Effect of Nanofluids on Electric Vehicle Battery Cooling System Performance

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Abstract: The use of electric vehicles is becoming increasingly attractive today due to their high energy efficiency and low environmental damage. Limited battery capacity, long charging times and low battery life can be stated as the biggest obstacles to the widespread use of electric vehicles. However, the negative effect of temperature on battery life has been found as a result of research and this effect has made the necessity of a thermal management system in electric vehicles mandatory. In addition, suspensions of nanoparticles in a liquid are called nanofluids. Nanofluids are promising for increasing heat transfer with their high thermal conductivity coefficients. In my study, it was aimed to improve and observe the performance of the cooling system by adding different nanoparticles at different concentrations to the Water-Ethylene Glycol liquid used as a coolant in current mass production in Computational Fluid Dynamics Analysis through the design of the electric vehicle battery cooling system. The thermophysical properties of the nanofluids obtained by adding 50% Ethylene Glycol 50% Water mixture as the main coolant, $ZnFe_2O_4$, $NiFe_2O_4$, $CoFe_2O_4$ Magnetic Ferrite nanoparticles in different concentrations as nanoparticles to the coolant mixture in certain proportions were determined theoretically using models in the literature. Thermal conductivity, specific heat, viscosity values of nanofluids with different concentrations as 1%, 2%, 3% were calculated and the models were compared. In volumetric heat transfer, compared to the Water + Ethylene Glycol mixture, performance improvements of 9.2%, 10.9%, and 12.4% were achieved for $CoFe_2O_4$ at concentration ratios of 1%, 2%, and 3%, respectively. For $NiFe_2O_4$, performance improvements of 10.4%, 12.4%, and 13.7% were achieved at the same concentration ratios. For $ZnFe_2O_4$, performance improvements of 10.9%, 12.8%, and 14.6% were achieved at 1%, 2%, and 3% concentration ratios.

Keywords: Electric Vehicle, Nanofluid, Nanoparticle, Battery Model, Cooling.

1. INTRODUCTION

Nowadays, almost all automotive manufacturers worldwide are directing their resources towards the design and production of electric vehicles to reduce pollutants caused by vehicles with internal combustion engines, one of the major causes of air pollution and global warming, along with greenhouse gases and dependence on fossil fuels. One of the most important components of electric vehicles is the batteries that convert chemical energy into mechanical energy. Due to the working principle of batteries, heat is released as a result of electrochemical reactions. Thermal management systems are used to remove this heat from the batteries. The primary goal of electric vehicle battery systems equipped with a thermal management system is to maintain the battery pack's highest temperatures below a certain value, to keep the temperature differences within the modules formed by the battery cells and the pack at minimal levels. These tasks help to extend the service life and lifecycle of the battery packs; to ensure the highest possible performance throughout the battery's life and to enable the battery packs to operate under specified safety standard conditions.

In electric vehicles, battery packs equipped with thermal management systems utilize various cooling methods with different operational disciplines. These methods include liquid cooling, air cooling, cooling with heat pipes, and using phase change materials as examples of cooling disciplines. Each method has its advantages and disadvantages relative to each other. Moreover, systems that use these methods in combination also exist. Among these methods, the most commonly used and preferred in the commercial market is liquid cooling systems. These systems operate by transferring the heat generated in the cells of the battery modules through cooling plates, typically via a fluid passing through channels of varying designs.

Therefore, in liquid cooling systems, factors such as channel geometry, channel type, flow characteristics, coolant type, and coolant flow rate significantly influence heat transfer, system performance, and overall pressure drop. With advancing technological studies and analysis methods, optimizing these parameters that affect the efficiency of cooling systems has gained both speed and importance. In this article, the optimization of a battery pack comprising four cells and a cooling plate designed for a lithium-ion battery system is discussed; the article aims to observe the performance of the cooling system by adding nanoparticles in various concentrations to the Water-Ethylene Glycol liquid used as coolant in current

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mass productions through Computational Fluid Dynamics Analysis, thereby enhancing the efficiency of the electric vehicle battery cooling cycle.

2. METHOD

In this study, through the design of a cooling system for an electric vehicle battery module consisting of four cells, it was aimed to enhance and observe the performance of the cooling system by adding different nanoparticles at various concentration rates to the Water-Ethylene Glycol liquid currently used as a coolant in mass production. As the main cooling liquid, a 50% Ethylene Glycol and 50% Water mixture was used, and nanofluids were created by adding $ZnFe_2O_4$, $NiFe_2O_4$, and $CoFe_2O_4$ magnetic ferrite nanoparticles in nano-sized proportions at different concentrations into the coolant mixture. The thermophysical properties of these nanofluids were theoretically determined using models found in the literature. The thermal conductivity, specific heat, and viscosity values of nanofluids at concentrations of 1%, 2%, and 3% were calculated, and volumetric heat transfers were compared based on these models. This section describes the materials and methods used.

2.1. Computational Fluid Dynamics (CFD) Method

In this study, the CFD method was used, which allows us to analyze systems that involve the movement of fluids, heat transfer, and chemical reactions using computer software. The CFD solution employs the finite volume method. In the finite volume method, the first step involves dividing the solution domain into a certain number of discrete control volumes, and integration of the conservation equations is performed over each volume element. The integral form equations used for the control volume are converted into algebraic equations, and iterative methods are employed to approximate solutions.

2.2. Computational Fluid Dynamics (CFD) Model

For the Computational Fluid Dynamics analysis studies, the design of the battery module using a liquid cooling method with cooling plates consisting of four cells is shown in Figure **1**.

Design variables for a structure of 40,000 nodes and 531,000 elements were determined and a 3D model was created, after which the mesh for the CFD analyses was developed. Throughout the CFD analysis studies, ANSYS Spaceclaim and FLUENT software were used. A pressure-based solver was employed in the CFD analysis model. The steady setting was chosen as the time discretization scheme. The Realizable k-epsilon with Enhanced Wall Function was used as the turbulence model. The network structure and cross-sectional view of the battery module using cooling plates and the liquid cooling method are shown in Figure **2**.

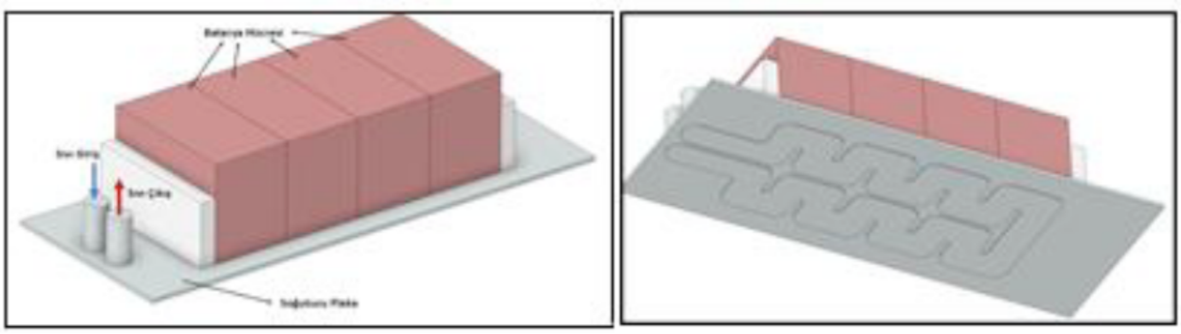

Figure 1: The battery module using a liquid cooling method with cooling plates consisting of four cells.

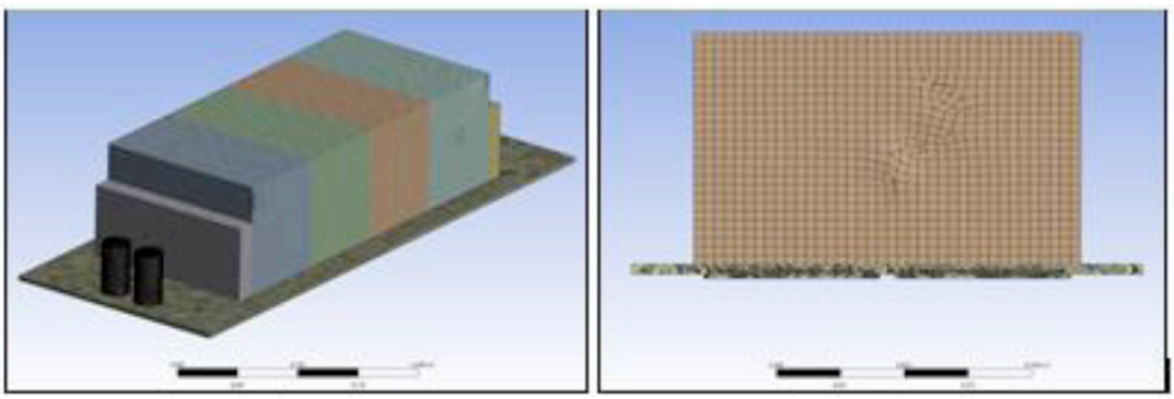

Figure 2: The network structure and cross-sectional view of the cooling method using cooling plates and liquid cooling.

Network structure of 940,000 Nodes and 531,000 Elements was used in the analysis.

ANSYS Spaceclaim and FLUENT software were used throughout the CFD analysis studies.

A pressure-based solver was used in the CFD analysis model.

The steady setting was selected as the time discretization scheme.

The Realizable k-e, Enhanced Wall Function setting was used as the turbulence model. The energy option was activated.

The solid material properties used in the CFD analysis model are given in Table **1** below. In this study, the battery cell was modeled as anisotropic (the ability to exhibit properties with different values when measured along axes in different directions) in terms of thermal conductivity.

Table 1: Solid Material Properties used in the CFD Analysis Model

	Battery Cell	Aluminum
Density (kg/m^3)	2275	2719
Specific Heat (J/kg·K)	989	871
Thermal Conductivity (W/m·K)	0.35 in x-direction 22 in y-direction 22 in z-direction	202.4

In the boundary condition values, the volumetric temperature of the battery cells was set at 363K (90°C) and was kept constant throughout the analysis. The fluid velocity entering through the cooling plate inlet was 0.368415 m/s (10 liters/minute), with a turbulence intensity of 5% and a turbulent viscosity ratio value set at 10. The temperature of the incoming coolant was set at 333K (60°C). At the outlet boundary condition, the gauge pressure was set to 0 and the pressure profile multiplier was used at 1. In the solution method settings, a coupled scheme was used for the pressure-velocity coupling as part of the design setup. The flow direction view of the liquid cooling method using cooling plates is shown in Figure **3**.

In the solution residuals, the convergence settings for the continuity and momentum equations have been set to 10^{-3}, and for the energy equation to $10^{-6.}$ A convection boundary condition has been applied to all surfaces in contact with the ambient air, and a heat transfer coefficient of 5 W/(m²K) has been defined. Spatial discretization settings are given in Table **2**. The initial and boundary conditions for the numerical analyses are provided in Table **3**.

Table 2: Spatial Discretization Settings

Gradient	Least Squares Cell Based
Pressure	Second Order
Momentum	Second Order Upwind
Turbulet Kinetic Energy	First Order Upwind
Turbulent Dissipation Rate	Second Order Upwind
Energy	Second Order Upwind
Pseudo Time Method	Global Time Step

2.3. Calculation of the Thermophysical Values (Thermal Conductivity, Specific Heat, Viscosity) of Nanofluids

Systems such as heat pipes and heat exchangers are used to transfer energy from one place to another. In these systems, traditional liquids such as water, oil, and ethylene glycol are used as working fluids

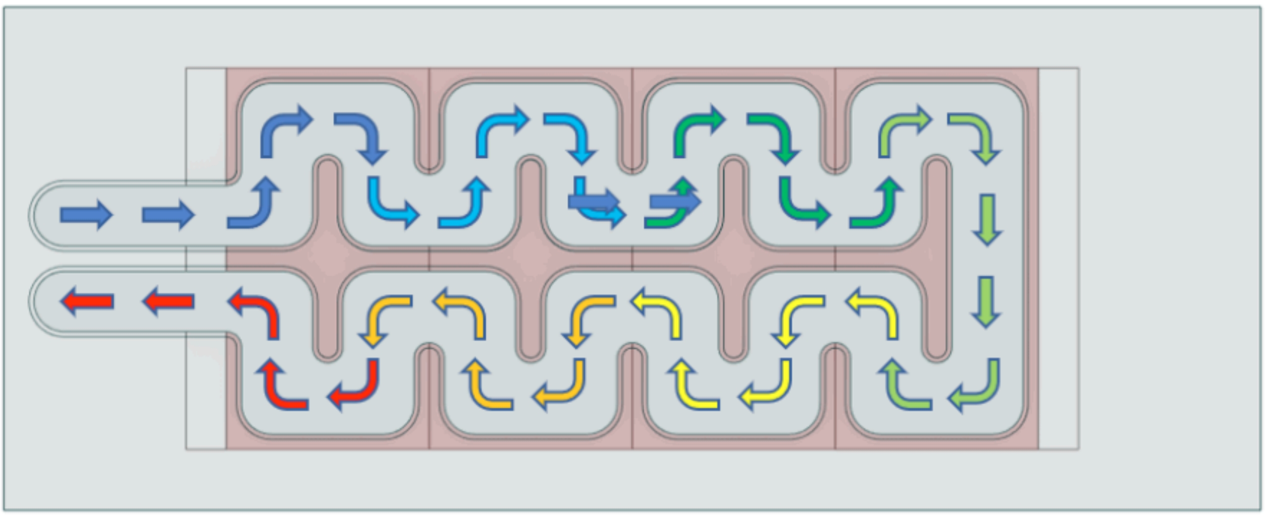

Figure 3: The flow direction view of the liquid cooling method using cooling plates.

Table 3: Initial and Boundary Conditions for the Analysis of the Four-Cell Module

Initial/Boundary Conditions	Value/Type
Input Type	Mass Flow Rate
Output Type	Pressure Output
Inlet Mass Flow Rate	10 liters/minute
Outlet Pressure	0 Pa
Water Temperature	60 ºC
Battery Temperature	90 ºC
Cooling Plate Temperature	60 ºC
Ambient Temperature	20 ºC
Simulation Mode	Continuous Mode

responsible for carrying heat. The most important parameters affecting the thermal performance of fluids used in heating and cooling systems are thermal conductivity, specific heat capacity, viscosity, and other thermophysical properties. Due to the low thermal conductivity of common traditional working fluids like pure water, the desired performance in thermal systems is not achieved. In recent years, research on nanofluids, which are created by adding nano-sized particles to the base fluid, has gained momentum to enhance the efficiency of thermal systems. There are several physical phenomena that improve the heat transfer performance of nanofluids. Since the thermal conductivity of solid metals is higher than that of the base fluid, thin solid metals suspended in the base fluid increase its thermal conductivity. The metal particles suspended in the working fluid increase its surface area and thermal capacity. The interaction and collisions between the particles increase the surface area of the fluid. Thus, faster heat transfer occurs between the particles (Aytaç, 2020).

In this study, thermal conductivity values were calculated using the Maxwell equation by adding nanoparticles at volumetric concentrations of 1%, 2%, and 3% to the base cooling fluid. Table **4** shows the thermal conductivity models for nanofluids (Kumar *et al.*, 2015).

In this study, specific heat values were calculated using the Xuan and Roetzel equation by adding nanoparticles at volumetric concentrations of 1%, 2%, and 3% to the base cooling fluid. Models developed in the literature are commonly used to obtain the specific heat values of nanofluids. This model is presented in Table **5** (Gupta *et al.*, 2017).

Table 5: Specific Heat Models for Nanofluids (Gupta *et al.*, 2017)

Model	Formulation
Xuan and Roetzel	$c_{pnanofluid} = \frac{(1-\varphi)(\rho c_p)_{basefluid} - \varphi(\rho c_p)_{nanoparticle}}{(1-\varphi)(\rho)_{basefluid} + \varphi(\rho)_{nanoparticle}}$

In this study, viscosity values were calculated using the Einstein equation by adding nanoparticles at volumetric concentrations of 1%, 2%, and 3% to the base cooling fluid.

When looking into the literature, various theoretical studies have been conducted and models have been developed by researchers to determine the viscosity values of nanofluids. Einstein developed a model for spherical particles at very small volumetric ratios. These models are presented in Table **6** (Senthilkumar, A. P., 2012).

Table 6: Viscosity Models for Nanofluids (Senthilkumar, A. P., 2012)

Model	Formulation
Einstein	$\frac{\mu_{nanofluid}}{\mu_{basefluid}} = 1 + 2.5\varphi$

3. FINDINGS

In this study, through the design of an electric vehicle battery cooling system analyzed by Computational Fluid Dynamics, it was aimed to enhance and observe the performance of the cooling system by adding different nanoparticles at various concentration ratios to the Water-Ethylene Glycol liquid currently used as a coolant in mass production. As the main cooling liquid, a 50% Ethylene Glycol and 50% Water mixture was used, and nanofluids were created by adding $ZnFe_2O_4$, $NiFe_2O_4$, and CoFe2O4 magnetic ferrite nanoparticles in nano-sized proportions at different concentrations into the coolant mixture. The

Table 4: Thermal Conductivity Models for Nanofluids (Kumar *et al.*, 2015)

Model	Formulation	Explanation
Maxwell	$\frac{k_e}{k_l} = \frac{k_p + 2k_l + 2(k_p - k_l)\phi}{k_p + 2k_l - 2(k_p - k_l)\phi}$	Applicable for spherical particles.

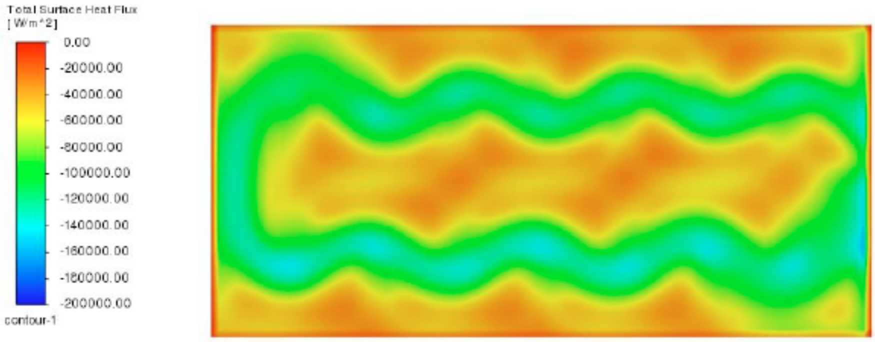

Figure 4: Total surface heat flux (W/m²) of the 50%-50% water-ethylene glycol mixture, flow view of the liquid cooling method with cooling plates.

thermophysical properties of these nanofluids were theoretically determined using models from the literature. The thermal conductivity, specific heat, and viscosity values of nanofluids with concentrations of 1%, 2%, and 3% were calculated and compared.

The flow view of the liquid cooling method with cooling plates, showing the 50%-50% water-ethylene glycol mixture's temperature (K), velocity (m/s), and total surface heat flux (W/m²), is presented in Figure **4**.

Experimental Design 1: After the addition of 1% nanofluid to the current 50%-50% water-ethylene glycol test setup, the thermal conductivity, specific heat, viscosity, volumetric heat transfer, inlet-outlet temperature, and temperature difference data were obtained using the relevant equations. These values are presented in Table **7**.

For Experimental Design 1, after the addition of 1% $ZnFe_2O_4$, $NiFe_2O_4$, and $CoFe_2O_4$ nanofluids, the temperature (K), velocity (m/s), and total surface heat flux (W/m²) of the liquid cooling method with cooling plates are shown in Figures **5**-**7**.

Table 7: Thermal Conductivity, Specific Heat, Viscosity, Volumetric Heat Transfer, Inlet-outlet Temperature, and Temperature Difference Data for Experimental Design 1

	Water + Ethylene Glycol	$ZnFe_2O_4$	$NiFe_2O_4$	$CoFe_2O_4$
Specific Heat (J/kg·K)	3488,5	3462,63	3459,61	3460,61
Thermal Conductivity (W/m·K)	0,3976	0,4133	0,4103	0,4095
Density (kg/m^3)	1077	1116,35	1120,33	1115,3
Viscosity (cP)	2,70	1,01	1,03	1,09
Q (Watt)	2185	2424	2456	2422
Inlet Temperature (K)	333	333	333	333
Outlet Temperature (K)	336,4991	336,7345	336,7015	336,6804
Delta_T (K)	3,4991	3,7345	3,7015	3,6804

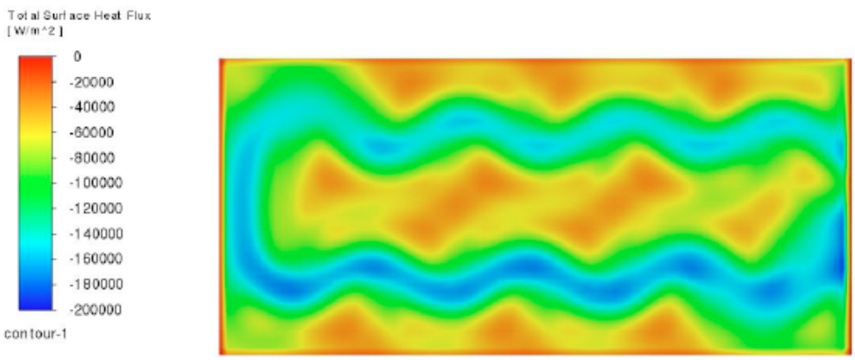

Figure 5: Total surface heat flux (W/m²) after the addition of 1% $ZnFe_2O_4$ nanofluid, flow view of the liquid cooling method with cooling plates.

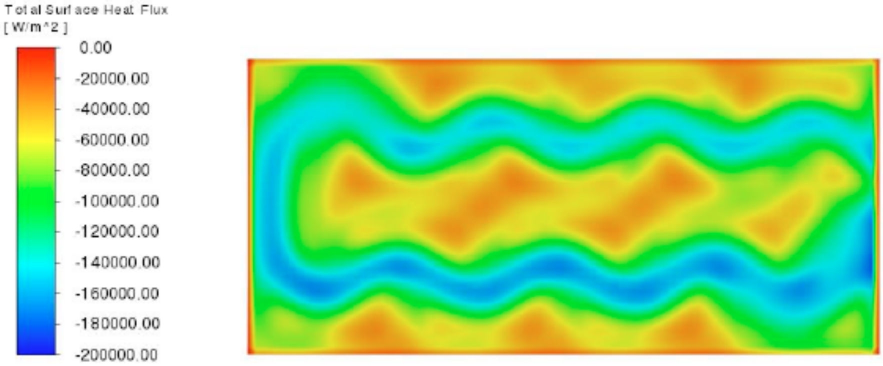

Figure 6: Total surface heat flux (W/m²) after the addition of 1% $NiFe_2O_4$ nanofluid, flow view of the liquid cooling method with cooling plates.

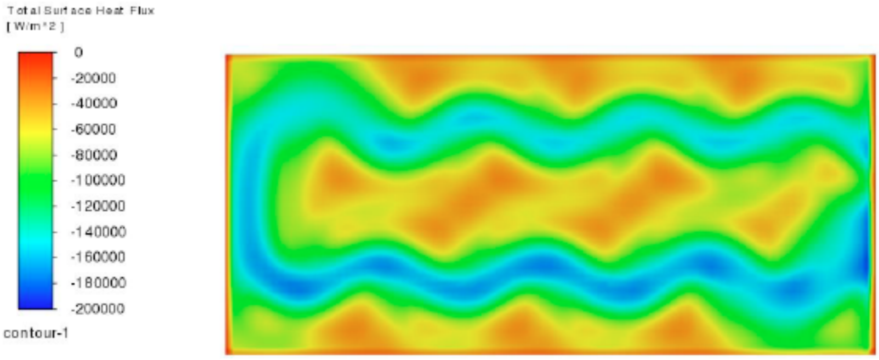

Figure 7: Total surface heat flux (W/m²) after the addition of 1% $CoFe_2O_4$ nanofluid, flow view of the liquid cooling method with cooling plates.

Experimental Design 2: After the addition of 2% nanofluid to the current 50%-50% water-ethylene glycol test setup, the thermal conductivity, specific heat, viscosity, volumetric heat transfer, inlet-outlet temperature, and temperature difference data were obtained using the relevant equations. These values are presented in Table **8**.

For Experimental Design 2, after the addition of 2% $ZnFe_2O_4$, $NiFe_2O_4$, and $CoFe_2O_4$ nanofluids, the temperature (K), velocity (m/s), and total surface heat flux (W/m²) of the liquid cooling method with cooling plates are shown in Figures **8**-**10**.

Experimental Design 3: After the addition of 3% nanofluid to the current 50%-50% water-ethylene glycol test setup, the thermal conductivity, specific heat, viscosity, volumetric heat transfer, inlet-outlet temperature, and temperature difference data were obtained using the relevant equations. These values are presented in Table **9**.

Table 8: Thermal Conductivity, Specific Heat, Viscosity, Volumetric Heat Transfer, Inlet-outlet Temperature, and Temperature Difference Data for Experimental Design 2

	Water + Ethylene Glycol	$ZnFe_2O_4$	$NiFe_2O_4$	$CoFe_2O_4$
Specific Heat (J/kg·K)	3488,5	3436,76	3430,73	3432,73
Thermal Conductivity (W/m·K)	0,3976	0,42978	0,42344	0,4216
Density (kg/m^3)	1077	1155,7	1163,66	1153,6
Viscosity (cP)	2,70	1,05	1,07	1,13
Q (Watt)	2185	2466	2456	2423
Inlet Temperature (K)	333	333	333	333
Outlet Temperature (K)	336,4991	336,7345	336,7015	336,6804
Delta_T (K)	3,4991	3,7345	3,7015	3,6804

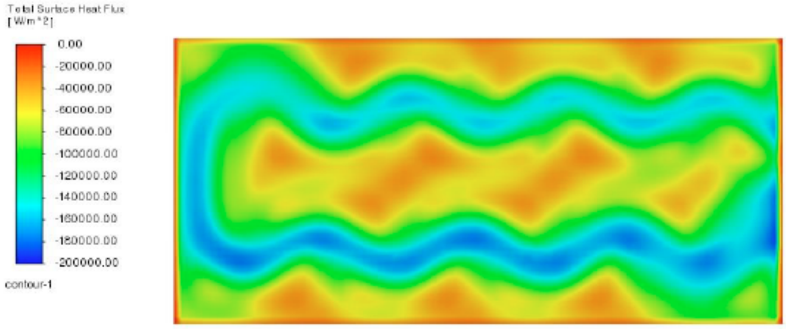

Figure 8: Total surface heat flux (W/m²) after the addition of 2% $ZnFe_2O_4$ nanofluid, flow view of the liquid cooling method with cooling plates.

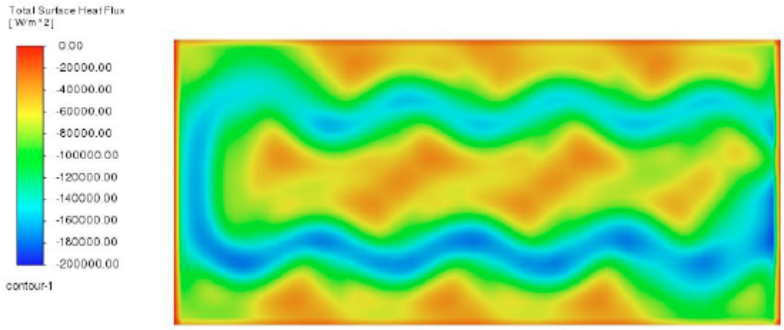

Figure 9: Total surface heat flux (W/m²) after the addition of 2% $NiFe_2O_4$ nanofluid, flow view of the liquid cooling method with cooling plates.

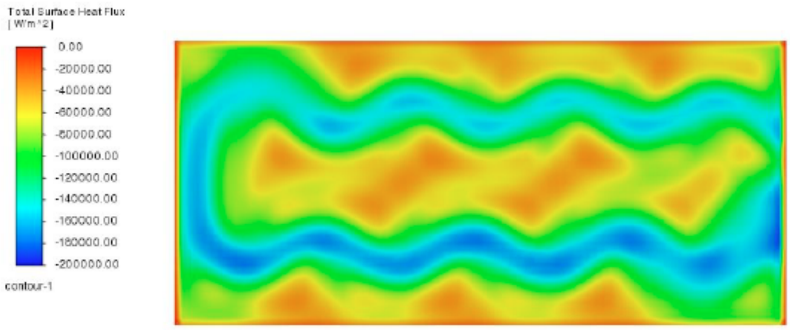

Figure 10: Total surface heat flux (W/m²) after the addition of 2% $CoFe_2O_4$ nanofluid, flow view of the liquid cooling method with cooling plates.

Table 9: Thermal Conductivity, Specific Heat, Viscosity, Volumetric Heat Transfer, Inlet-outlet Temperature, and Temperature Difference Data for Experimental Design 3

	Water + Ethylene Glycol	$ZnFe_2O_4$	$NiFe_2O_4$	$CoFe_2O_4$
Specific Heat (J/kg·K)	3488,5	3410,89	3401,84	3404,84
Thermal Conductivity (W/m·K)	0,3976	0,4468	0,437	0,4342
Density (kg/m^3)	1077	1195,05	1197,75	1191,9
Viscosity (cP)	2,70	1,07	1,09	1,15
Q (Watt)	2185	2505	2485	2457
Inlet Temperature (K)	333	333	333	333
Outlet Temperature (K)	336,4991	336,6963	336,6691	336,6424
Delta_T (K)	3,4991	3,6963	3,6691	3,6424

For Experimental Design 3, after the addition of 3% $ZnFe_2O_4$, $NiFe_2O_4$, and $CoFe_2O_4$ nanofluids, the temperature (K), velocity (m/s), and total surface heat flux (W/m²) of the liquid cooling method with cooling plates are shown in Figures **11-13**.

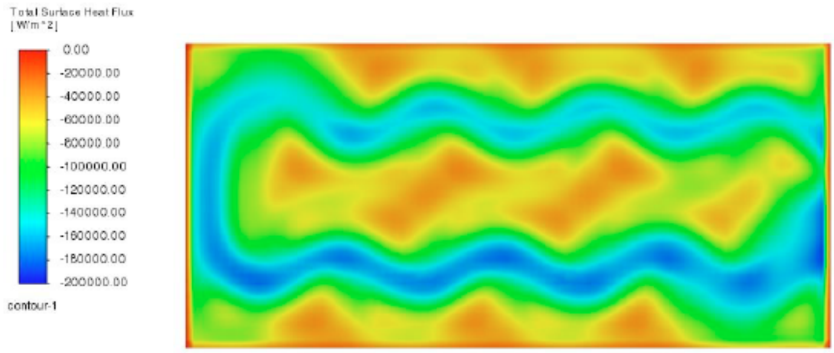

Figure 11: Total surface heat flux (W/m²) after the addition of 3% $ZnFe_2O_4$ nanofluid, flow view of the liquid cooling method with cooling plates.

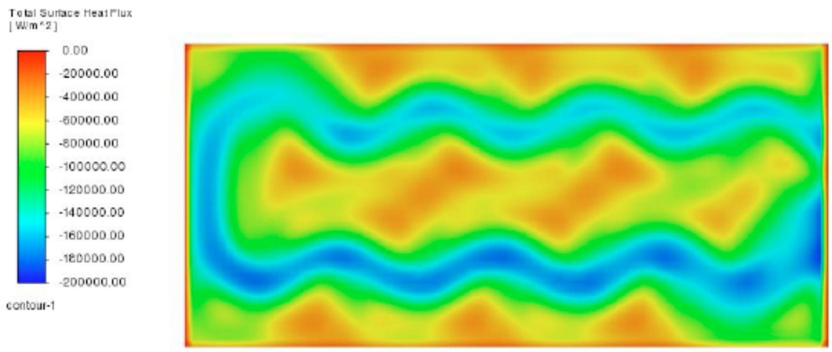

Figure 12: Total surface heat flux (W/m²) after the addition of 3% $NiFe_2O_4$ nanofluid, flow view of the liquid cooling method with cooling plates.

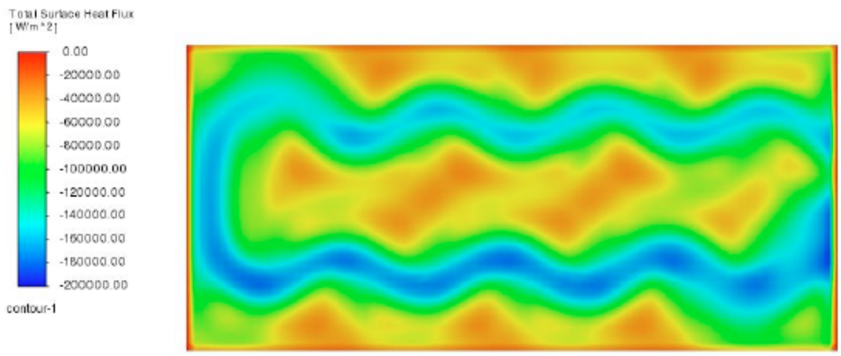

Figure 13: Total surface heat flux (W/m²) after the addition of 3% $CoFe_2O_4$ nanofluid, flow view of the liquid cooling method with cooling plates.

During the calculations, the volumetric heat transfer of magnetic nanofluids was not fixed at 400 W but taken as a function of f(T, SOC), a constant temperature of 90°C and a fluid inlet temperature of 60°C were used, with a delta T of 30°C. Calculations were performed for concentrations of 1%, 2%, and 3%.

After the addition of 1%, 2%, and 3% nanofluids to the current 50%-50% water-ethylene glycol test setup, the volumetric heat transfer data and percentage comparison values for Experimental Design 1, Experimental Design 2, and Experimental Design 3 were obtained using the relevant equations. These values are presented in Figure **14**.

In volumetric heat transfer, compared to the Water + Ethylene Glycol mixture, performance improvements of 9.2%, 10.9%, and 12.4% were achieved for $CoFe_2O_4$ at concentration ratios of 1%, 2%, and 3%, respectively. For $NiFe_2O_4$, performance improvements of 10.4%, 12.4%, and 13.7% were achieved at the same concentration ratios. For $ZnFe_2O_4$, performance improvements of 10.9%, 12.8%, and 14.6% were achieved at 1%, 2%, and 3% concentration ratios, respectively.

4. DISCUSSION

In this study, analysis was conducted on the volumetric heat transfer of cooling plates, which

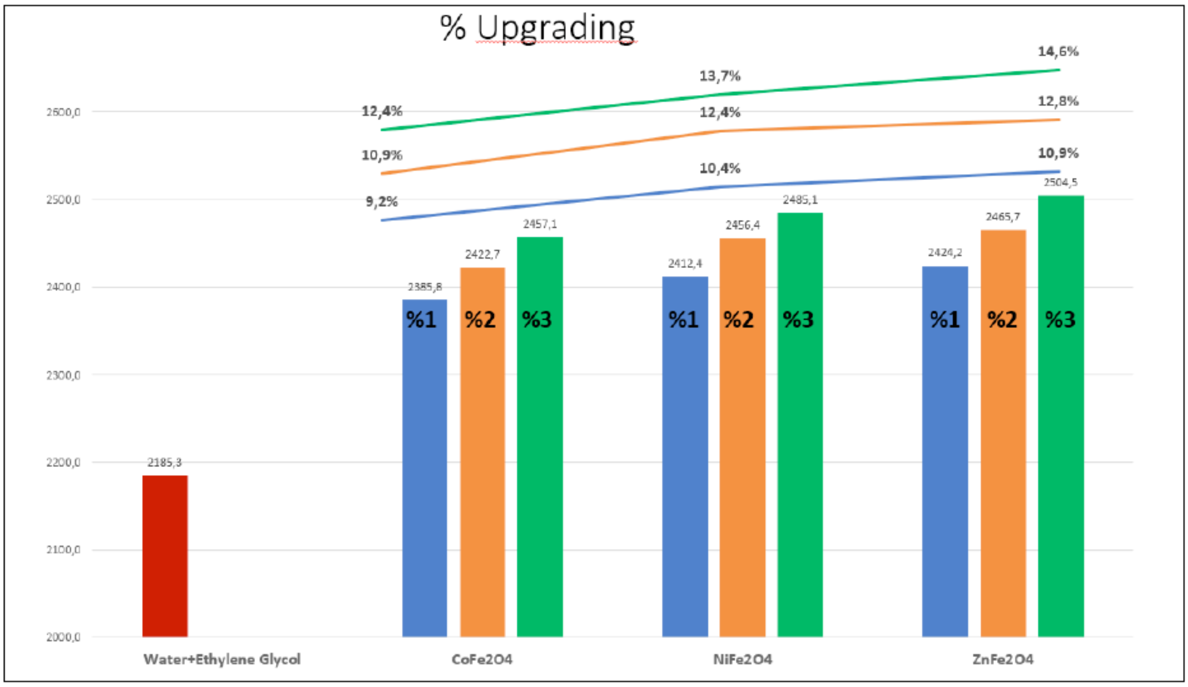

Figure 14: Volumetric heat transfer data and percentage comparison values for Experimental Design 1, Experimental Design 2, and Experimental Design 3.

contain channels through which coolant flows, using nanofluids created by adding nanoparticles at different volumetric concentrations to the liquid cooling method of a battery module consisting of four cells. After the design of the four-cell battery module and cooling plates, a mesh independence analysis was performed, followed by identifying the outputs, and then process design was prepared for conducting the draft and final analyses.

The specific heat capacity, thermal conductivity coefficient, viscosity, and density values of the cell and solid model material properties, as well as the properties of the coolant, were calculated. The volumetric heat transfer was not fixed at 400 W; instead, it was taken as a function of f(T, SOC), with a constant temperature of 90°C, a fluid inlet temperature of 60°C, and a delta T of 30°C. Calculations were performed at concentrations of 1%, 2%, and 3%. Based on the study, some conclusions can be stated as follows:

- Increased nanoparticle concentration improved the thermal efficiency of all systems.
- In volumetric heat transfer, compared to the 50% Water + 50% Ethylene Glycol mixture, $ZnFe_2O_4$ achieved percentage efficiency increases of 10.9%, 18.4%, and 14.6% at concentration ratios of 1%, 2%, and 3%, respectively.
- In volumetric heat transfer, compared to the 50% Water + 50% Ethylene Glycol mixture, $NiFe_2O_4$ achieved percentage efficiency increases of 10.4%, 12.4%, and 13.7% at concentration ratios of 1%, 2%, and 3%, respectively.
- In volumetric heat transfer, compared to the 50% Water + 50% Ethylene Glycol mixture, $CoFe_2O_4$ achieved percentage efficiency increases of 9.2%, 10.9%, and 12.4% at concentration ratios of 1%, 2%, and 3%, respectively.

As shown in Table **10**, when the results obtained in similar studies in the literature are examined, it is seen that the nanoparticles selected in this study play a role in increasing the performance compared to others in terms of cooling capacity.

5. CONCLUSION

Nanofluids show promise for enhancing heat transfer due to their high thermal conductivity coefficients. It was observed that the thermal conductivity of oxide and hybrid nanofluids is greater than that of the base fluid across all mixing ratios. According to the results, in all models used, as the volumetric concentration of nanofluids increases, the specific heat values decrease.

When comparing volumetric heat transfer values to the Water + Ethylene Glycol mixture at concentration ratios of 1%, 2%, and 3%, noticeable differences were observed. As volumetric concentration increased, an increase in volumetric heat transfer was achieved in each model.

Table 10: A Brief Description for Research's Previous Works

Authors	Magnetic nanofluids	Volume Fraction range	Dependent variables such as: Temperature, flow rate, heat flux ... etc.	Type of study	Obtained results
Sözen *et al.*,2016	Alumina and fly-ash	2 wt. %	Mass flow rate, input power	Heat transfer improvement of a parallel and cross-flow concentric tube heat exchanger under nanofluids working fluid	the efficiencies of the parallel and the counter-flow concentric tube heat exchanger systems, which were 31.2% and 6.9%, respectively, in the case of utilizing fly-ash nanofluid as a working fluid in the system
Baba *et al.*, 2018	Fe_3O_4/PW	0.02%, 0.04%, 0.06%, 0.08%, 0.1%, 0.2%, 0.4%	40 lpm	Magnetic nanofluids used in counter-flow DPHE with fins placed inside	Using MNF enhanced the thermal performance by 80% to 90%.
Authors	Magnetic nanofluids	Volume Fraction range	Dependent variables such as: Temperature, flow rate, heat flux ... etc.	Type of study	Obtained results
Babat *et al.*, 2022	Fe_3O_4/PW & Fe_2O_3/PW	0.5 wt. %.	Mass flow rate and concentration ratio	The effects of using magnetic nanofluids on the convective heat transfer coefficient and the thermal efficiency of a parallel-flow and counter-flow concentric tube heat exchanger system	The thermal conductivity of the (Fe_3O_4/PW) & (Fe_2O_3/PW) magnetic nanofluids was approximately 15% and 10.28% more heightened than pure water which was the base fluid.
Sözen *et al.*, 2018	TiO_2/PW TiO_2/Triton X-100 TiO_2/ SDBS	0.5 wt. %	Mass flow rate, input heat, various base fluids.	Experimentally studied the surface-active mechanism effects, and the impacts of the adding nanoparticles to the base fluid, on the performance of the natural convective heat pipe type	The heat resistant and the enhancements of the thermal system were higher than that of Triton X-100 surfactant, on the other hand, there was no impacts of the surfactant on the thermal conductivity of the heat pipe.
Tharayil *et al.*, 2015	Aqueous-gr aphene	0.001 to 0.006 wt. %	Input power, weight percent, and the declination angle	Analyzed the thermal attributes of a small-scale heat pipe working by injecting nanofluid	Employing nanofluid as an operating medium improved both the thermal index factor of the heat pipe and reduced the temperature in the evaporator region.
Authors	Magnetic nanofluids	Volume Fraction range	Dependent variables such as: Temperature, flow rate, heat flux ... etc.	Type of study	Obtained results
Menlik *et al.*, 2015	MgO/PW	5 wt. %	Mass flow rate, input heat, weight percent	Experimented nanofluids inside a copper natural convection heat pipe	The results demonstrated that the efficiency of the system was increased by 26% under utilizing MgO nanofluid corresponding to pure water.

- When $CoFe_2O_4$, the selected nanoparticle, was added to the 50% Ethylene Glycol + 50% Water mixture as the main cooling fluid at a 1% concentration, the volumetric heat transfer was calculated as 2385.8 Watts. At a 2% concentration, the volumetric heat transfer was 2422.7 Watts, and at a 3% concentration, it was 2457.1 Watts.
- When $NiFe_2O_4$ was added to the 50% Ethylene Glycol + 50% Water mixture as the main cooling fluid at a 1% concentration, the volumetric heat transfer was calculated as 2412.4 Watts, at a 2% concentration it was 2456.4 Watts, and at a 3% concentration it was 2485.1 Watts.
- When $ZnFe_2O_4$ was added to the 50% Ethylene Glycol + 50% Water mixture as the main cooling fluid at a 1% concentration, the volumetric heat transfer was calculated as 2424.2 Watts, at a 2% concentration it was 2465.7 Watts, and at a 3% concentration it was 2504.5 Watts.

In future studies, the impact of thermophysical properties on performance could be examined by using different nanofluids at various concentrations.

Research could be conducted to compare literature models with experimental studies. Measurements could be taken to assess the effects of different nanoparticle volumetric ratios and various temperature values on thermophysical properties. Performance evaluation could also be conducted using different base fluids instead of the water-ethylene glycol mixture based on the identified thermophysical properties.

CONFLICTS OF INTEREST

This study is a study reporting the results of the Master's thesis study conducted by Murat Gümüş under the supervision of Prof. Dr. Adnan SÖZEN. It was prepared with equal contributions among the authors. There is no conflict of interest.

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