Investigation on Temperature Affecting the Internal Resistance of the Battery.

1. Introduction

For years I have been a gearhead so as a car enthusiast. In the not-so-long history of automobiles, cars are once popular with internal combustion engine powered. It seems that other power source like hydrogen, electric power and jet power were being forgotten. However, in the recent years, most car companies started to switch their car lineups to electric vehicles, as known as EVs. Categorized in pure battery full electric cars, hybrid cars, and plug-in hybrid cars. All of them use batteries and electric motors as power source in a certain way.

About 2 months before, I was in my dad's hybrid car, going home from school. I was thinking, "I've seen this car driving in urban, and I've seen this car running on highways and suburb areas, but it seems like I've never seen this car driving on ice and snowy days." So, I was thinking if the battery temperature affects EV performance. To make an internal combustion engine work in extreme cold weather it needs engine oil with the right working temperature. However, when it comes to batteries it tends to work worse when in extremely cold weather. On cold winter days, electric vehicles can lose half their driving range due to poor battery performance. At $-40\ ^\circ C$, lithium-ion batteries retain just 12% of their capacity.[1]

2. Background information

The basic model of an EV power system is a circuit system. Which the battery on board as the power supply of the electric motor, and the electric motor is the energy output of the car. The current is the opposite direction of the electrons' moving direction, and the voltage decides how large the value of power will be output into the motor. Voltage divided by current is the value of the resistance. So, the resistance of batteries affects the electric motor's performance, and hence the performance of EV's.

This experiment will mainly focus on how the low temperature of the battery affects the resistance of the battery since this is where this experiment started. And heating a battery is a dangerous task so remeber to conduct this experiment in a lab.

Lithium-ion batteries, with a high energy density (up to 705 W/L) and power density (up to 10000 W/L), exhibit a high capacity and great working performance. As rechargeable batteries, lithium-ion batteries serve as power sources in various application systems.

Temperature, as a critical factor, significantly impacts the performance of lithium-ion batteries and limits the application of lithium-ion batteries. Moreover, different temperature conditions result in different adverse effects. Accurate measurements of temperature inside lithium-ion batteries and understanding the effect of temperature are important for proper battery management. [2]

The internal resistance can be determined, by connecting a circuit of known resistance and measuring the current that flows:

$$I = \frac{e}{R+r}, \therefore r = \frac{e-V}{I}$$ [3]

Where I is the current flows through the battery itself, E stands for the emf, R stands for the battery's external resistance and r stands for the battery's internal resistance. Lithium-ion batteries perform best when the temperature is within a certain range. At subzero temperatures, batteries tend to have lower capacities and power availability, which could affect how well they work in vehicles in cold climates. To study the internal resistance of $LiMnNiO$ and $LiFePO_4$ batteries, they were tested at a wide range of temperatures from 50°C to −20°C. Using impedance spectroscopy, it was possible to identify major internal resistances such as the cathode internal, the anode internal, and the conductive. At subzero temperatures, the anode internal resistance was almost twice as high as the cathode internal resistance. A model has been presented of the individual resistance increase as a function of temperature. Furthermore, the dependency of cell impedance on state of charge (SOC) and temperature has been analyzed in detail.[4]

3. Research Question and hypothesis

How does the surface temperature ($-5.00, 0.00, 5.00, 10.00$ and 25.00 ± 0.01 Celsius degrees, °C) of one AA unitt, size 7 battery affect its internal resistance?
As the battery surface temperature increases the value of its internal resistance will decrease. This means that temperature enables the reaction inside an electrochemical cell to occur faster thereby decreasing the internal resistance of the battery.[5]

4. Methodology

Independent Variable	**Method of manipulation**
Surface temperature of the batteries. AA unit, size7 with 1.5V output for each battery. ($-5.00, 0.00, 5.00, 10.00$ and 25.00 ± 0.01 Celsius degrees, °C)	The temperature of the batteries will be decreased using the refrigerator. I will put the batteries into the refrigerator to cool them down to the conditions (temperatures) I need.
Dependent Variable	**How measurements are taken**
The internal resistance of the battery. (Ohm, Ω)	I take the value of current flowing through the circuit and the value of voltage across the light bulb, and use the formula $r = \frac{e-V}{I}$ to calculate the internal resistance.
Controlled Variable	**Reason and methods of controlling**
The same bulb used in the experiment with the resistance measured in unit ohm, Ω.	The scenario I am conducting is when a car is stationary under very cold conditions so I need to maintain the same one. Also, different light bulb may have slightly different internal resistance because of the usage.
The same battery specification.	It must be the same AA battery with 1.5V for each because the same specification provides the same internal resistance, the same voltage power output, and the same current flow through the circuit.
Temperature for every Trial.	It is difficult to maintain the temperature of the battery once it is taken out of the refrigerator and placed in the circuit. This is an assumption (assume the temperature of the battery does not change during the experiment) which must be made because the temperature of the battery surface temperature is the variable that I change.

Materials

The following materials will be used to conduct this IA:

Materials	**Specification**
An electronic multimeter.	±0.001
Two batteries.	AA battery, size 7, 1.5V for each.
Wires.	N/A
A switch.	N/A
A light bulb.	2.5V, 3A.
A refrigerator.	N/A

Table 1. Material and equipment list.

Procedures

The following steps will be taken to conduct this IA:

1.Confirm the experiment environment is at room temperature.

2.Built up the circuit with only batteries, wires, the switch, and the light bulb in it.

3.Use the electronic multimeter, and confirm the resistance of the light bulb.

4.Measure the non-load voltage of the battery.

5.Measure the voltage in the circuit.

6.Use the formula $I = \frac{e}{R+r}$, $\therefore r = \frac{e-V}{I}$ to calculate the resistance in the battery.

7.Repeat process 2-6 five more times.

8.Place the batteries into the refrigerator to simulate the environment of cold temperature days and change the temperature of the battery to 10.00 °C, 5.00 °C, 0.00 °C, and −5.00 °C, respectively.

9.Repeat processes 2-7 for each temperature.

10.Record the data and use the formula to calculate the different resistances of the battery.

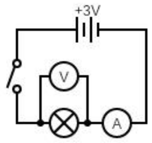


Figure 1. Circuit diagram for my experiment setup.

Ethical and Safety Concerns

When using the refrigerator to cold the battery, be careful when doing so. This is because the battery's working temperature is not supposed to be too low, especially for the normal AA batteries used in the experiments. They might have leakage, lack of performance which causes the circuit to have problems like short circuit for instance.

5. Data Analysis

Qualitative data

To set up the experiment, install the batteries into the battery pack. Then, connect the battery pack with two wires on each side of the battery pack. Connect one side with a switch (leave it open), a wire, and a bulb respectively. Close the circuit after everthing is set, the bulb will glow with light, after connecting the multimeter into the circuit, there will be current & voltage value on the screen depends on the way the multimeter is inserted.

Quantitative data

Tables below show the raw data of current and voltage from the multimeter from the experiment.

Current(Ampere, A) ±0.001 / Temperature (°C) ±0.01	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Average
10.00 Celsius degrees	0.242	0.241	0.243	0.240	0.241	0.2414
5.00 Celsius degrees	0.238	0.237	0.239	0.239	0.238	0.2382
0.00 Celsius degrees	0.232	0.233	0.232	0.231	0.233	0.2322
-5.00 Celsius degrees	0.229	0.229	0.227	0.228	0.229	0.2284
25.00 Celsius degrees	0.248	0.249	0.245	0.246	0.246	0.2468

Table 2. Current Measured.

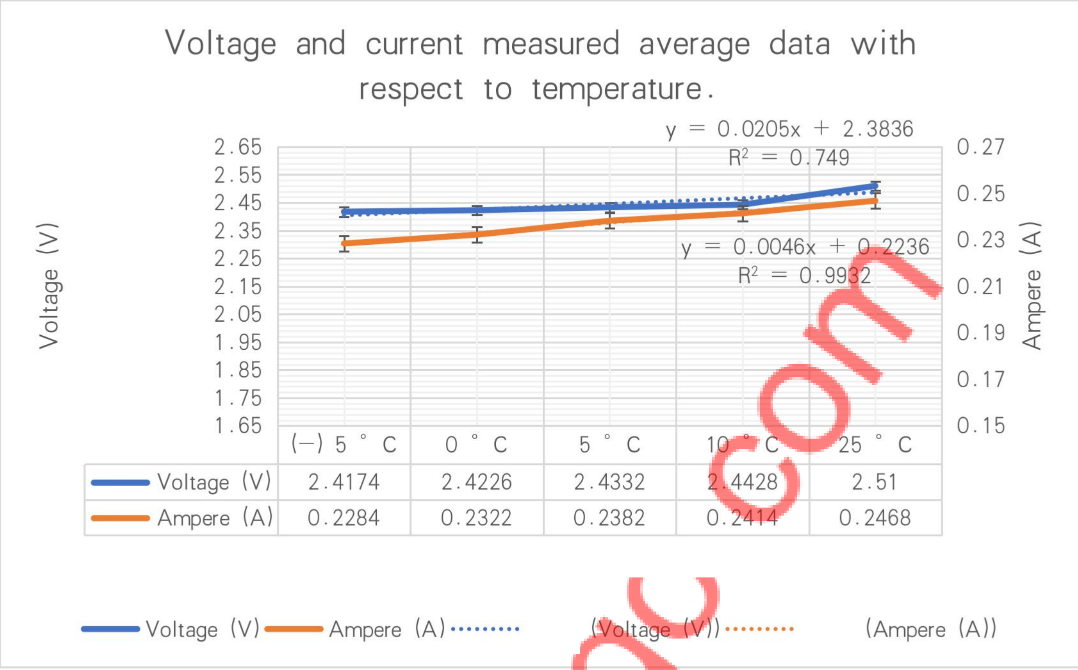
Voltage(Volt, V) ±0.001 / Temperature (°C) ±0.01	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Average
10.00 Celsius degrees	2.443	2.444	2.443	2.438	2.446	2.4428
5.00 Celsius degrees	2.432	2.433	2.430	2.436	2.435	2.4332
0.00 Celsius degrees	2.420	2.422	2.422	2.425	2.424	2.4226

-5.00 Celsius degrees	2.416	2.420	2.419	2.415	2.417	2.4174
25.00 Celsius degrees	2.511	2.509	2.510	2.507	2.513	2.5100

Table 3. Voltage measured.

Graphing

Graph below shows the voltage and current measured as average data with respect to temperature.



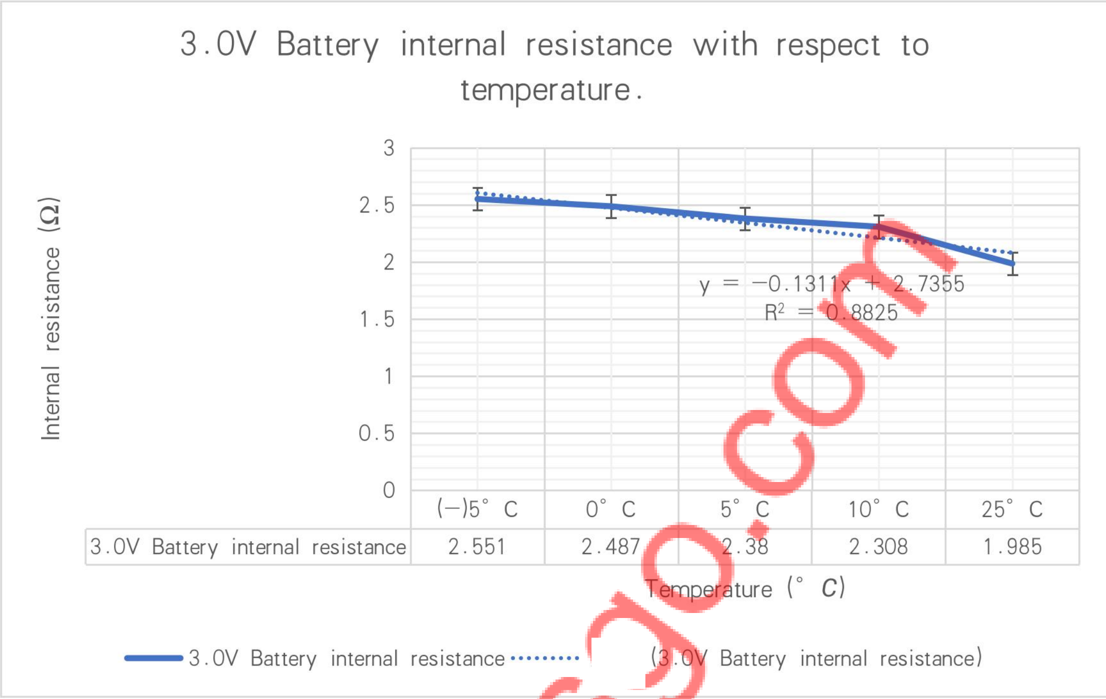
Graph 1. Voltage and current measured average data with respect to temperature.

Calculation

Calculation	**Error propagation**
Because I am using the same multimeter to calculate the data, every raw uncertainty is 0.001.	Since the data used in calculation is averaged, then uncertainty: $0.0001 = 0.01\%$ $\therefore$ absolute uncertainty $= 0.01\% \times 5 = 0.05\%$ $0.05\% + 0.05\% = 0.1\% = 0.001$
The battery internal resistance under 25 °C: $r = \frac{e - V}{I} = \frac{3V - 2.5100V}{0.2468A} \approx 1.98541329\Omega$	$0.05\% + 0.05\% = 0.1\% = 0.001$
The battery internal resistance under 10 °C: $r = \frac{e - V}{I} = \frac{3V - 2.4428V}{0.2414A} \approx 2.308202154\Omega$	$0.05\% + 0.05\% = 0.1\% = 0.001$
The battery internal resistance under 5 °C: $r = \frac{e - V}{I} = \frac{3V - 2.4332V}{0.2382A} \approx 2.379513014\Omega$	$0.05\% + 0.05\% = 0.1\% = 0.001$
The battery internal resistance under 0 °C: $r = \frac{e - V}{I} = \frac{3V - 2.4226V}{0.2322A} \approx 2.48664944\Omega$	$0.05\% + 0.05\% = 0.1\% = 0.001$
The battery internal resistance under −5 °C: $r = \frac{e - V}{I} = \frac{3V - 2.4174V}{0.2284A} \approx 2.550788091\Omega$	

The battery internal resistance under 25 °C: $r = 1.985\Omega \pm 0.001$.
The battery internal resistance under 10 °C: $r = 2.308\Omega \pm 0.001$.
The battery internal resistance under 5 °C: $r = 2.380\Omega \pm 0.001$.
The battery internal resistance under 0 °C: $r = 2.487\Omega \pm 0.001$.
The battery internal resistance under −5 °C: $r = 2.551\Omega \pm 0.001$.

Graph visualisation



Graph 2. Battery internal resistance vs temperature.

Interpretation

In the RQ and hypothesis section, I predicted that as the battery surface temperature increases, then the value of its internal resistance will decrease. From graph 2 above, at −5°C the internal resistance 2.551Ω, as which, I need to declare at first, is the value of two batteries because I connected two batteries in series together. Then it decreases to 1.985Ω gradually as the temperature raises to room temperature 25 degree Celsius. This result confirms my hypothesis as the temperature increase the internal resistance of battery will decrease, as in this case, with a gradient of −0.1311 by taking the value from the linear best fit line. I chose a linear best fit line is because I was not sure how the trend will be exact. So, I went for linear to get a better simpler view for easier interpretation. R^2 is the statistical measure in a regression model that determines the proportion of variance in the dependent variable that can be explained by the independent variable. In other words, r-squared shows how well the data fit the regression model (the goodness of fit). R-squared can take any value between 0 to 1.[6] The more it is close to 1, the better it fitted with the original data. The R-square in this model is around 0.8825 so this is a very well-fitted fit line. This feature indicates that if I change my experiment conditions then this theory is highly possible to be correct again. Also referring to the error bars in graph 2 it shows that the trend line is not out of the error bars I added, which means they are smaller than the value of the standard deviation. Which is also a proof that the data calculated is precise.

6. Evaluation

Conclusion

This investigation aims to investigate the surface temperature of a battery affecting its internal resistance using a circuit to measure the voltage difference and the current flow. After interpretating graph 2 my hypothesis is fully verified. From the aspect of quantitative data, human eye simply cannot see electrons' flow, change in temperature and the change in internal resistance, but by applying a circuit map and a multimeter, I would able to observe the change in the circuit,

and hence, proving the hypothesis is easier.
To conclude, between the surface temperatures of −5°C to 25°C, the higher the temperature, the lower the internal resistance of a battery, the lower the temperature, the higher the internal resistance o f a battery.

Strengths

One strength of my investigation is that I used a digital multimeter instead of the traditional analog voltmeter and ammeter, by using a digital measure instrument I would be able to obtain more precise data because I can obtain more decimal places in my raw data.
Another advantage of my investigation is shown in graph 1. Because I measured the data five times, I would be able to lower the error due to random error, which means the data set is more accurate. Another indicator is the graph trend in graph 1 because there are no significant outliers since the data fits the best fit line well.

Weakness

Errors	**How to improve**
Lack of practicality. This basically means the experiment itself. I want to measure the most accurate data without too many place that could go wrong. So, I choose the simplest circuit I could take measure, which, the reason why I used a light bulb instead of a resistor is because I wanted to use a device, like what it is like in a real car. However, this system is way too simple for real life situations because of lack of complexity. This system could not simulate the real battery load under a situation that a car needs to be powered for.	To build a more complex circuit that contains multiple methods of light bulb connection including series connection and parallel connection.
The measurement method for temperature. For this problem I used a normal electronic thermometer accurate to 2 decimal places, but it could only detect the temperature close around. So, I must place the battery on its sensor to make the measurement as accurate as possible.	By using a temperature probe and a LabQuest may solve this issue, but in my opinion the better way is to use an electronic thermographic camera that can detect heat.

Future Work

In the future, I would like to conduct this experiment by comparing the internal resistance of a battery under different air pressure, or how the complexity of a circuit affects the internal resistance of a battery. Since I already know the temperature will affect the internal resistance of a battery in a certain way, I wonder if different factors like air pressure could have the same effect as well.
In that experiment I would also have three different comparison experiments as well, one the lights will be connected in series, on will be connected in parallel, and one will have both. The hardship is to change the air pressure Perhaps I will try using a plastic box and a vacuum cleaner to achieve this change in experiment situation.

Works Cited

[1]: Bourzac, Katherine, and C&EN. "Rechargeable Battery Weathers Extreme Cold Conditions." Acs.org, 1 Mar. 2018, cen.acs.org/articles/96/i10/Rechargeable-battery-weathers-extreme-cold-conditions.html.

[2]: Ma, Shuai, et al. "Temperature Effect and Thermal Impact in Lithium-Ion Batteries: A Review." Progress in Natural Science: Materials International, vol. 28, no. 6, Dec. 2018, pp. 653–666, www.sciencedirect.com/science/article/pii/S1002007118307536, 10.1016/j.pnsc.2018.11.002.

[3]: "Internal Resistance | Batteries & Other Power Supplies." Www.science-Campus.com, www.science-campus.com/engineering/electrical/dc_theory/chapter6/dctheory_6_7.html. Accessed 22 Feb. 2022.

[4]: Hossain Ahmed, Sazzad, et al. "Effects of Temperature on Internal Resistances of Lithium-Ion Batteries." Journal of Energy Resources Technology, vol. 137, no. 3, 1 May 2015, asmedigitalcollection.asme.org/energyresources/article-abstract/137/3/031901/373140/Effects-of-Temperature-on-Internal-Resistances-of, 10.1115/1.4028698. Accessed 15 Jan. 2021.

[5]: BYJU'S. "How Does Temperature Affect the Internal Resistance of a Battery?" BYJU'S, 9 Dec. 2020, byjus.com/jee-questions/how-does-temperature-affect-the-internal-resistance-of-a-battery/. Accessed 28 Sept. 2022.

[6]: CFI Education Inc. "R-Squared - Definition, Interpretation, and How to Calculate." Corporate Finance Institute, 2022, corporatefinanceinstitute.com/resources/knowledge/other/r-squared/.