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Research Article

Thermal Analysis of Heat Generation and Dissipation in Electric Vehicle Battery Systems Using Nanofluids

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Abstract

Maintaining the right temperature is one of the most important factors in improving the safety, performance, and lifespan of lithium-ion batteries used in electric vehicles (EVs). As batteries generate heat during charging and discharging, an efficient cooling system is needed to prevent overheating and ensure reliable operation. This study investigates the heat generation and dissipation characteristics of an EV battery system using a nanofluid as the cooling medium. A computational analysis was carried out to evaluate the cooling performance of the battery under continuous operating conditions. The nanofluid entered the cooling channel at an inlet temperature of 30°C, allowing effective removal of heat from the battery surface.

The simulation results show that the nanofluid provides efficient heat transfer, resulting in a more uniform temperature distribution throughout the battery module. The battery temperature was successfully maintained at approximately 30°C, indicating that the cooling system effectively removed the generated heat while preventing the formation of localized hot spots. Compared with conventional cooling fluids, the nanofluid demonstrated better heat transfer capability, leading to improved thermal management and enhanced battery reliability.

Overall, the study highlights the potential of nanofluid-based cooling systems for electric vehicle battery thermal management. By effectively controlling heat generation and dissipation, this approach can improve battery efficiency, increase battery life, and enhance the overall safety and performance of electric vehicle battery systems.

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1. INTRODUCTION

The world is moving from internal combustion engine (ICE) to electric vehicle. For the past 5 years the consumers are demanding more of electric segment automobile either it is full electric vehicle or hybrid technologies combining electric and ICE trend. All electric vehicle, have electric motor instead of IC engine. The vehicles use large traction battery back to power electric motor. Because it run on electricity so vehicle emits no exhaust from tailpipe. The thermal management system in electric vehicle is needed as it need to operate in very cold and very hot climate condition.

With the demand of electric vehicle, the companies are now focusing on producing electric powertrain. Manufactures have adopted different method of producing electric vehicle but the battery- electric technology has seen a rapid development and implication in automobile industry.

With the rapid increase in demand the challenge to maintain the battery temperature is most difficult and important parameter in electric vehicle due to high charging time and less range available as compared to IC engine. The selection of material for battery and its design is also important as it decide the temperature variation in it.

Ahmadou Samba et al. [1], in the paper "Analysis of Thermal Modeling and Thermal Management in Battery Electric Vehicles," emphasized that temperature is one of the most significant factors affecting the performance, efficiency, and lifespan of lithium-ion batteries. The study highlighted the advantages of pouch cells, including their design flexibility, ease of manufacturing, and lower production costs. Furthermore, the authors reported that the optimal operating temperature range for lithium-ion batteries is 25–40 °C, while electric vehicles are typically expected to operate under environmental conditions ranging from −30 °C to 60 °C. These findings underscore the importance of an effective battery thermal management system (BTMS) to maintain battery temperature within the desired range.

Jian Xu et al. [2], in "Thermal Management of High-Power Lithium-ion Battery Using Mini-channelAluminum Tubes," investigated the influence of battery cell size on thermal behavior, noting that variations in heat transfer area per unit volume significantly affect heat dissipation. The study evaluated mini-channel aluminum tube cooling and demonstrated that liquid cooling provides superior thermal performance compared with air cooling and phase change material (PCM)-based cooling. The enhanced cooling effectiveness was attributed to improved heat transfer characteristics and optimized channel configurations.

In the paper "Thermal Management System with Nanofluids for Electric Vehicle Battery Cooling Modules," the authors [3] reviewed existing battery cooling techniques, including air cooling, liquid cooling, and phase change materials, while identifying the limited application of nanofluids in electric vehicle battery thermal management.

The study proposed the use of nanofluids flowing through corrugated mini-channels to improve heat transfer between the coolant and the battery surface. The research further examined the effects of coolant flow direction and cooling capacity, demonstrating the potential of nanofluids to enhance thermal management performance.

The paper "Thermal Cooling Characteristics of Li-ion Battery Pack with Thermoelectric Ferrofluid Cooling Module" by the authors [4] investigated the thermal performance of a lithium-ion battery pack integrated with a thermoelectric ferrofluid cooling module. Through experimental analysis, the study evaluated temperature distribution under varying operating conditions, including hot-side and cold-side flow rates, thermoelectric input voltage, coolant type, and ferrofluid concentration. The results showed that the thermoelectric cooling system significantly improved cooling performance, maintaining the battery temperature below 30 °C, thereby enhancing battery safety and operational efficiency.

The rapid growth of electric vehicles (EVs), hybrid electric vehicles (HEVs), and renewable energy storage systems has significantly increased the demand for high-performance lithium-ion (Li-ion) batteries. Due to their high energy density, long cycle life, and low self-discharge rate, Li-ion batteries have become the preferred energy storage technology for modern transportation and portable electronic devices. However, during high-rate charging and discharging operations, these batteries generate a considerable amount of heat, which can lead to elevated cell temperatures and temperature non-uniformity within the battery pack. Excessive heat accumulation adversely affects battery performance, accelerates capacity degradation, reduces cycle life, and may even trigger thermal runaway, posing serious safety risks. Therefore, an efficient Battery Thermal Management System (BTMS) is essential to maintain the battery within the optimal operating temperature range and ensure its safety, reliability, and longevity (Wu et al., 2021; Liu et al., 2021).

Several thermal management techniques have been developed to address the thermal challenges associated with Li-ion batteries. Among these, air cooling is widely adopted because of its simplicity and low cost, but its relatively low heat transfer capability limits its effectiveness in high-power battery applications. Liquid cooling systems offer significantly higher cooling performance due to the superior thermal properties of liquids. Lan et al. (2016) [5] demonstrated that aluminum mini channel-based liquid cooling effectively reduced the maximum battery temperature while improving temperature uniformity across the battery pack. Their study highlighted the advantages of compact mini channel structures in enhancing heat transfer under high heat generation conditions.

To further improve cooling efficiency, researchers have proposed advanced cooling strategies beyond conventional liquid cooling. Saw et al. (2018) [6] introduced a mist cooling-based thermal management system in which fine water droplets evaporate on the cooling surface, providing high heat removal

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through latent heat transfer. Their results showed that mist cooling significantly reduced battery temperature while requiring relatively low coolant flow rates, making it a promising technique for high-power battery applications.

Hybrid cooling methods have also attracted considerable attention because they combine the advantages of different thermal management technologies. Mashayekhi et al. (2020) [7] developed a hybrid cooling system integrating phase change materials (PCM) with Al_2O_3 nanofluid flowing through aluminum mini channels. The combination of latent heat storage by PCM and enhanced convective heat transfer provided by nanofluids effectively reduced peak battery temperatures and improved thermal uniformity compared to conventional cooling methods.

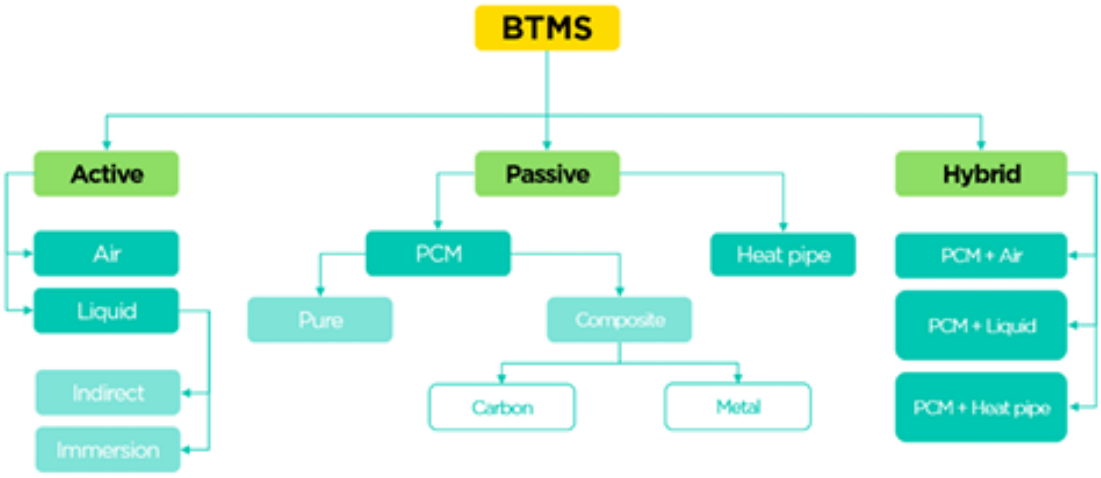
Comprehensive review studies have summarized the current state of battery thermal management technologies and identified future research directions. Wu et al. (2021) [8] reviewed various BTMS approaches, including air cooling, liquid cooling, phase change materials, heat pipes, and hybrid cooling systems, emphasizing that hybrid thermal management strategies offer superior thermal performance while addressing the limitations of individual techniques. Similarly, Liu et al. (2021) [9] highlighted recent advancements in BTMS, discussed the challenges associated with thermal runaway prevention, energy consumption, system complexity, and cost, and emphasized the need for innovative cooling technologies capable of maintaining both thermal safety and high battery performance.

Batteries are the largest, most expensive and most important component of electric vehicle. It is the heart of electric vehicle. The effect of climate and road condition are harsh, and it's very critical that we understand the battery care and charging requirements carefully.

Temperature is the most critical parameter in battery systems as it impacts the battery's performance. The heat is generated in electric vehicle when electric current flows during charging and discharging of battery as the current faces resistance which causes the temperature to increase. So, it is most important to control the temperature in electric vehicle.

Thermal management in an EV battery is of utmost important since it needs to operate in very cold and very hot weather condition.

There is no single alternative for selecting BTMS for battery-pack. The following figure shows the outline of thermal management technologies.



Here, we are using liquid technology on active battery thermal management systems. Between air-based and liquid-based BTMS for same battery module, temperature difference within the module increases with an increase in air flow rate, better temperature difference is seen in liquid cooling system. The liquid cooling method is more energy efficient than air cooling. In this project, nanofluid as liquid coolant material is used for BTMS.

A nanofluid is a fluid containing nanometer-sized particles, called nanoparticles. The nanoparticles used in nanofluid are typically made of metals, oxide, carbides or carbon nanotubes. Common based fluids include water, ethylene glycol and oil. The properties of nanofluid are increases thermal conductivity, increased heat transfer and increased critical heat flux.

Battery module is combination of components of battery system that includes at least the following components: a battery, battery management electronics for battery cell balancing, voltage and temperature measurement and connectors.

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Battery Module

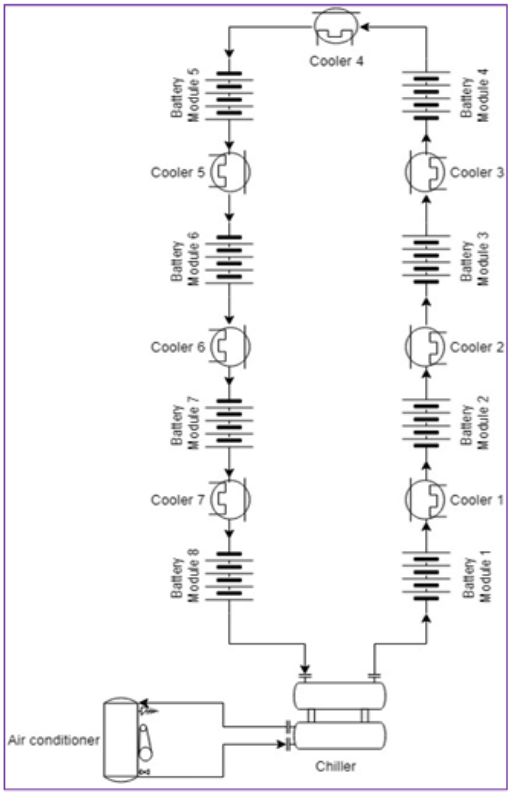
Battery cell is the smallest unit, comprised of 4 key components including cathode, anode, electrolyte and separator. The characteristics of a battery cell play a pivotal role in the overall performance of electrified vehicles.



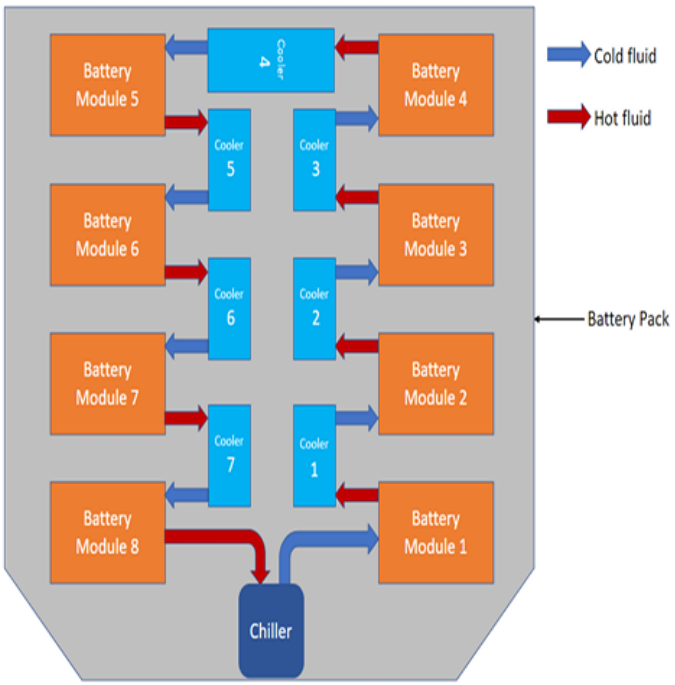
Battery Cell

The thermal network design to analyse the thermal behaviour of nanofluid with respect to different temperatures.

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On the basis of network diagram, a prototype in Ansys software is created to find the variation of temperature in different battery module.



Arrangement of Battery pack and nanofluid flow

B= Battery (module) surface temperature

F= Nano-fluid inlet temperature

V= inlet velocity of nano-fluid

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C=Thermo-Electric Cooler Temperature
b "n" in= inlet liquid temperature of battery "n"
b "n" out = outlet liquid temperature of battery "n"
"n" = battery's number in sequence
c= Heat lost by nano-fluid due to cooler
h=Heat gained by nano-fluid due to battery.

Analysis parameter

Analysis parameter is based on different working condition of EVs such as climate condition, speed of vehicle etc. The following parameter are used to analyze the thermal behavior of batteries and nanofluid.

Input Parameter

The temperature of nano-fluid at inlet is 18°C, temperature of batteries module is 30°C, the velocity of nano-fluid is 1m/s. The thermo-electric cooler temperatures are C1, C2, C3, C4, C5, C6, C7.

Output Parameter

The temperature of battery inlet and outlets are b1 in, b1 out, b2in, b2out upto 8in and 8 out. The cooling of liquid in every cooler (c) is (c1=b1out-b2in), (c2=b2out-b3in) upto (c7=b7out-b8in). The heating of liquid in every battery (h) is (h1=b1out-b1in), (h2=b2out-b2in), upto (h8=b8out-b8in).

The input
data that are put in ansys software is given below

	Input Parameter (To be put in ANSYS)									
				Cooler Temperature						
Test	Battery Temp	Inlet fluid tempera	Inlet veloc	C7	C6	C5	C4	C3	C2	C1
1	30	18	1	18	18	18	14	18	6	18
2	30	18	1	18	18	18	14	18	6	14
3	30	18	1	18	18	18	14	18	6	10
4	30	18	1	18	18	18	14	18	6	6
5	30	18	1	18	18	18	14	18	6	2
6	30	18	1	18	18	18	14	18	2	18
7	30	18	1	18	18	18	14	18	2	14
8	30	18	1	18	18	18	14	18	2	10
9	30	18	1	18	18	18	14	18	2	6
10	30	18	1	18	18	18	14	18	2	2
11	30	18	1	18	18	18	14	14	18	18
12	30	18	1	18	18	18	14	14	18	14
13	30	18	1	18	18	18	14	14	18	10
14	30	18	1	18	18	18	14	14	18	6
15	30	18	1	18	18	18	14	14	18	2
16	30	18	1	18	18	18	14	14	14	18
17	30	18	1	18	18	18	14	14	14	14
18	30	18	1	18	18	18	14	14	14	10
19	30	18	1	18	18	18	14	14	14	6
20	30	18	1	18	18	18	14	14	14	2
21	30	18	1	18	18	18	14	14	10	18
22	30	18	1	18	18	18	14	14	10	14
23	30	18	1	18	18	18	14	14	10	10
24	30	18	1	18	18	18	14	14	10	6
25	30	18	1	18	18	18			10	2
26	30	18	1	18	18	18	14	14	6	18
27	30	18	1	18	18	18	14	14	6	14
28	30	18	1	18	18	18	14	14	6	10
29	30	18	1	18	18	18	14	14	6	6
30	30	18	1	18	18	18	14	14	6	2
31	30	18	1	18	18	18	14	14	2	18
32	30	18	1	18	18	18	14	14	2	14
33	30	18	1	18	18	18	14	14	2	10
34	30	18	1	18	18	18	14	14	2	6
35	30	18	1	18	18	18	14	14	2	2

Plot Area

The output result obtained from the software is below.

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Output Parameter (Hatch value from ANSYS)															
Battery In and Out Temperature (k)															
B1 In	B1 Out	B2 In	B2 Out	B3 In	B3 Out	B4 In	B4 Out	B5 In	B5 Out	B6 In	B6 Out	B7 In	B7 Out	B8 In	B8 Out
291.15	292.88	292.8	294.29	293.6	295.02	294.85	296.16	295.75	296.89	296.63	297.58	297.29	298.15	297.8	298.58
291.15	292.88	292.62	294.16	293.46	294.89	294.73	296.05	295.66	296.81	296.55	297.51	297.22	298.09	297.74	298.54
291.15	292.88	292.45	293.98	293.31	294.77	294.61	295.95	295.56	296.72	296.47	297.45	297.16	298.04	297.69	298.49
291.15	292.88	292.27	293.83	293.16	294.64	294.49	295.85	295.46	296.64	296.39	297.38	297.09	297.98	297.64	298.45
291.15	292.88	292.09	293.67	293.01	294.52	294.37	295.75	295.36	296.56	296.31	297.13	297.03	297.93	297.59	298.4
291.15	292.88	292.8	294.29	293.43	294.87	294.71	296.03	295.64	296.79	296.53	297.5	297.21	298.08	297.73	298.53
291.15	292.88	292.62	294.14	293.28	294.74	294.59	295.93	295.54	296.71	296.46	297.43	297.14	298.03	297.68	298.48
291.15	292.88	292.44	293.98	293.13	294.62	294.47	295.83	295.44	296.63	296.38	297.36	297.08	297.97	297.63	298.44
291.15	292.88	292.27	293.83	292.98	294.49	294.34	295.73	295.34	296.54	296.3	297.3	297.02	297.92	297.58	298.39
291.15	292.88	292.09	293.67	292.83	294.36	294.22	295.63	295.25	296.46	296.22	297.23	296.95	297.86	297.52	298.35
291.15	292.88	292.8	294.29	294.14	295.48	295.12	296.38	295.96	297.07	296.8	297.72	297.42	298.26	297.91	298.68
291.15	292.88	292.62	294.14	293.99	295.35	295	296.27	295.86	296.98	296.72	297.66	297.36	298.21	297.86	298.64
291.15	292.91	292.47	294.04	293.89	295.28	294.93	296.23	295.81	296.95	296.69	297.65	297.35	298.22	297.87	298.63
291.15	292.88	292.27	293.83	293.7	295.1	294.76	296.07	295.67	296.82	296.56	297.52	297.23	298.1	297.75	298.54
291.15	292.88	292.09	293.67	293.55	294.97	294.64	295.97	295.57	296.74	296.48	297.45	297.17	298.04	297.7	298.5
291.15	292.88	292.8	294.29	293.96	295.32	294.98	296.25	295.84	296.97	296.7	297.64	297.35	298.2	297.84	298.63
291.15	292.88	292.62	294.14	293.81	295.2	294.86	296.15	295.75	296.88	296.62	297.58	297.28	298.14	297.79	298.58
291.15	292.88	292.44	293.98	293.66	295.07	294.73	296.05	295.65	296.8	296.55	297.51	297.22	298.09	297.74	298.54
291.15	292.88	292.27	293.83	293.52	294.95	294.61	295.95	295.55	296.72	296.47	297.44	297.15	298.03	297.69	298.49
291.15	292.88	292.09	293.67	293.37	294.82	294.49	295.84	295.46	296.64	296.39	297.37	297.09	297.98	297.63	298.44
291.15	292.88	292.8	294.29	293.78	295.17	294.83	296.13	295.73	296.87	296.61	297.56	297.27	298.13	297.78	298.57
291.15	292.88	292.62	294.14	293.63	295.05	294.71	296.03	295.63	296.79	296.53	297.5	297.2	298.08	297.73	298.53
291.15	292.88	292.45	293.98	293.49	294.92	294.59	295.93	295.53	296.7	296.45	297.43	297.14	298.02	297.68	298.48
291.15	292.89	292.27	293.83	293.34	294.79	294.47	295.82	295.44	296.62	296.37	297.36	297.08	297.97	297.62	298.44
291.15	292.88	292.09	293.67	293.19	294.67	294.35	295.72	295.34	296.54	296.29	297.29	297.01	297.91	297.57	298.39
291.15	292.88	292.8	294.29	293.61	295.02	294.69	296.01	295.61	296.77	296.51	297.48	297.19	298.07	297.72	298.52
291.15	292.89	292.62	294.13	293.44	294.87	294.55	295.9	295.52	296.68	296.44	297.42	297.14	298.02	297.66	298.46
291.15	292.88	292.44	293.98	293.31	294.77	294.44	295.8	295.42	296.6	296.36	297.35	297.06	297.96	297.61	298.43
291.15	292.88	292.27	293.83	293.16	294.64	294.32	295.7	295.32	296.52	296.28	297.28	297	297.9	297.56	298.38
291.15	292.88	292.09	293.67	293.01	294.52	294.2	295.6	295.22	296.44	296.2	297.21	296.94	297.85	297.51	298.34
291.15	292.88	292.8	294.29	293.43	294.87	294.54	295.89	295.5	296.67	296.42	297.4	297.12	298	297.66	298.46
291.15	292.88	292.62	294.14	293.28	294.74	294.42	295.78	295.4	296.59	296.34	297.33	297.05	297.95	297.6	298.42
291.15	292.88	292.44	293.98	293.13	294.62	294.3	295.68	295.3	296.51	296.26	297.27	296.99	297.89	297.55	298.37
291.15	292.88	292.27	293.83	292.98	294.49	294.18	295.58	295.2	296.42	296.18	297.2	296.92	297.83	297.5	298.33
291.15	292.88	292.09	293.67	292.88	294.36	294.06	295.48	295.11	296.34	296.1	297.13	296.86	297.78	297.45	298.28

The data obtained for cooling of liquid in every cooler and heating of liquid in every battery is below

Auto-Generated							Auto-Generated							
Cooling across TS (c_n)							Heating across Battery (h_n)							
c1	c2	c3	c4	c5	c6	c7	h1	h2	h3	h4	h5	h6	h7	h8
0.087	0.687	0.168	0.404	0.261	0.294	0.35	1.733	1.495	1.417	1.303	1.137	0.951	0.86	0.789
0.263	0.7	0.163	0.399	0.257	0.292	0.348	1.733	1.536	1.438	1.323	1.151	0.963	0.87	0.796
0.439	0.673	0.157	0.394	0.253	0.288	0.345	1.734	1.537	1.459	1.341	1.166	0.974	0.878	0.802
0.615	0.667	0.152	0.389	0.25	0.285	0.342	1.733	1.558	1.482	1.361	1.18	0.986	0.888	0.809
0.791	0.66	0.148	0.384	0.246	0.102	0.34	1.733	1.579	1.504	1.381	1.195	0.817	0.897	0.816
0.087	0.864	0.161	0.398	0.256	0.291	0.347	1.733	1.495	1.442	1.326	1.154	0.965	0.872	0.796
0.264	0.858	0.156	0.393	0.252	0.288	0.345	1.734	1.516	1.465	1.345	1.169	0.976	0.881	0.803
0.44	0.852	0.152	0.388	0.249	0.284	0.342	1.734	1.538	1.487	1.365	1.183	0.988	0.89	0.81
0.615	0.846	0.146	0.384	0.246	0.282	0.34	1.733	1.559	1.509	1.384	1.199	1	0.9	0.817
0.79	0.839	0.141	0.379	0.242	0.279	0.337	1.734	1.579	1.53	1.403	1.213	1.012	0.909	0.824
0.087	0.153	0.354	0.414	0.268	0.301	0.356	1.734	1.496	1.337	1.252	1.105	0.926	0.84	0.775
0.264	0.145	0.349	0.409	0.264	0.297	0.353	1.734	1.517	1.358	1.272	1.119	0.937	0.849	0.781
0.439	0.148	0.35	0.421	0.262	0.293	0.352	1.76	1.569	1.391	1.297	1.14	0.96	0.863	0.764
0.615	0.132	0.338	0.399	0.258	0.292	0.348	1.734	1.558	1.402	1.31	1.149	0.961	0.868	0.794
0.791	0.126	0.333	0.395	0.254	0.288	0.345	1.733	1.58	1.424	1.33	1.164	0.972	0.877	0.801
0.088	0.331	0.347	0.408	0.264	0.297	0.353	1.734	1.496	1.362	1.275	1.123	0.94	0.852	0.783
0.264	0.324	0.342	0.404	0.26	0.294	0.35	1.733	1.517	1.385	1.295	1.138	0.951	0.861	0.789
0.439	0.317	0.337	0.399	0.257	0.291	0.347	1.733	1.537	1.406	1.315	1.153	0.963	0.87	0.795
0.614	0.311	0.332	0.394	0.253	0.288	0.345	1.734	1.558	1.428	1.334	1.166	0.975	0.879	0.803
0.791	0.305	0.327	0.389	0.249	0.285	0.343	1.733	1.58	1.451	1.353	1.181	0.986	0.889	0.81
0.087	0.508	0.341	0.402	0.259	0.293	0.349	1.734	1.495	1.389	1.298	1.14	0.953	0.862	0.79
0.263	0.502	0.336	0.398	0.256	0.291	0.347	1.733	1.516	1.412	1.318	1.155	0.966	0.872	0.798
0.439	0.496	0.331	0.393	0.252	0.287	0.344	1.734	1.537	1.434	1.337	1.17	0.976	0.881	0.804
0.617	0.488	0.326	0.388	0.249	0.285	0.342	1.735	1.558	1.455	1.356	1.185	0.989	0.891	0.811
0.791	0.482	0.321	0.383	0.245	0.281	0.34	1.733	1.579	1.477	1.376	1.199	1	0.9	0.818
0.087	0.687	0.335	0.397	0.255	0.29	0.346	1.733	1.496	1.416	1.322	1.158	0.968	0.873	0.798
0.264	0.69	0.32	0.388	0.242	0.279	0.352	1.735	1.508	1.435	1.349	1.166	0.977	0.879	0.799
0.439	0.674	0.325	0.387	0.248	0.284	0.341	1.733	1.538	1.46	1.361	1.187	0.991	0.892	0.812
0.616	0.667	0.32	0.382	0.244	0.281	0.339	1.733	1.559	1.482	1.38	1.202	1.002	0.902	0.819
0.791	0.661	0.314	0.378	0.241	0.278	0.337	1.734	1.58	1.504	1.399	1.217	1.014	0.911	0.826
0.087	0.865	0.329	0.391	0.251	0.287	0.343	1.734	1.495	1.443	1.345	1.176	0.982	0.885	0.806
0.263	0.858	0.324	0.386	0.247	0.283	0.341	1.733	1.516	1.465	1.365	1.19	0.993	0.894	0.813
0.439	0.851	0.318	0.381	0.244	0.281	0.338	1.733	1.537	1.486	1.384	1.205	1.005	0.904	0.819
0.615	0.845	0.313	0.377	0.241	0.277	0.335	1.733	1.558	1.508	1.404	1.22	1.017	0.912	0.827
0.791	0.788	0.308	0.371	0.237	0.274	0.333	1.733	1.579	1.481	1.422	1.234	1.028	0.922	0.833

The heat gain by liquid in all battery obtained is below, it shows the heat gain value is decreasing when the liquid flow is moving from battery 1 to 8.

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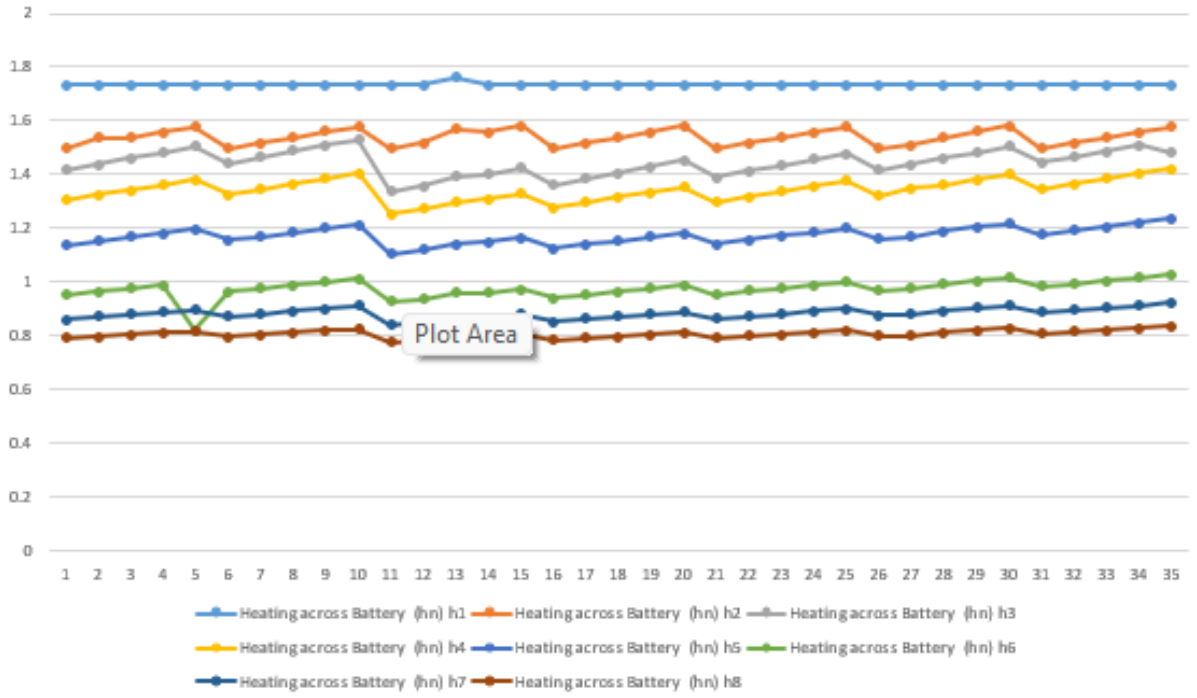


Figure1 Heat gain (heating) of nanofluid @ 30°C

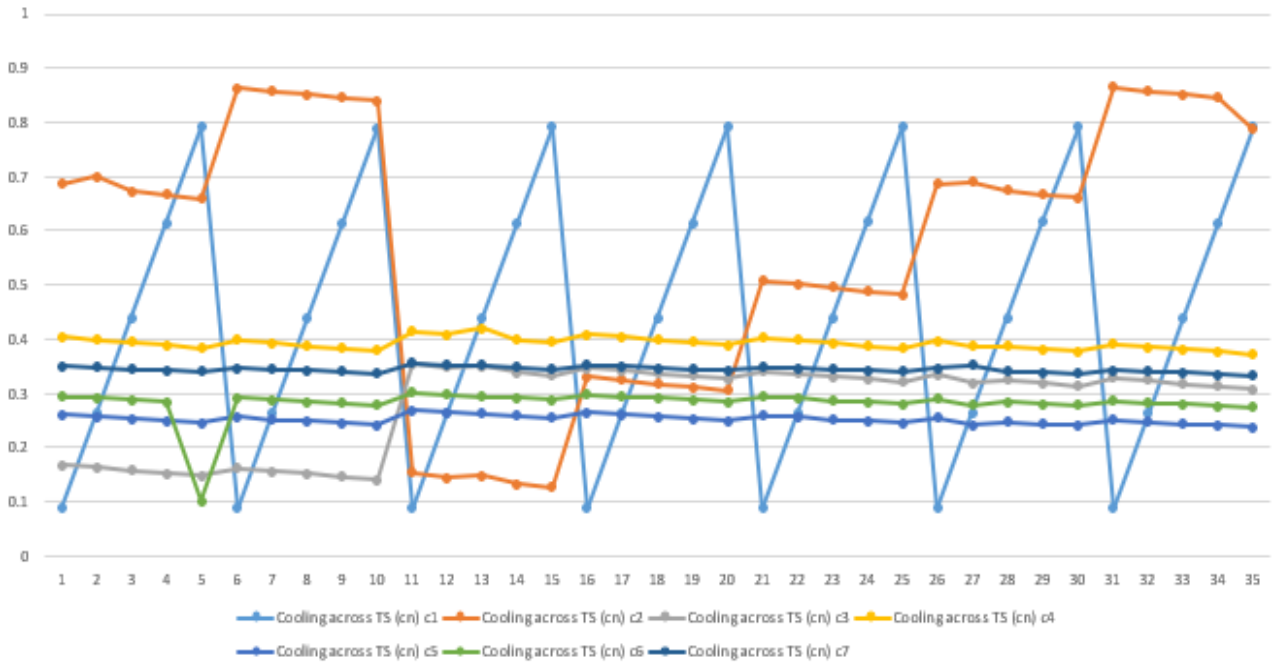


Figure 2 Heat loss (cooling) of Nano-fluid @ 30°C

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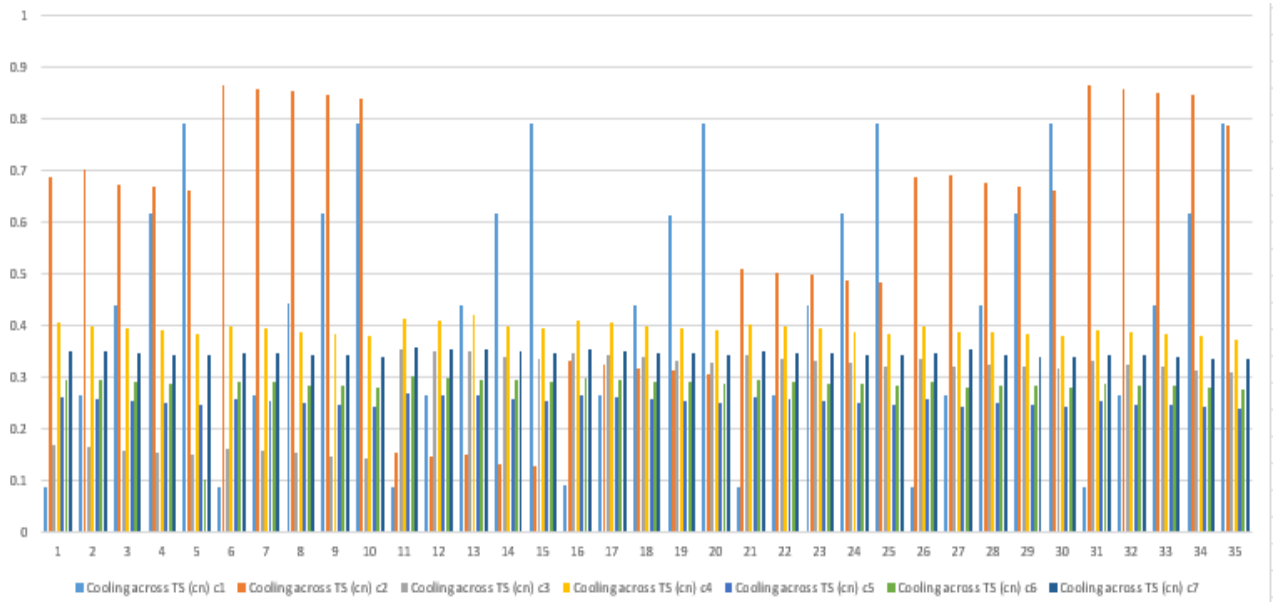


Figure 3 Cooling Performance @30°C

RESULTS

The nanofluid flows through cooling jacket and absorb heat from battery surface module resulting in heat of nanofluid after that the nanofluid flow through jacket where a cooler is installed to cool the nanofluid, thus the heat loss takes place and the temperature of nanofluid is reached is below 30°C. Thus, the heating of battery is avoided with the use of nanofluid.

CONCLUSION

The value obtained from Ansys software shows that the nanofluid plays a crucial role in maintaining the temperature across the battery module. The heat gain and loss by nanofluid is governed by heat exchanger phenomenon. The battery temperature is maintained within the temperature range thus; the battery life and performance are improved.

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