

Enhanced Thermal Management of Electric Vehicle Batteries Using Graphene-Based Nanofluid Coolant

Bernard Sagaiyaraj ^{*}, Sofea Zawawi ^{**}, Fareez Allany ^{***}

Abstract Efficient thermal management of prismatic lithium-ion batteries is critical for electric vehicle (EV) performance, safety, and longevity. The thermal conductivity of conventional water-based cooling systems is restricted, which raises battery temperature and increases energy consumption. This study examines AQUENE, a distinctive mixture of graphene-based nanofluid as an advanced coolant for prismatic battery packs. This graphene-based nanofluid offers improved thermal conductivity, stability, and minimal increase in viscosity compared to water. It consists of 1% functionalized graphene dissolved in deionized water. A 1.5-RT water-cooled chiller connected with a 4S1P prismatic battery pack under controlled charge-discharge cycles was implemented for experimental evaluation. Battery surface temperature, chiller energy consumption, pumping power, and energy efficiency ratio were the key performance indicators. AQUENE decreases the peak battery temperature by 1.01% compared to water. Energy efficiency improved by 23.43%, while chiller compressor energy consumption decreased by 22.46%. The results demonstrate that AQUENE enhances convective heat transfer, reduces thermal stress, and improves system energy efficiency without significant retrofitting. Implementation in EV battery thermal management systems can extend battery lifespan, enable more compact cooling designs, and reduce operational energy demand, contributing to sustainable mobility and decarbonization goals.

Keywords Graphene nanofluid, electric vehicle battery, thermal management, heat transfer, energy efficiency, prismatic lithium-ion battery, convective cooling, nanotechnology, battery cooling systems

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I. Introduction

The demand for efficient thermal management of lithium-ion batteries has increased over the years due to the global adoption of electric vehicles (EVs). Effective heat dissipation is crucial because high or inconsistent temperatures within prismatic battery packs can lower the performance, limit cycle life, and increase safety issues (Zhang et al., 2023). Traditional liquid-based cooling strategies, such as water or glycol-based fluids in closed-loop systems, are limited by low thermal conductivity and suboptimal convective heat transfer. Due to these limitations, higher energy is consumed, cell temperatures become inconsistent, and larger or more complex cooling systems are required (Wu et al., 2019). Thermal management inconsistencies will worsen the battery degradation and create further difficulties for large-scale EV applications (Chen et al., 2021).

Nanofluids, which are suspensions of nanoparticles in base fluids, have become an attractive option for high-performance thermal management, with improved thermal conductivity and heat transfer without requiring significant system changes. Particularly, Graphene is a great option for nanofluid application due to its remarkable thermal conductivity and structural stability (Mehrali et al., 2014; Pavia, 2021; Elsaid et al., 2021). Research has proven that by applying the mechanisms such as Brownian motion, particle migration and micro-convection at fluid-solid interfaces, graphene-based nanofluids can improve convective heat transfer (Borode et al., 2021; Mehrali et al., 2014; Pavia, 2021).

This study introduces AQUENE, a graphene-based nanofluid for prismatic EV battery cooling. This paper demonstrates a structured analysis of its composition, thermophysical properties, and performance under controlled charge-discharge cycles. Analysis of factors such as battery surface temperature, chiller energy consumption, and energy efficiency reveals graphene nanofluids' potential as an effective and long-lasting solution for EV battery thermal management.

II. Nanofluid Characterization

1. Supplier-Provided Data

Blue Snow Frontier Technologies is the technology owner who formulated AQUENE, the graphene-based nanofluid for the enhanced thermal management of prismatic EV batteries. The supplier discloses three main components of AQUENE, namely functionalized graphene, water as the base fluid, and pH

stabilizer. The graphene concentration is approximately 1 wt%, while the remaining 99 wt% consists of the base fluid.

Table 1. AQUENE Specification Provided by Supplier

Parameter	Value
Appearance	Black liquid, odorless
Particle Size	Approx. 500 nm
Operating Temp.	4 - 80 °C
Density (at 20 °C)	998.7 kg/m ³
Dynamic Viscosity (at 20 °C)	1.0809 cP
pH	8.0 - 9.0

At 20 °C, AQUENE has 18.5% higher thermal conductivity (0.709 W/m·K) than water (0.598 W/m·K) and 21.5% higher thermal diffusivity (0.174 mm²/s versus 0.143 mm²/s for water), enabling faster internal heat propagation (Sagaiyaraj, 2023). Convective heat transfer coefficients were substantially improved under both laminar (1042.2 vs 109.4 W/m²·K) and turbulent flow (7743.9 vs 4694.5 W/m²·K), contributing to improved heat dissipation, reduced compressor runtime, and enhanced energy efficiency (up to 26% under laminar and 18.8% under turbulent conditions) (Sagaiyaraj, 2023).

2. Viscosity Measurement

The rheological properties of AQUENE were evaluated using a rotational viscometer at 23 °C. The measured dynamic viscosity of the nanofluid ranged from 1.02 to 1.04 cP over shear rates of 525-750 s⁻¹, corresponding to rotational speeds of 70-100 RPM and shear stresses of 5.36-7.79 dyne/cm².

The low viscosity, close to that of water (1.0 cP at room temperature), ensures minimal pumping requirements and low pressure drop in closed-loop battery cooling systems. The stability of viscosity across the tested shear rates confirms that the nanofluid will maintain consistent flow behavior under varying operating conditions, supporting reliable convective heat transfer performance.

3. Zeta Potential Measurement

To assess colloidal stability, the zeta potential of AQUENE was measured using a PALS (Phase Analysis Light Scattering) system. The sample exhibited a zeta potential of -45.11 mV, indicating strong electrostatic repulsion and excellent dispersion stability. The corresponding electrophoretic mobility was -

3.53 $\mu\text{m}\cdot\text{cm}/(\text{V}\cdot\text{s})$. Measurements were conducted at 25 °C in water, with a pH of 8.0.

The high magnitude of the zeta potential suggests that the graphene nanoparticles remain well-dispersed over extended periods, minimizing the risk of sedimentation and enhancing reliability in closed-loop battery cooling applications.

4. Particle Size Characterization

Dynamic Light Scattering (DLS) was used to determine the hydrodynamic size distribution of graphene nanoparticles in AQUENE. The effective particle diameter (D50) was 528.6 nm, with a polydispersity index (PDI) of 0.222, indicating a relatively narrow and uniform size distribution. Size analysis by intensity, volume, and number revealed mean diameters of 601.96 nm, 618.99 nm, and 439.04 nm, respectively. The distribution ranged from 297.7 nm (D10) to 938.5 nm (D90), with a lognormal geometric standard deviation of 1.56.

The DLS results confirm that AQUENE contains well-dispersed, predominantly submicron graphene nanoparticles, with a uniform size distribution that supports stable, clog-free operation in liquid cooling systems. The narrow size distribution also helps consistent heat transfer and reduces the risk of particle sedimentation or agglomeration.

5. Raman Spectroscopy

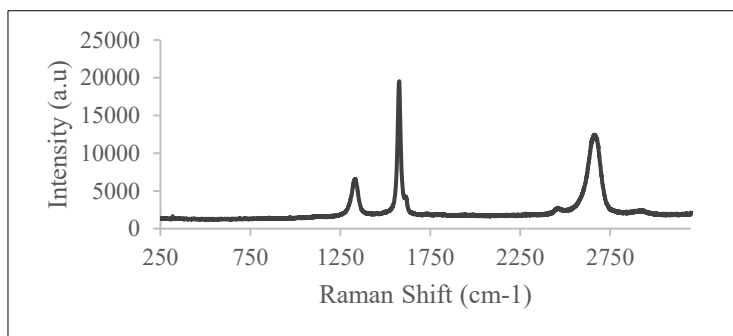


Figure 1. Raman Spectra of AQUENE

Raman spectra were obtained using a Renishaw inVia spectrometer with a 633 nm laser. The characteristic D, G, and 2D bands were observed at 1330, 1578, and 2665 cm^{-1} , respectively (Figure 1). The D/G intensity ratio (~ 0.33) indicates a balance between structural integrity and functionalization, while the

2D/G ratio (~0.63) confirms the presence of few-layer graphene, which is beneficial for thermal conductivity and mechanical stability.

6. X-Ray Photoelectron Spectroscopy (XPS)

XPS analysis was performed to investigate the surface elemental composition and chemical characteristics of the graphene nanoparticles in AQUENE. Measurements were conducted using an AXIS Ultra DLD (Kratos, UK) equipped with an Al K α X-ray source (1486.6 eV).

The survey scan revealed the following surface composition: carbon (C 1s) 72.02 at%, oxygen (O 1s) 23.34 at%, silicon (Si 2p) 9.07 at%, and sodium (Na 1s) 0.23 at%. The predominance of carbon confirms that graphene is the major component at the nanoparticle surfaces, while the oxygen content indicates the presence of surface functional groups, likely introduced during functionalization to enhance dispersion and colloidal stability. Minor signals from silicon and sodium suggest low levels of contaminants, supporting the chemical purity of the nanofluid.

III. Experimental Setup

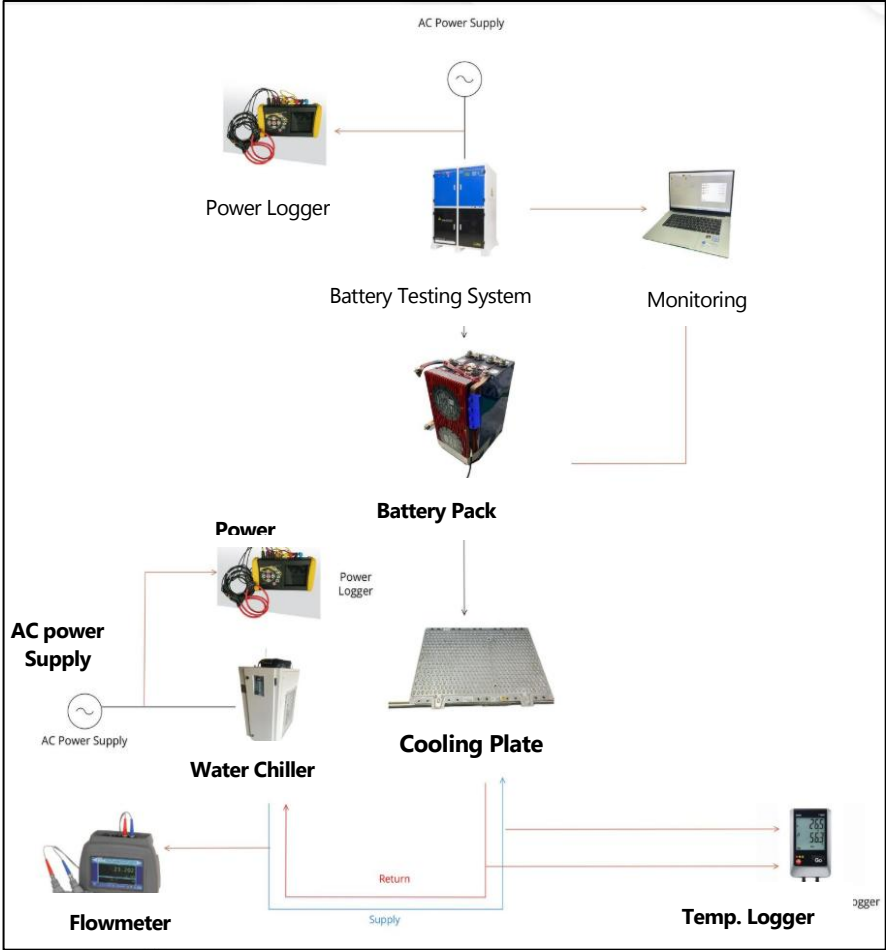


Figure 2. The Battery Cooling Test Configuration



Figure 3. The Battery Cooling Test Rig



1.5 RT Water-cooled Chiller



Ultrasonic Flowmeter Sensor



Flowmeter Readings



4-Channel Thermal logger



4SiP Prismatic Battery Pack



Temperature Sensor at Inlet and Outlet of the Chiller

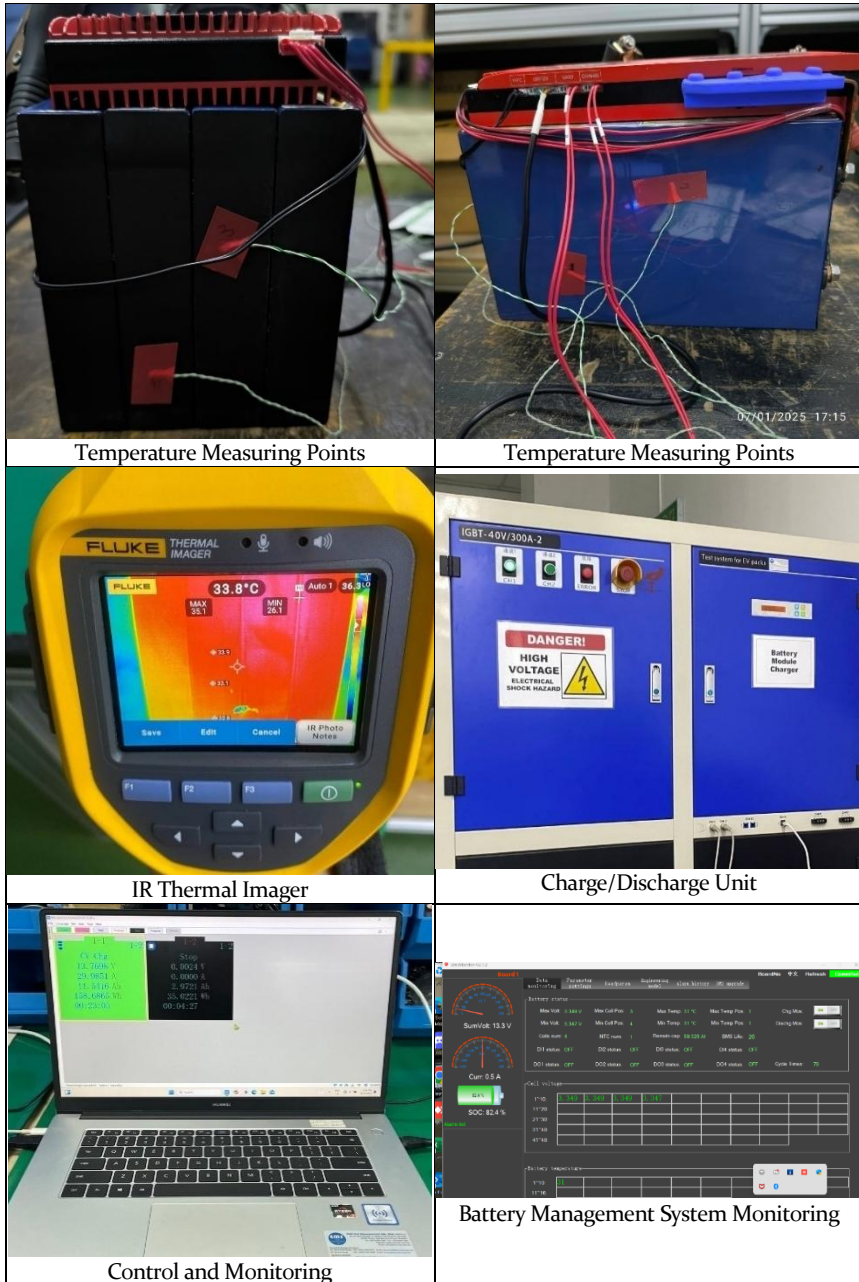


Figure 4. Compilation of Experiment Setup Photos

IV. Methodology

AQUENE thermal performance was evaluated using a 5.3 kW water-cooled chiller as the cooling source, and a lithium-ion battery pack connected in 4 series and 1 parallel, resulting in 12.8 V nominal voltage and 72 Ah battery capacity as the heat source. A flat cooling plate was placed under the battery pack, acting as the main heat exchanger. Four temperature sensors were placed on the four different points as follows to monitor both the cooling system and the battery thermal performance;

- Outlet of the chiller (chilled water supply) – T1
- Inlet of the chiller (chilled water return) – T2
- Two identified hotspots on the battery surfaces – T3, T4

Two tests were conducted on the battery pack, which is charging from 50% to 100% state of charge (SOC) and discharging from 100% to 50% at a constant current of 40 A. This resulted in the battery pack rising to a maximum temperature of approximately 40 °C without sacrificing the battery health. Before the test begins, the battery is ensured to be fully charged at 100% SOC to allow the battery management system (BMS) to calibrate.

The test was conducted over two weeks with two different coolants: water as the coolant in the first week as the system baseline, and AQUENE for comparison in the second week. The chiller setup is as follows;

- Setpoint: 20 °C (chiller supply temperature)
- Bypass valve between supply and return pipe opened to 40% (to control the supply flow rate)
- Chilled water supply pressure of 5 psi
- Flow rate between 2 and 3 L/min

Supply-return temperature differentials, power consumption, and chiller efficiency under the controlled charge-discharge cycle were continuously monitored.

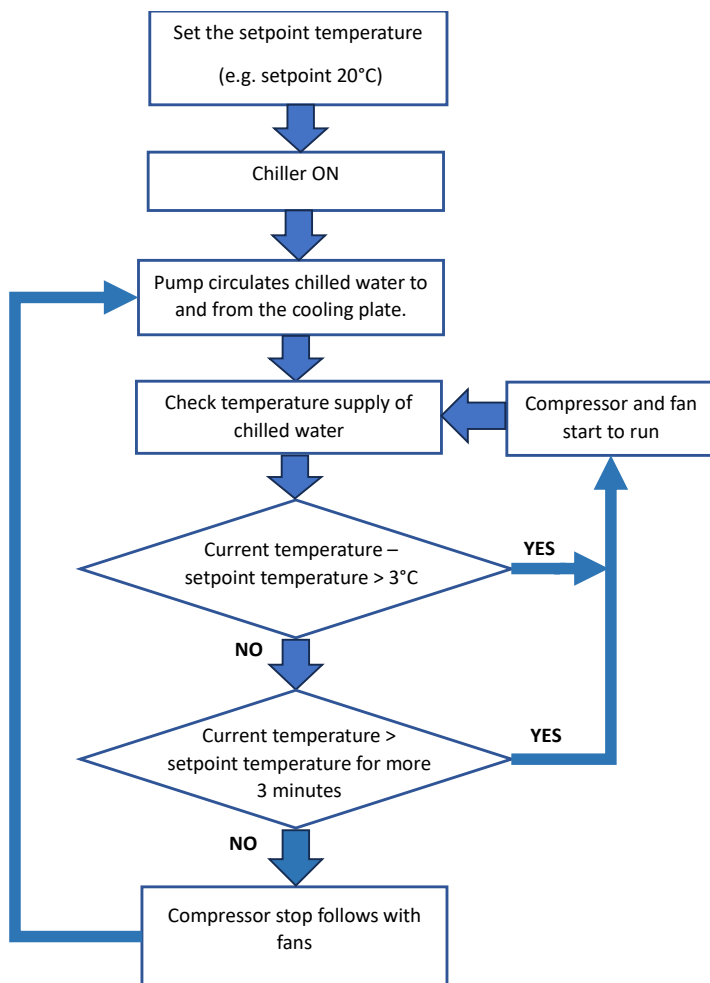


Figure 5. Algorithm Block Diagram of SCP40 Chiller

The ambient temperature of indoor where the battery pack was located and outdoor where the chiller was located were monitored during the test. The battery thermal performance test was conducted as follows;

1. The BMS was calibrated by charging the battery to 100% SOC each day before any test was conducted.
2. The chiller water tank was filled until the specified level.
3. Power and temperature data logging was started for both the chiller and the battery testing system with a 1-minute logging frequency.

4. The chiller was switched on for a while to stabilize the temperature on the cooling plate before the discharging process began.
5. The battery testing system was set to discharge mode at 40 A constant current.
6. The discharging process started once the cooling plate achieved a temperature between 20 and 21 °C.
7. The discharging process stopped when the battery pack reached 50% SOC.
8. The battery testing system was set to charging mode at 40 A constant current.
9. The charging process started, and the battery pack was charged until it reached 100% SOC.
10. Steps 6 to 9 were repeated continuously from 10:00 to 17:00 daily.

This test procedure was repeated five days consecutively using water as the coolant to establish a baseline before changing to AQUENE, and the test was repeated for another five days. The water coolant was converted to AQUENE by diluting the concentrate AQUENE formula in the coolant. The chiller was maintained with the same chiller setup as the baseline, and the system was allowed to run for several hours to ensure even dispersion of AQUENE in the system. Once the coolant achieved the specific AQUENE concentration required, the same test procedure was repeated.

This approach ensured that both coolants could be evaluated under similar operational and environmental conditions. The performance of temperature, power consumption, and cooling efficiency can be compared directly

V. Performance Metrics

Battery Thermal Metrics

- Peak battery temperature (°C)
- Median battery temperature (°C)
- Steady-state temperature difference (ΔT , °C) across hotspots

Cooling System / Chiller Metrics

- Total cooling load (RTH)
- Total chiller power consumption (kWh)
- Pump power consumption (kWh)
- Compressor power consumption (kWh)
- Chiller efficiency (kW/RT)
- Average compressor run time per cycle (minutes/cycle)
- Number of chiller cycles

Energy Efficiency Metrics

- Normalized chiller energy consumption (kWh, adjusted for outdoor temperature)
- Percentage reduction in compressor energy consumption
- Percentage improvement in chiller energy efficiency (kW/RT)

Table 2. Performance Metrics of Water vs Nanofluid

	UOM*	Water	Nanofluid
Battery Peak Temperature	°C	32.73	32.40
Battery Median Temperature	°C	28.22	27.00
Total Cooling Load	RTh	0.54	0.54
Total Power Consumption	kWh	2.46	2.39
Total Power Consumption by Pump	kWh	1.82	1.89
Total Power Consumption by Compressor	kWh	0.65	0.50
Chiller Efficiency	kW/RT	1.21	0.92
Average Chiller running cycle	minute/cycle	13.98	12.67
Number of Chiller Cycle	cycle	27	23

*UOM = Unit of Measurement

VI. Results

Table 3. Cooling Performance Comparison of Water vs AQUENE

Coolant	Compressor Energy (kWh)	Cooling Load (RTh)	Chiller Efficiency (kW/RT)
Water (baseline)	0.65	0.54	1.21
AQUENE	0.50	0.54	0.92
Improvement (%)	22.46%	-	23.43%

Table 3 presents the comparison of cooling performance between conventional water coolant and AQUENE graphene-based nanofluid. Key metrics include compressor energy consumption, cooling load, chiller efficiency, outdoor temperature during testing, normalized energy consumption adjusted

for ambient conditions, and the relative improvement in chiller efficiency with AQUENE.

From the table, it can be observed that AQUENE achieved a lower compressor energy consumption (0.50 kWh vs 0.65 kWh) and significantly improved chiller efficiency (0.92 kW/RT vs 1.21 kW/RT) compared to water. AQUENE shows a **23.43%** improvement in energy efficiency and **22.46%** compressor energy reduction, demonstrating its superior thermal management capability while maintaining stable operation.

VII. Implications on Electric Vehicles (EV) and Commercial Benefits

The integration of AQUENE as a coolant into the electric vehicle (EV) battery management system provides significant practical and commercial benefits. AQUENE is able to reduce the peak battery temperature and provide a better thermal uniformity at steady-state. These benefits reduce the thermal stress on individual cells, resulting in more reliable long-term performance, extended battery lifespan, and reduced replacement cost. AQUENE's main advantages—enhanced heat transfer and higher thermal diffusivity—offer the opportunity to design more compact and space-efficient cooling system designs, such as smaller pumps, pipes, and heat exchangers, without sacrificing the cooling capacity. Thus, with a more compact cooling system, overall vehicle weight can be reduced and offers more space in the vehicle itself. These can directly improve the vehicle's power consumption and payload capacity.

In practice, an efficient cooling system will result in lower auxiliary power demands, hence offering more driving range as the total energy consumption is reduced. AQUENE also offers EV safety improvements, as stable and uniform thermal management ensures that each cell in the battery pack operates within the designed temperature range, hence lowering the risk of thermal runaway occurring during utilization. Last but not least, the typical coolant used in the EV system contained glycol that offers anti-freezing properties to the coolant, while it is very useful in cold climates, it performs poorly in tropical climates, as those properties are not applicable and to make things worse it will accelerate the corrosion process in the system which will increase the risk of clogging, sedimentation and pump failures. These issues will not happen with AQUENE as it is made from a non-reactive element, carbon, and is a well-dispersed nanofluid.

Commercially, the integration of AQUENE offers fleet operators and vehicle manufacturers with measurable cost and performance advantages, including reduced energy cost, extended battery lifespan, lower maintenance expenses,

and a compact vehicle system. This technology is scalable to multiple vehicles with consistent performance and offers an advanced thermal management solution while supporting sustainable and cost-effective EV operation.

VIII. Conclusion

The rheological, colloidal, and particle characterization confirmed that AQUENE possesses low viscosity, excellent dispersion stability, and a uniform submicron particle size distribution, supporting reliable and clog-free operation in closed-loop cooling systems. Raman spectroscopy and XPS analysis further verified the high-purity few-layer graphene with functionalization, which contributes to the improved thermal conductivity and stability of the nanofluid.

This research showed that AQUENE significantly improves the thermal management of prismatic lithium-ion batteries in electric vehicle applications. The experiment conducted demonstrated that the AQUENE improvement over water coolant, the peak and overall battery temperatures were reduced, proving that the coolant provides greater heat transfer and steady-state temperature uniformity across the cells in the battery pack. The compressor power consumption reduced 22.46% while handling the same 0.54 RTh total heat generated from the battery during the charge-discharge tests, resulting in an improvement in chiller efficiency of 23.43%

Overall, the integration of AQUENE into EV battery thermal management systems can extend battery life, reduce thermal stress, and allow for more compact and energy-efficient cooling system designs. These results highlight the potential of graphene-based nanofluids as a practical and sustainable solution for high-performance battery cooling, paving the way for longer driving ranges, reduced operational energy demand, and enhanced safety in electric vehicles.

IX. Recommendation

Based on the findings of this study, several recommendations can be made to further enhance the thermal management of prismatic lithium-ion batteries using graphene-based nanofluids.

Firstly, large-scale testing in actual electric bus battery packs is recommended. To validate the laboratory-scale results under real-world driving and environmental conditions. This includes varying load cycles based on actual bus operation, ambient temperatures, and long-term operation.

Secondly, optimization of nanofluid concentration, flow rate, and chiller configuration should be explored to maximize cooling efficiency while minimizing pumping power and energy consumption.

Thirdly, long-term stability and compatibility studies can be conducted to ensure that repeated thermal cycling does not degrade the nanofluid or impact battery components.

Finally, integration with advanced battery management systems (BMS) and smart cooling controls could further enhance energy efficiency and extend battery lifespan, supporting the deployment of more compact and lightweight cooling systems in commercial electric buses.

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