat transfer by conduction is given by a second order differential equation, and heat transfer by convection is governed by Newton's law of cooling [25].

3. Results and Discussion

3.1. Thermophysical Characteristics

These thermophysical characteristics principally depend on the parameters of the solid particles as well as the base fluid (water), specifically the volume fraction of nanoparticles in suspension and particle shape. The aforementioned relationships could be utilised to estimate the characteristics of nanofluids.

The concentration of nanoparticles, as well as the characteristics of the base fluid, all affect the density of nanofluids. In general, when nanoparticles are added to a base fluid, the density of the nanofluid rises relative to the base fluid. Here, CuO in water shows the maximum density among the three nanofluids. At ambient temperature, there is an increase of 4.45% in density when CuO is compared to ZnO and an increase of 18.1% when CuO is compared to Al_2O_3. As the concentration of nanoparticles increases, the density of the nanofluid also increases. However, at very high concentrations, the agglomeration and settling of nanoparticles may cause the density of the nanofluid to plateau or even decrease.

As the concentration of nanoparticles in a nanofluid decreases, the particle–particle interactions increase, and the Brownian motion of particles decreases. This causes the kinematic viscosity of the nanofluid to increase. Nevertheless, the impact of nanoparticle concentration on kinematic viscosity is influenced by the base fluid's characteristics as well as aspects including form, size, and surface chemistry. The kinematic viscosity of nanofluids could also be influenced by temperature and shear rate. The kinematic viscosity of nanofluids reduces as the temperature rises as a result of the fluid's decreased viscosity. At ambient temperature, there is an increase of 42.94% in viscosity when Al_2O_3 is compared to ZnO and an increase of 59.1% when Al_2O_3 is compared to CuO. Here, Al_2O_3 in water shows the highest kinematic viscosity among the three nanofluids as it has the highest molecular mass, followed by ZnO nanofluid, and the least is shown by CuO nanofluid as it has the least molecular mass, Figures 6 and 7.

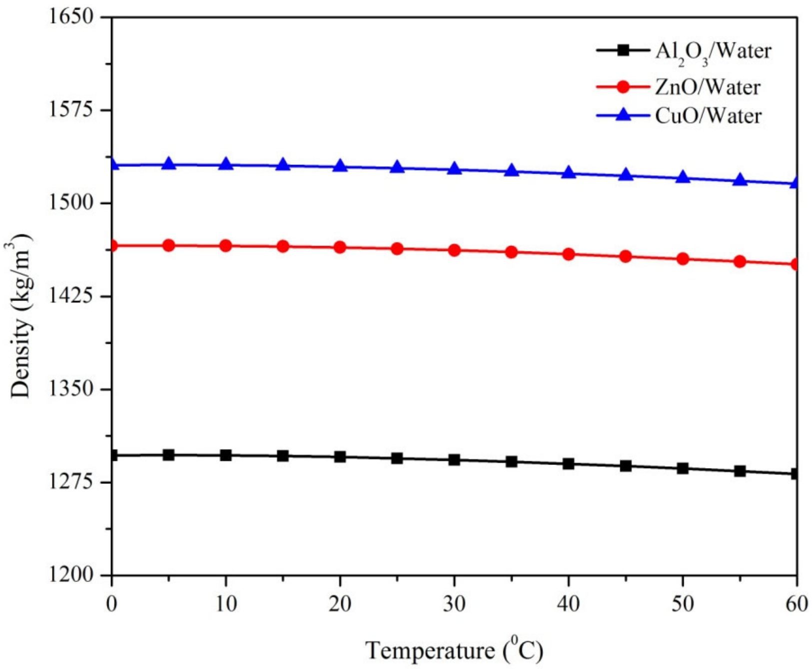

Figure 6. Comparing density of three different nanofluids.

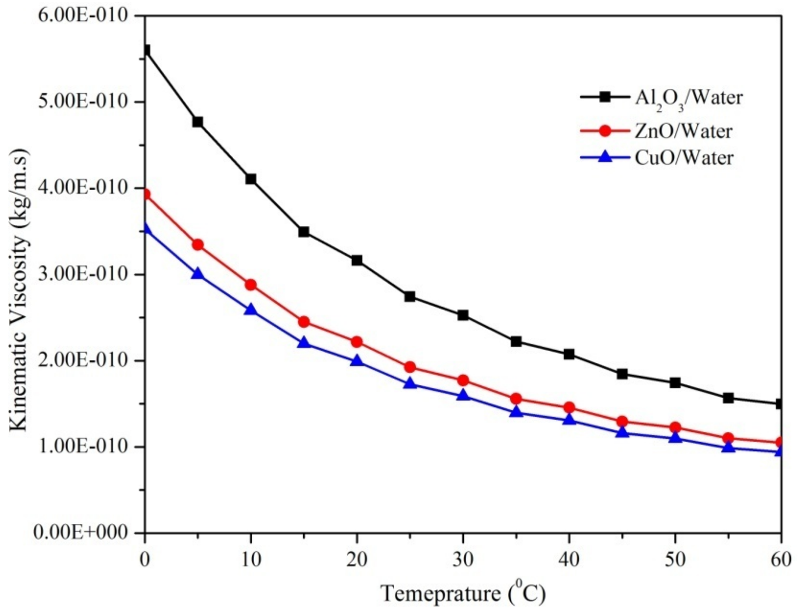

Figure 7. Comparing kinematic viscosity of three different nanofluids.

Nanofluids offer higher thermal conductivity than the fluids that are currently being used for motor cooling. The primary reason for this is the Brownian motion, which promotes the formation of nanoparticle clusters even at low concentrations. Among the three nanofluids investigated in the research, the thermal conductivity of the ZnO nanofluid is the highest, followed by Al_2O_3, while the CuO nanofluid exhibits the lowest thermal conductivity, shown in Figure 8. At ambient temperature, there is an increase of 22.5% in viscosity when ZnO is compared to Al_2O_3 and an increase of 48.94% when ZnO is compared to CuO. As the temperature of nanofluids increases, the intermolecular force of attraction between liquid molecules also increases. This causes the molecules of the liquid to move apart, leading to a decrease in the thermal conductivity of the nanofluid.

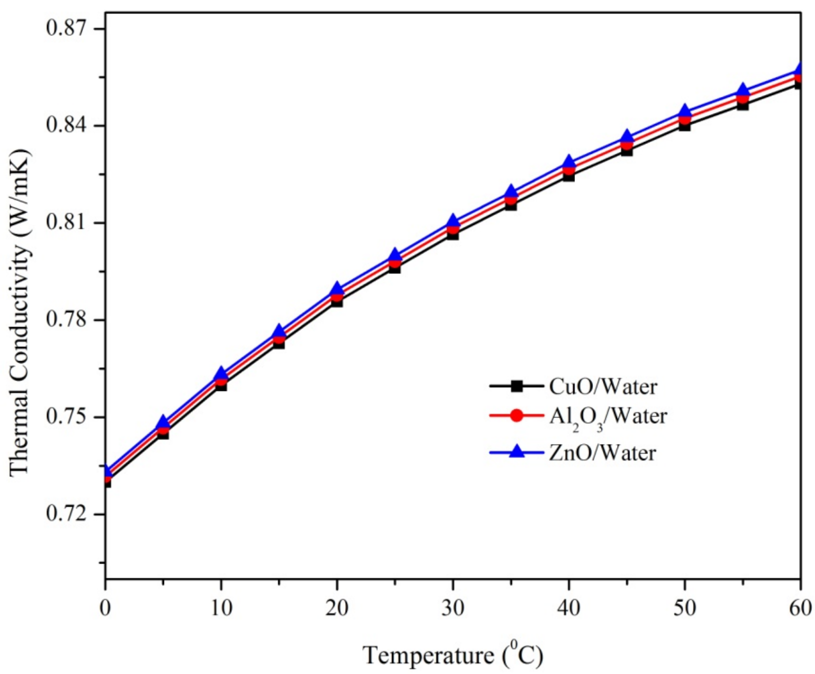

Figure 8. Comparing thermal conductivity of three different nanofluids.

The specific heat capacity of nanofluids could also vary depending on temperature and pressure. The specific heat capacity of nanofluids may change as the temperature increases, due to alterations in the thermophysical characteristics of the base fluid and nanoparticles. At ambient temperature, there is an increase of 7.9% in specific heat capacity when CuO is compared to Al_2O_3 and an increase of 8.67% when CuO is compared to ZnO. Out of the three nanofluids used for research, the specific heat capacity of CuO nanofluid is highest, followed by Al_2O_3, and the least is of ZnO. Additionally, due to the compression of the base fluid and nanoparticles under high pressures, nanofluids' specific heat capacities may be reduced, Figure 9.

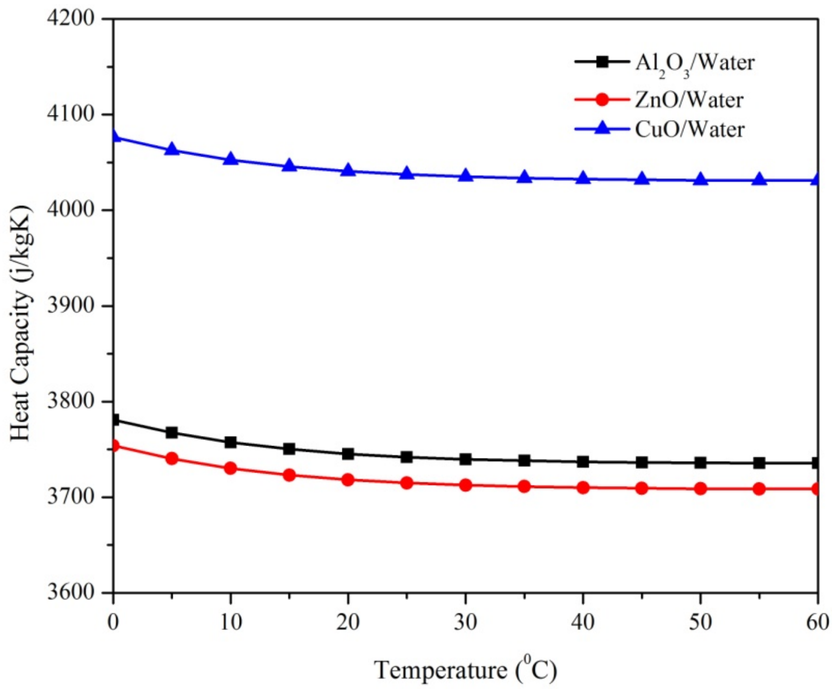

Figure 9. Comparing specific heat capacity of three different nanofluids.

3.2. Temperature Distribution

The temperature distribution over induction motor with water, CuO, ZnO, and Al_2O_3-based nanofluids is shown in Figures 10–13, respectively.

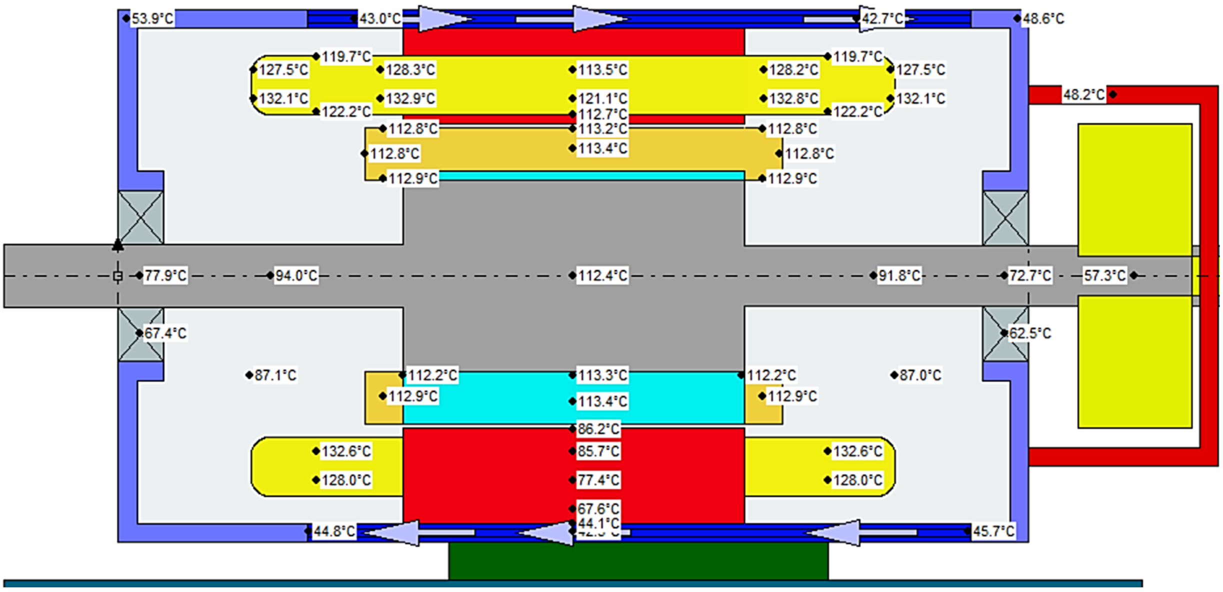

Figure 10. Temperature distribution at each section of the motor when water is used.

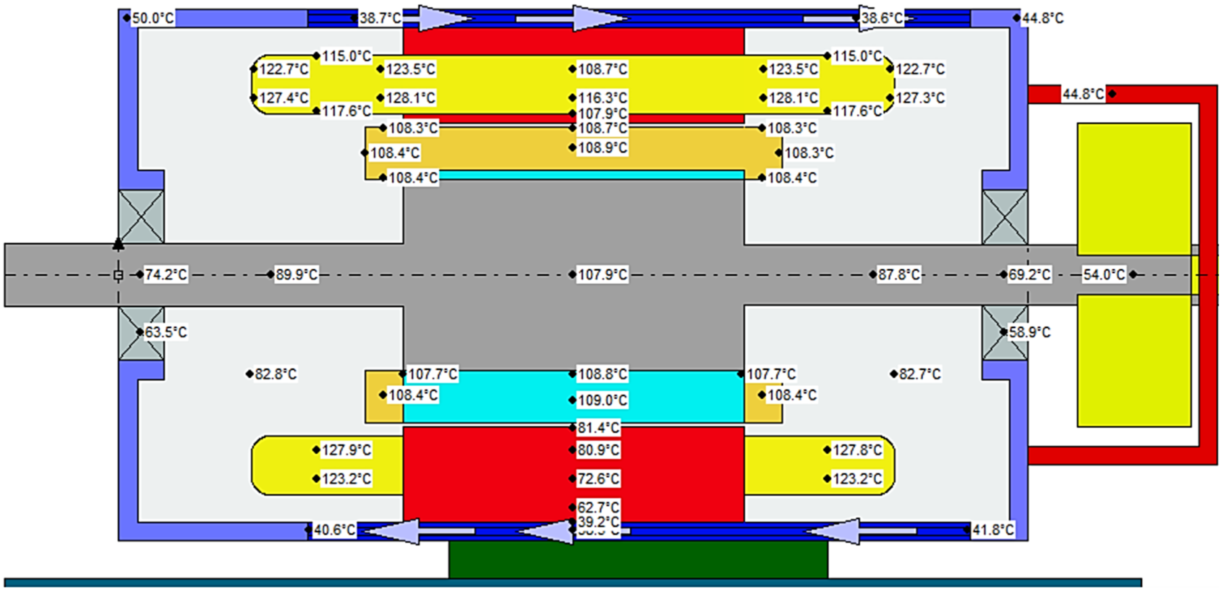

Figure 11. Temperature distribution at each section of the motor when CuO-based nanofluid is used.

The reductions of the temperatures throughout the motor when nanofluids are allowed to flow instead of water are listed. The temperature reductions at the major parts of the motor are then noted in Table 6. The usage of the CuO nanofluid results in a 10% decrease in the temperature of the motor's housing (front), according to the findings. Since it outperforms the currently used cooling schemes in the industry (such as air cooling or water cooling), the CuO-based nanofluid makes this technique a more effective one for cooling electric motors because it shows the maximum reduction when used as a coolant. The findings also demonstrate that the temperature of the motor components was significantly lowered as compared to the water-based cooling system with nanofluids, as seen in Table 6.

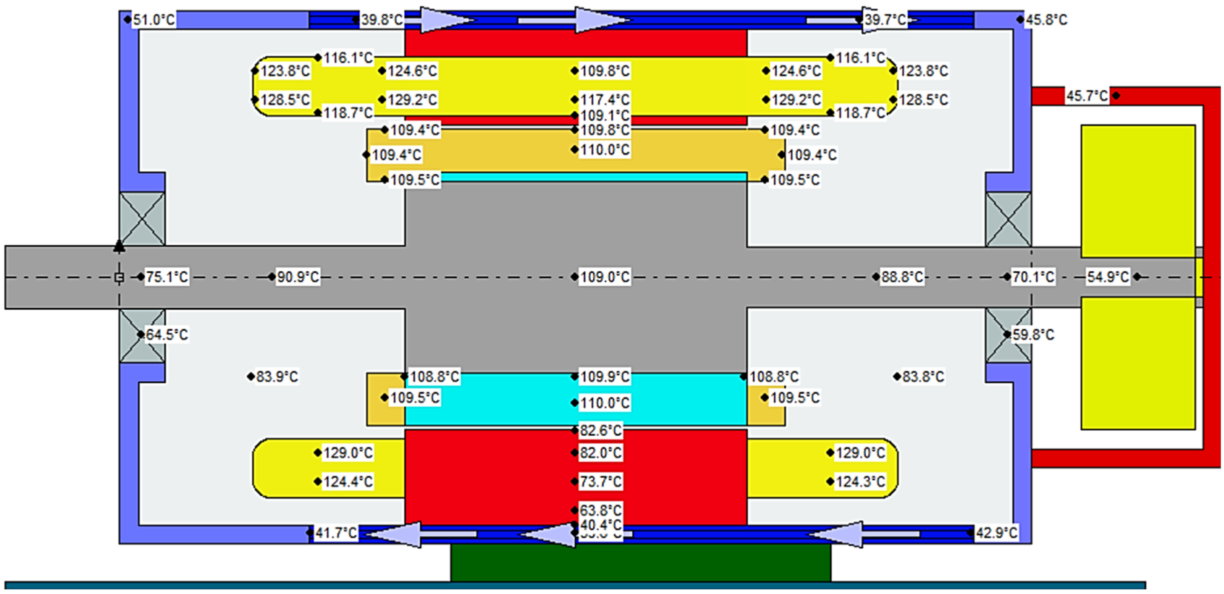

Figure 12. Temperature distribution at each section of the motor when ZnO-based nanofluid is used.

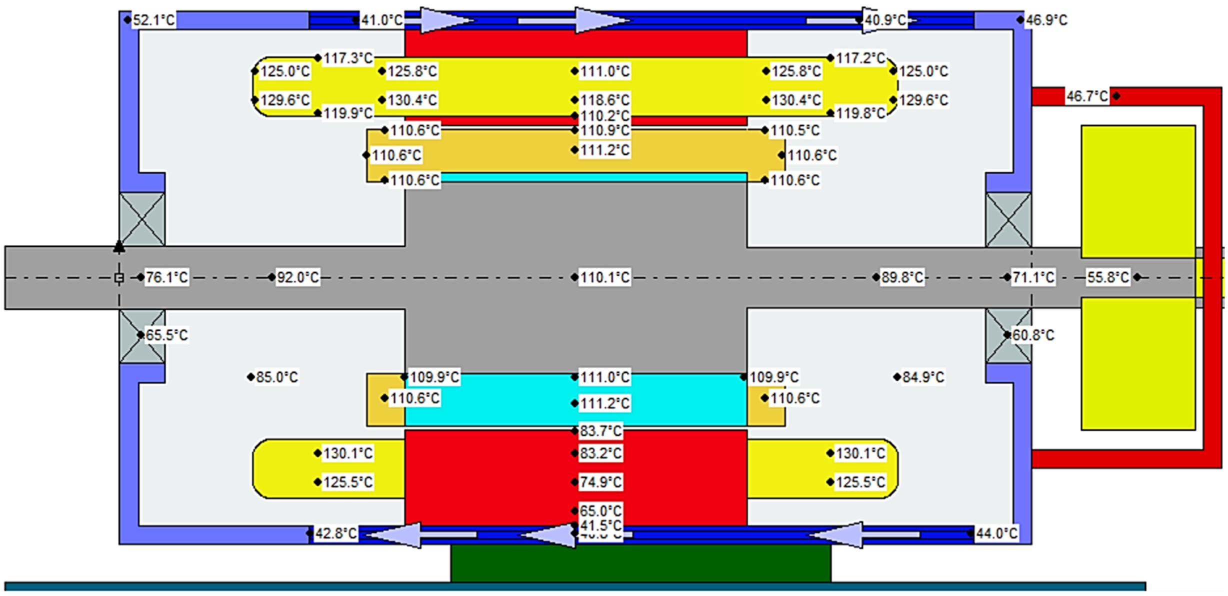

Figure 13. Temperature distribution at each section of the motor when Al_2O_3-based nanofluid is used.

Table 6. Percentage of reduction in temperature at various parts of the motor.

Parts	Temperature (°C)				Percentage of Reduction		
	Water	**Al_2O_3-*Based Nanofluid***	**CuO-*Based Nanofluid***	**ZnO-*Based Nanofluid***	**Al_2O_3-*Based Nanofluid***	**CuO-*Based Nanofluid***	**ZnO-*Based Nanofluid***
Endcap front	53.915	52.074	50.04	51.047	3%	7%	5%
Winding avg.	123.91	121.42	119.14	120.27	2%	4%	3%
Housing OH front	42.914	40.984	38.7	39.831	4%	10%	7%
Rotor bar avg.	113.4	111.16	108.94	110.04	2%	4%	3%
Shaft centre	112.4	110.1	107.9	109	2%	4%	3%
Shaft rear	72.715	71.06	69.244	70.142	2%	5%	4%
Shaft front	77.898	76.06	74.157	75.098	2%	5%	4%
Stator surface	86.2448	83.729	81.407	82.57	3%	6%	4%

Table 7 (comparison) indicates the percentage temperature drop when water is used as the cooling medium. The aforementioned findings have already been published in an investigation by Nikita et al. [21]. As a consequence, this comparison proves that the software ANSYS Motor-CAD's numerical technique approach produces findings that are acceptable.

Table 7. Comparison of temperature at motor parts using water cooling for different materials.

Parts	Temperature (°C)		Percentage Difference (in Temperature)
	PA6GF30 30% GPFR (Glass Fibre-Reinforced Polymer) [20]	Aluminium (Alloy 195 Cast)	
Shaft centre	104.5	112.4	7.23
Shaft rear	75.5	72.715	3.76
Shaft front	84.9	77.898	8.60
Stator surface	69.4	86.2448	21.65
Rotor bar avg.	105.2	113.4	7.50
Winding avg.	107.5	123.91	14.18

Table 7 shows percentage difference in temperature at the various parts of the induction motor in two different cases: first, when the material of the electric induction motor's casing is a suitable lightweight material, namely PA6GF30 30% GPFR (Glass Fiber-Reinforced Polymer) [21]; and secondly, when standard aluminium (alloy 195 cast) is chosen. Analysis also indicated that CuO-based nanofluid is more efficient compared to the Al_2O_3-based nanofluid and ZnO-based nanofluid. Additionally, the percentage of reduction of maximum and minimum temperatures in the electric motor are much better compared to water as coolant, Al_2O_3-based nanofluid, and ZnO-based nanofluid, as seen in Table 8.

Table 8. Percentage of reduction in ambient, maximum, and minimum temperature.

Area	Temperature (°C)				Percentage of Reduction		
	Water	Al_2O_3-*Based Nanofluid*	CuO-*Based Nanofluid*	ZnO-*Based Nanofluid*	Al_2O_3-*Based Nanofluid*	CuO-*Based Nanofluid*	ZnO-*Based Nanofluid*
Ambient	40	40	40	40	-	-	-
Maximum	132.9	130.4	128.1	129.2	2%	4%	3%
Minimum	42.5	40.8	38.5	39.6	4%	9%	7%

Nanofluids offer better thermal conductivity because they are nanoparticles suspended in a base fluid. Nanofluids are relatively stable and can be used for extended periods of time without significant deterioration. However, as a relatively recent innovation, the use of nanofluids in electrical cooling systems requires further research to fully understand their functionality and long-term implications. Nanofluids have demonstrated potential in a number of uses, including those using cooling fluid. Due to their distinctive characteristics, such as their high thermal conductivity (refer to Figure 8), nanofluids have the potential to be effective in heat transfer applications. Nanofluids provide a number of benefits over more conventional cooling fluids such as water or oil in the context of cooling. Their improved heat transfer capacity, which enables more effective cooling, is one of the key benefits. Effective temperature control systems greatly improve motor health and increase longevity. However, it could be challenging to control the cooling process. Traditional active techniques, on the other hand, typically result in the forced circulation and circulation of particular cooling materials and substances, including water and air. The fundamental problem is that, in some cases, the cooling impact might be relatively restricted [26]. Lower operating temperatures, less energy use, and better system performance could all be affected by this. Using the above simulations, it was noted that CuO nanofluid could significantly reduce motor temperatures at different sections.

Figure 14 illustrates the variation of temperature at different parts of the induction motor when water was allowed to flow through housing jacket. Due to its large heat capacity, excellent thermal conductivity, and capability to absorb heat as it vaporises, water makes a great coolant. Water is utilised as a cooling medium in induction motors to remove heat produced by the continuous operation of the motor. Most often, a cooling jacket which encloses the motor is circulated with water. Conduction is the process by which heat from the motor is transferred to the water, which is then pumped off from the induction motor and into a heat exchanger or cooling tower where the heat is released into the air or another medium. The cooling procedure is then repeated when the water is returned to the motor.

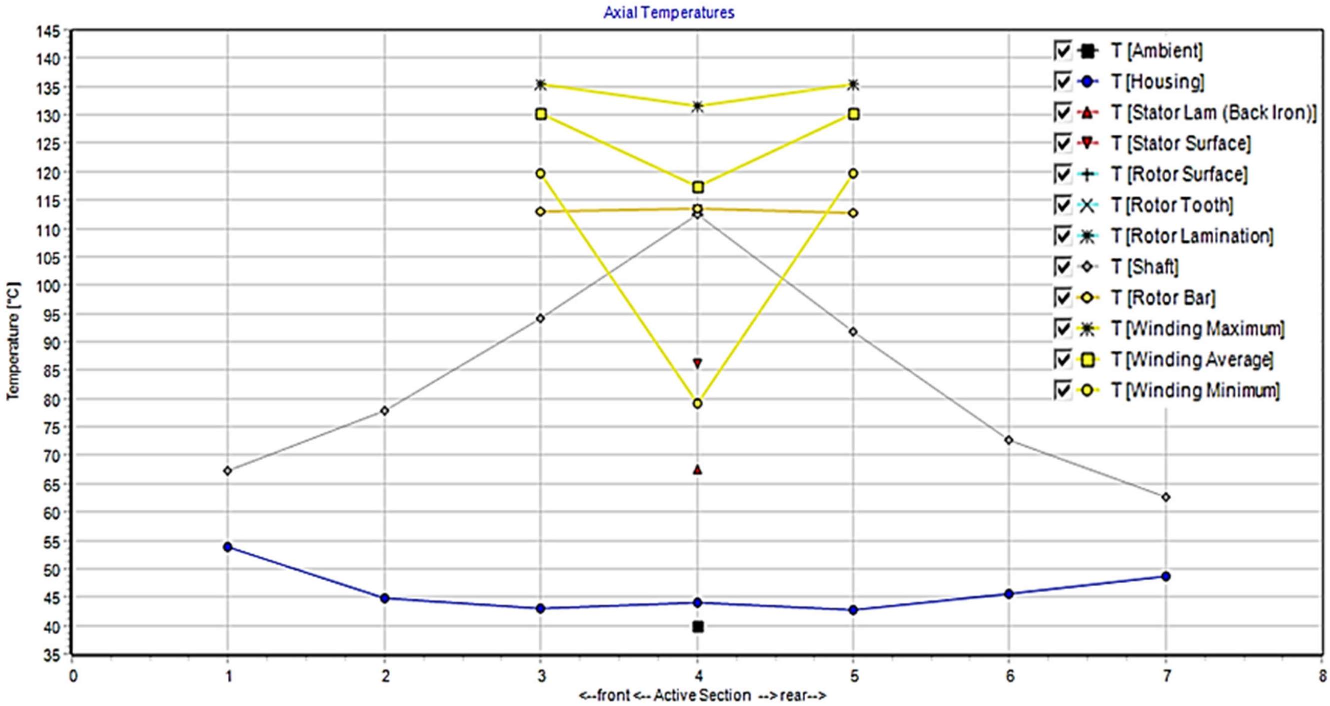

Figure 14. Variation in axial temperature at different sections of the motor for water-cooled motor.

Figure 15 illustrates the variation of temperature at different parts of the induction motor when CuO was allowed to flow through the housing jacket. Induction motors have been demonstrated to operate more efficiently and at lower temperatures when coolants made of nanofluids such as CuO are used. The axial temperature profiles would serve as a useful tool for assessing how well the nanofluid cooled the motor and for refining the motor cooling systems design, as seen in Figure 15.

CuO was found to be a better coolant at every section as compared to water since the temperature at each part of the motor was significantly reduced while CuO was used. Additionally, the percentage of reduction was found maximum when CuO was used, followed by ZnO and then Al_2O_3. Hence, the surface area for heat transfer is further increased by the CuO (as compared to others, as seen in Figure 16) nanoparticles' tiny size since they could fit into even the tiniest spaces between the motor's parts.

The motor industry could gain from using a nanofluid as a coolant to lower motor temperatures in a number of ways, including the following:

Reduced Temperature: As motor temperature drops, its efficiency rises. The efficiency of a motor could be increased by using a nanofluid as a coolant to lower its temperature. Lower energy costs and more production may follow from this.

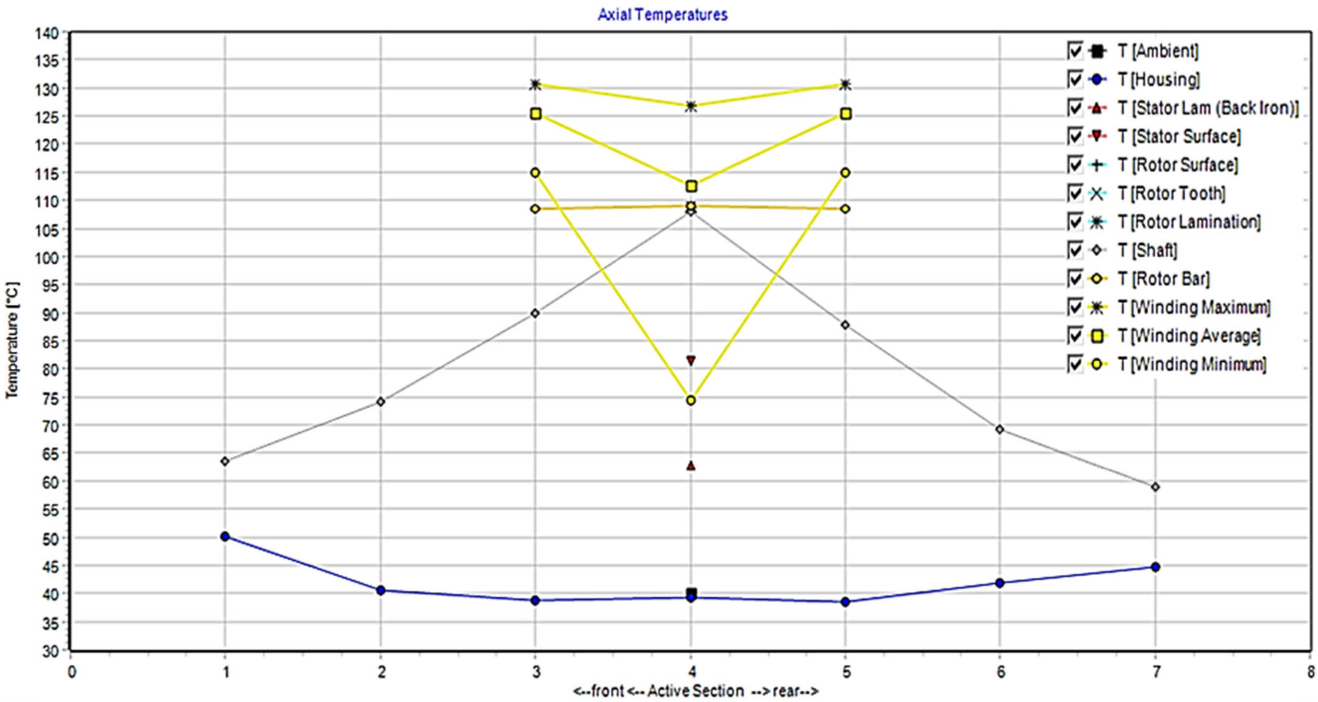

Figure 15. Variation in axial temperature at different sections of the motor for CuO-based nanofluid cooled motor.

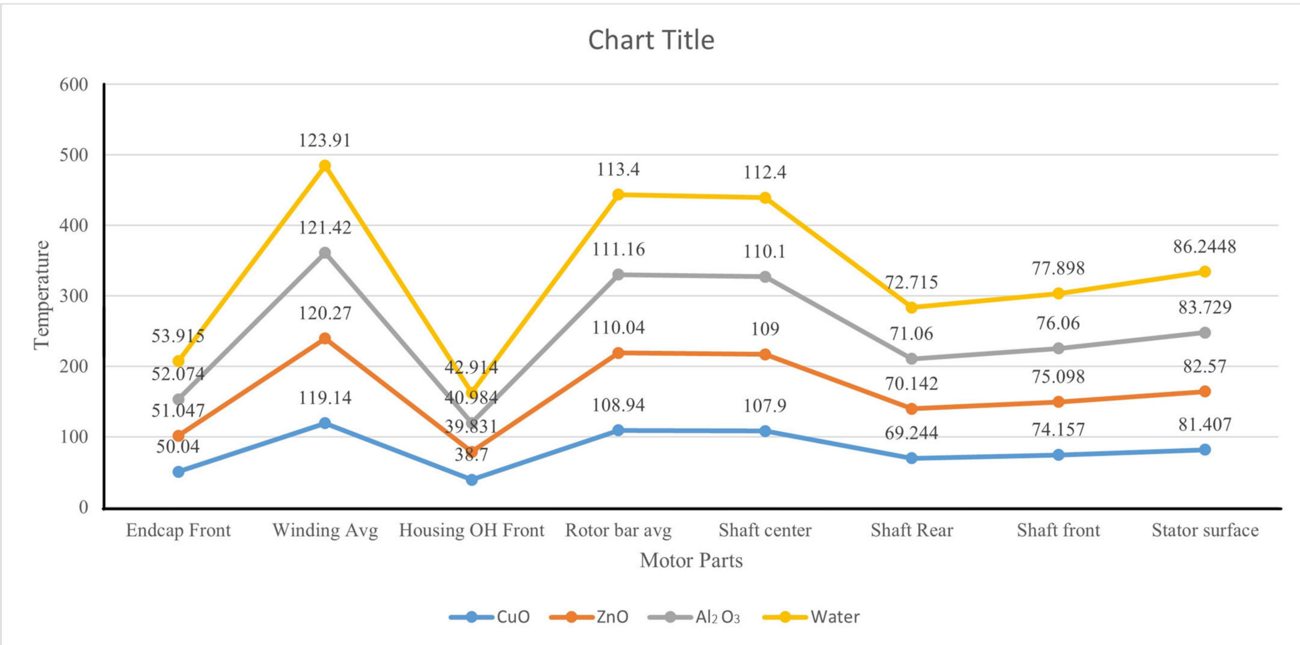

Figure 16. Comparison between the water and nanofluids—temperature at various sections of the motor.

Extended Life: Motors are susceptible to wear and tear from high temperatures, which shortens their lives. The motor's lifespan could be increased by lowering its temperature by employing a nanofluid as a coolant. As an effective coolant, nanofluid circulating around the motor absorbs the heat that it emits, thus extending its lifespan. This approach is frequently utilised in high-performance applications or in confined spaces since it is generally more effective than air cooling [27–29].

Lower maintenance Costs: When motors operate at high temperatures, maintenance is needed more frequently. Lower maintenance expenses could be achieved by using a nanofluid coolant to lower the motor's temperature and, consequently, lessen the requirement for maintenance.

Enhanced Safety: Workers' safety may be put at risk by motors operating at high temperatures. The danger of accidents could be lowered by utilising a nanofluid coolant to lower the motor temperature, making the workplace safer.

4. Conclusions

According to the experimental findings, using nanofluids could significantly decrease temperature rise and losses in various motor components. The following decreases in percentage of variation are seen when CuO-based nanofluid is used: a 7% decrease in the endcap (front) temperature, 10% decrease in the housing (front), 5% decrease in the shaft (rear) and shaft (front) temperature, a reduction of 4% in the maximum temperature, and a significant reduction of 9% in the minimum temperature (Table 7). These findings suggest that the introduction of nanofluids could enhance the induction motor's cooling capability and general efficiency, making it a potential choice for high-performance electrical devices. The possible explanations for such findings are as follows:

CuO could transfer heat more effectively than conventional fluids due to its high thermal conductivity. The better thermal conductivity of nanofluids could aid in the swift and efficient dissipation of heat out of the motor, thereby reducing the likelihood of overheating and increasing the motor's lifespan. Secondly, even if the motor is subjected to substantial loads or prolonged operation, a large specific heat capacity of CuO-based nanofluids helps to guarantee that the temperature of the motor stays steady and within the safe limits of operation.

CuO is a stable, non-toxic substance that is extensively used and reasonably priced. Because of this, it is an excellent option for use as motor cooling and other applications where effective heat transmission is crucial. Overall, it has been simulated and studied that CuO-based nanofluids work well as coolants for induction motors and other such applications where heat transmission is crucial. They are a desirable replacement for conventional coolants due to their excellent specific heat capacity, low toxicity, stability, and, especially, thermal conductivity.

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Nomenclature

Q	Dissipated power density
T	Temperature
λ	Thermal conductivity
ρ	Density
Tw	Surface temperatures
T∞	Ambient cooling medium temperatures
α	Heat transfer coefficient

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