Evaluation of multiple cooling strategies identify anti-freeze liquid FRAM® and paraffin wax as promising stabilizers of lithium-ion battery energy efficiency

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ABSTRACT
Rechargeable lithium-ion batteries are widely used in vertical lift drones and electric vehicles, owing to 10 times longer shelf life than lead-acid batteries. While lithium-ion batteries are climate-friendly, statistics point to growing fire-risk, as their performance drops 25% below 41°F and explosions occur above 95°F. Their greatest caveat is "thermal runaway," an exothermic reaction chain which sharply increases the internal temperature causing destabilization. Multiple cooling strategies (air, liquid, or phase-change materials) differentially impact optimal battery temperature, and the resulting safety, durability, and performance efficiency of these batteries. To harness greater cost-benefit economics, this study evaluates cooling strategies to optimize energy efficiency of lithium-ion batteries. Fully-charged lithium-ion battery was connected to the discharger and examined at low, moderate, or high temperatures (~50ºF, 70ºF or 80ºF), mirroring mild winters and summers while maintaining safety standards. Using infra-red thermometer, surface thermal uniformity of the battery was recorded at 0, 10, 15, 20 minutes along with corresponding amperage indicating energy efficiency. Procedure was repeated with forced air cooling (small fan), indirect liquid cooling (water or anti-freeze liquid FRAM®), or using phase change materials (paraffin wax). Lowered thermal uniformity due to air- or water-cooling decreased energy efficiency, while FRAM® or paraffin wax cooling increased the energy efficiency irrespective of the ambient temperatures. These findings indicate that anti-freeze liquid FRAM® and paraffin wax cooling strategies at varied temperature zones each positively impact thermal uniformity and energy efficiency, warranting applied investigations of numerous configurations of lithium-ion containing batteries.

Note*:** This study won the 2nd place in the Feb 2025 Cobb/Paulding Regional Science Fair, Marietta, Georgia. https://www.ccsdscience.com/blog/2025-cobbpaulding-science-fair-results awarded to Aditi V. Gopalakrishnan, who is currently a senior at Walton High School, Marietta, GA30062, USA; corresponding author: aditig2026@gmail.com

INTRODUCTION
Lithium-ion batteries are rapidly rechargeable commercial energy sources that use lithium (Li) metal ions as a key component of its electrochemistry and are widely favored due to their energy density and lower weight (1). These batteries are used widely from smartphones and laptops to medical devices, personal mobility vehicles, and even children's ride-on toys. The most popular recent utility that has drawn considerable public attention is the vertical lift drones carrying heavy payloads – for rapid mail-order delivery, long range surveillance, and electric vehicles (1). The latter duo are remarkable in both civilian (2) and military operations wherein low-maintenance grid-scale energy are used in aviation, marine and military operations (1,3), likely made feasible by the 10 times higher shelf life than regular lead-acid batteries. Li-based batteries are particularly compelling and widely utilized - especially in electric vehicles (EVs) including Tesla, Rivian and

some Ford Mustang vehicles where size, weight and components are critical factors – owing to their economic advantages, including extended run time, size customization, and fast charging and net-zero carbon footprint. It should be noted that these EVs predominantly use Lithium Iron Phosphate batteries as they are suitable for frequent fast-charging, and don't degrade quickly due to thermal runaway, despite their reduced voltage capacity, higher cost, low energy density and bulky mass (4). However, lithium-based batteries are hard to recycle, and besides, the processing of one ton of mined lithium emits fifteen tons of CO_2 (5).

These rechargeable and affordable Li-ion batteries pose everyday challenges that compromise their cost to benefit analyses. Despite an anticipated lifespan of 2-5 years or 300-500 charge cycles, they degrade quickly as their performance falls by 25% below 41°F or they can explode above 95°F (6). The biggest caveat is the "thermal runaway" of these batteries – a chain of exothermic reactions that sharply increase the internal battery temperature causing it to destabilize and degrade (7). The second biggest caveat is capacity degradation owing to the battery's reduced ability to hold a full charge with frequent use and exposure to heat. The third biggest caveat is battery swelling due to toxic gas buildup caused by overcharging or deep discharge. And finally, fast-charging these batteries may lead to overcharging and overheating.

The critical need of Li-ion batteries is to maximize performance efficiency, durability and safety standards in order to reap greater cost-benefit ratio. Practical cooling strategies include ensuring adequate airflow around the device and storing it in a well-ventilated area to help dissipate heat, avoiding extreme temperatures, and utilizing recommended charging devices such that batteries are charged between 20-80% capacity. Furthermore, commercial cooling strategies that include battery management systems or heat sinks that allow effective heat dissipation and prevent overheating (8,9,10). Despite these cooling strategies, users have experienced 30 minutes of battery life against an anticipated 6-12h, thus requiring frequent recharging and hence degrading/aging more rapidly. Thus, optimizing Li-ion battery performance hinges on effective thermal management using practical cooling strategies.

The objective of this study is to evaluate multiple cooling strategies that can optimize performance efficiency of lithium-ion batteries. Therefore, the experimental design focused on battery performance and recharging at different temperatures to mimic everyday challenges to prolong battery life. Specifically, the questions were as follows: (i) What are the practical everyday cooling strategies that can be utilized to enhance safety, performance efficiency and durability? (ii) How does varying ambient temperatures affect battery temperature and performance efficiency? To this end, we hypothesized that multiple cooling strategies (air, liquid, or phase-change materials) at various temperature conditions such as either summer or winter will differentially impact optimal battery temperature, which affects the safety, durability, and efficiency of lithium-ion batteries.

METHODS

Figure 1. *Materials* shown in (A) were *setup* as shown in (B) using the various cooling methods and data

Materials shown in Figure 1A were purchased through Amazon and the Lithium-ion batteries were connected to the battery discharger as shown in Figure 1B. The dependent variables were room temperature designated at ~70ºF, along with low temperatures of ~50ºF and high temperatures of ~80ºF to mimic mild summer and winter, so as to maintain safety standards for the experimental model. The independent measured variables or the two evaluation criteria were as follows: (1) thermal uniformity recorded *via* the surface temperature of the battery at baseline, 10, 15, and 20 mins using an infrared surface thermometer, and (2) the energy efficiency analyzed by noting the corresponding amperage on the display screen of the charger/discharger unit. The control variable is designated as each of the above two evaluation criteria measured at room air with no cooling intervention. Below is a breakdown of the different cooling strategies used as illustrated in Figure 1B: (1) Forced air cooling using a small fan placed ~5 inches away, (2) Indirect liquid cooling by the exposure of the batteries to motorized circulation of water or anti-freeze liquid (FRAM®,(11)) through a polyethylene tubing, or (3) Phase change material cooling wherein the batteries are embedded between two blocks of paraffin wax.

Data recording and Statistical analyses. MS Excel was used to record and tabulate data. GraphPad Prism (ver. 10.0.1) was used to generate graphs and analyze statistical differences by comparing two means (unpaired Student's 2-tailed t test) or three means (one-way ANOVA, *post hoc* comparison test by Bonferroni) for the measurements in room air versus other cooling strategies. Correlation analyses was performed between the variables.

RESULTS

Optimal performance at moderate ambient temperatures utilizing paraffin wax or AntiFreeze FRAM® liquid. Findings in Figure 2 and Table 1 demonstrate that the surface temperature of Lithium-ion battery that was measured at a moderate ambient temperature of ~70F, heats up by

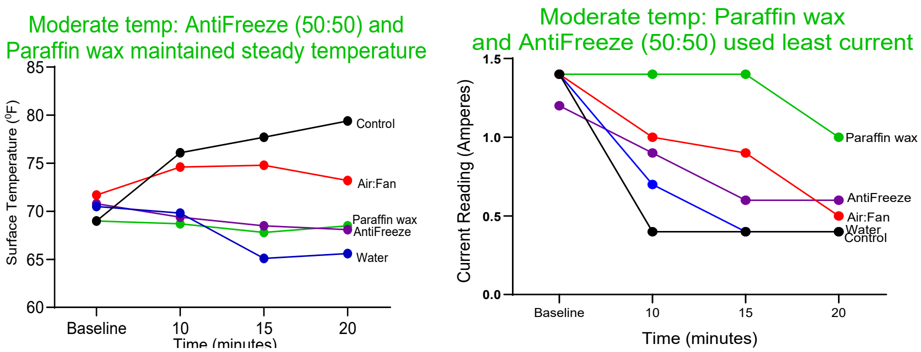

Figure 2. At moderate ambient temperature of ~70F, paraffin wax is most reliable at maintaining optimal battery performance. Graphs show surface temperatures and corresponding amperage recorded for the various cooling strategies utilized.

Table 1. Temperature and Amperage at three different ambient temperatures.

Ambient Temperature (°F)	Cooling Strategy	Lithium-ion Battery Surface Temperature (°F)					Lithium-ion Battery Current Reading (A)					Efficiency (P_f/P_i)%	Strategy/ Control
		Baseline	10 mins	15 mins	20 mins	Δ at endpoint	Baseline	10 mins	15 mins	20 mins	Δ at endpoint		
Low: 51°F (Garage)	Control	54.5	58.4	60.9	58.6	4.1	1.4	1.1	1.0	0.8	0.6	57.1%	1.0
	Air: small fan	52.5	37.7	35.2	35.4	-17.1	1.4	0.9	0.9	0.5	0.9	35.7%	0.6
	Water	58.6	55.7	50.3	45.8	-12.8	1.4	0.9	0.7	0.6	0.8	42.9%	0.8
	AntiFreeze	58.5	56.5	55.6	54.5	-4.0	1.4	1.4	1.4	1.4	0.0	100.0%	1.8
	Paraffin wax	64.0	62.4	62.8	61.5	-2.5	1.4	1.4	1.3	1.2	0.2	85.7%	1.5
Moderate: 72°F (Room Air)	Control	69.0	76.1	77.7	79.4	10.4	1.4	0.4	0.4	0.4	1.0	28.6%	1.0
	Air: small fan	71.7	74.6	74.8	73.2	1.5	1.4	1.0	0.9	0.5	0.9	35.7%	1.3
	Water	70.5	69.8	65.1	65.6	-4.9	1.4	0.7	0.4	0.4	1.0	28.6%	1.0
	AntiFreeze	70.8	69.4	68.5	68.1	-2.7	1.2	0.9	0.6	0.6	0.6	50.0%	1.8
	Paraffin wax	69.0	68.7	67.8	68.5	-0.5	1.4	1.4	1.4	1.0	0.4	71.4%	2.0
High: 79.1°F (Heated Room)	Control	77.7	82.4	85.1	86.1	8.4	1.4	1.3	1.3	1.1	0.3	78.6%	1.0
	Air: small fan	79.3	79.1	79.1	77.9	-1.4	1.4	1.4	1.4	1.1	0.3	78.6%	1.0
	Water	78.9	78.9	76.4	76.4	-2.5	1.4	1.4	1.0	0.9	0.5	64.3%	0.8
	AntiFreeze	67.5	70.5	71.7	73.2	5.7	1.4	1.4	1.4	1.4	0.0	100.0%	1.3
	Paraffin wax	79.0	79.2	79.8	83.3	4.3	1.4	1.4	1.4	1.4	0.0	100.0%	1.3

~12F accompanied by an ~72% drop in the amperage. In the presence of the small air fan, a subtle increase of 2-3F in the first 15 minutes is brought back to baseline temperature, however, concomitant decrease in amperage by ~33% in the first 15 minutes further declines rapidly in the next five minutes by ~66%. In the second cooling strategy using circulating water surrounding the battery, there is a sustained subtle drop in the surface temperature by ~5% at the 15-minute timepoint, however this cooling effect is accompanied by a steep ~70% drop in amperage. Thus, the amperage of the battery in the presence of the air fan is comparable to that of the control battery which has no cooling strategies. In the cooling strategies that utilized paraffin wax and circulating AntiFreeze FRAM® liquid, the surface temperature stayed constant with no changes, however, the amperage drops by 50% with AntiFreeze FRAM® liquid while only a 33% drop in amperage is observed with paraffin wax cooling. These findings suggest that air and circulating water have ineffective performance efficiency comparable to absence of any cooling strategy. Interestingly, while both paraffin wax and circulating AntiFreeze FRAM® maintained thermal uniformity, paraffin wax cooling demonstrated the highest optimal Li-ion battery energy efficiency.

Maximal performance at low temperatures utilizing AntiFreeze FRAM® liquid. Figure 3 and Table 1 demonstrate that at ~50F which mimics mild winters, the surface temperature of

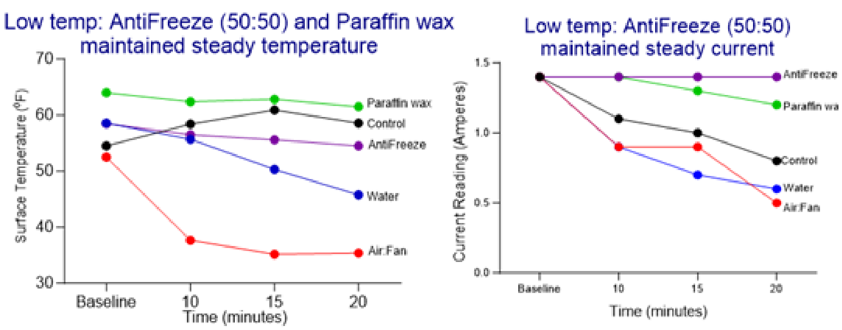

Figure 3. At low ambient temperatures of ~50F, AntiFreeze FRAM® liquid is most reliable at maintaining battery temperatures and function, with paraffin wax at a close second. Graphs show surface temperatures and corresponding amperage recorded for the various cooling strategies utilized.

Lithium-ion battery increases by ~4F combined with ~43% drop in performance efficiency. Both air fan and circulating water caused an alarming 17 and 13-point drop in surface temperature, respectively, and interestingly, the performance efficiency due to cooling with air fan and circulating water dropped by ~36% and 43%, respectively, which is lower than that of control. In contrast, while cooling with circulating AntiFreeze FRAM® liquid and paraffin wax caused a temperature drop by only 4 and 2.5 points, respectively, they were able to maintain maximal performance efficiency of the Lithium-ion battery at 100% and 86%, respectively. These findings collectively suggest that circulating AntiFreeze FRAM® was most effective at maintaining thermal uniformity with maximal battery energy efficiency at low temperatures.

Optimal performance at high temperatures via paraffin wax or AntiFreeze liquid FRAM® *cooling.* Figure 4 and Table 1 demonstrate that at ~80F which mimics hot summers, the surface temperature of Lithium-ion battery increases by ~10F combined with a ~30% drop in performance efficiency. Both air fan and circulating water was able to cause a subtle drop in temperature by 2-3F, *albeit* the performance efficiency of air fan dropped by ~30% comparable to the control while

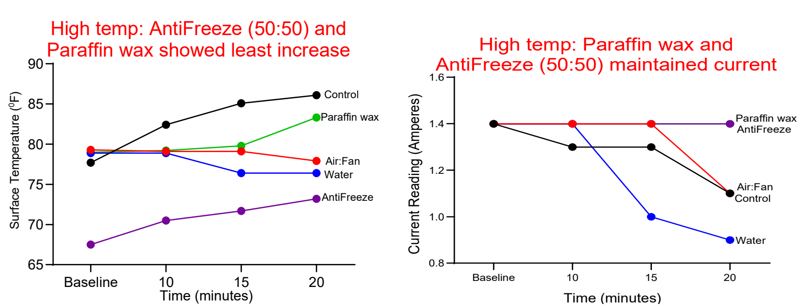

Figure 4. At high ambient temperatures of ~80F, paraffin wax is most reliable at maintaining battery temperatures and function. Graphs show surface temperatures and corresponding amperage recorded for the various cooling strategies utilized.

the cooling by circulating water caused an alarming 40% drop in efficiency. Interestingly, both paraffin wax and circulating AntiFreeze FRAM® liquid each cause a temperature increase of 2-3F; however, they can maintain the optimal performance efficiency of the Lithium-ion battery. Taken together, these findings suggest that paraffin wax and circulating AntiFreeze FRAM® each maintain the thermal uniformity and optimal energy efficiency of the Lithium-ion battery at high temperatures.

DISCUSSION

Lithium-ion batteries have become the cornerstone of modern energy storage, particularly in applications such as vertical lift drones and electric vehicles, due to their superior shelf life and energy density compared to traditional lead-acid batteries. However, their performance and safety are overly sensitive to temperature fluctuations, which presents a significant challenge in real-world applications. This study highlights the critical issue of thermal runaway, a hazardous exothermic reaction that can lead to battery destabilization and even explosions. These findings underscore the importance of maintaining optimal operating temperatures to ensure both safety and efficiency. To address this, the study evaluates various cooling strategies—air, liquid (water and anti-freeze), and phase-change materials—to determine their effectiveness in regulating battery temperature and enhancing performance. The experimental design simulates environmental conditions (mild winters and summers) and measures both surface temperature and amperage over time.

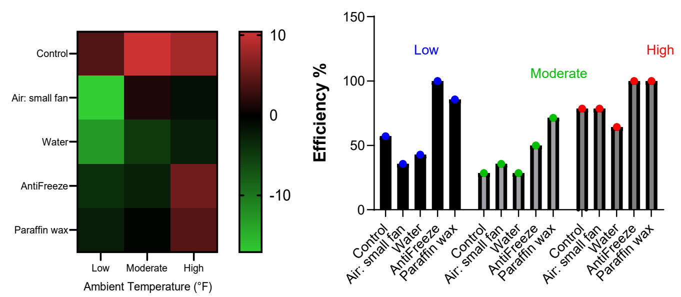

Figure 5. Data Summary. Optimal cooling and thermal stability is noted in moderate temperatures across all four strategies, with average energy efficiency being maximal *via* paraffin wax and anti-freeze FRAM® cooling for the three temperatures.

The study findings as shown in Figure 5, reveal that irrespective of the ambient temperature in which the battery was tested, the thermal stability and average energy efficiency was maximal when the cooling strategies used were paraffin wax or anti-freeze FRAM®. Forced air cooling by small air fan and indirect water cooling registered lower than optimal thermal stability and as a result, lower energy efficiency compared to even control at low temperature. As hypothesized, paraffin wax and FRAM® differentially impact optimal battery temperature, which in turn affects the safety, durability, and efficiency of lithium-ion batteries. Interestingly, while the cooling strategies that employ forced air cooling and indirect water cooling are effective at maintaining the surface battery temperatures that are equal to the respective control group or even cooler than the control group, as hypothesized, the energy efficiency was lower in these two groups across the three ambient temperatures.

The health relevance of these findings in the context of efficient lithium ion usage is underscored by reports showing that lithium therapy stabilizes disruptive calcium homeostasis, and subsequently, attenuates the downstream neuropathogenic processes of Alzheimer's disease and COVID-19 (12,13). There are multiple ways to expand the current study (14,15). Firstly, alternative phase change materials can be evaluated with different melting points and thermal conductivities to identify materials that offer better thermal regulation and energy efficiency than paraffin wax. Secondly, hybrid strategies can be employed to explore the feasibility of combining cooling methods (e.g., PCM + liquid cooling) and leverage the strengths of each and achieve superior thermal management. Thirdly, the study can be validated through trials in drones, electronic toys, and PlayStation under varying climate conditions to assess practical performance and reliability. Finally, material compatibility can be examined for interactions between cooling materials and battery casing or the various components of lithium-ion containing batteries to ensure chemical compatibility and yet preserve energy efficiency.

In conclusion, this study opens avenues for applied investigations into battery configurations that incorporate these cooling strategies. This could lead to the development of more robust battery systems capable of operating safely and efficiently across a wider range of environmental conditions for everyday use and preserve shelf life.

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