THE IMPACT OF TEMPERATURE AND WEAR ON LI-PO ACCUMULATORS DISCHARGE CHARACTERISTICS

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Abstract

The goal of this paper was to find out how the ambient temperature affects the discharge characteristics and the useful energy density of lithium polymer accumulators. Also, to identify how these parameters are affected by age and wear of these accumulators. Li-Po accumulators are the most used energy source for small unmanned aerial vehicles. It is very important to know limitations of this energy source to allow efficient and safe usage. Especially these days, when these machines are being introduced into many industries. It has been found that low temperatures have a negative impact on the available accumulator capacity, especially the older ones. High temperatures, on the other hand, only slightly increased the capacity of the new accumulator. The old accumulator was affected more, higher temperatures helped to increase its available capacity. Using information gathered form this paper would help them use Li-Po accumulators more efficiently and save money on new ones because of increased life time.

Keywords

Lithium-Polymer, accumulator, battery, energy density, capacity, temperature, unmanned aerial vehicles

1. Introduction

Unmanned aerial vehicles (UAV) are experiencing significant growth around the world and in many sectors of human activity. There are various types of designs and types of propulsions on the market. With the technology development process, these machines have become very quickly available and suitable for the general public and for various industries and services. The use in industrial applications is particularly attractive due to the promise of reduced costs compared to other solutions. In order to use unmanned vehicles effectively, we need to know the limitations of their propulsions and energy sources. This paper is based on master's thesis of first author.

This paper will be focused on the definition of influence of environment temperature and age and wear on Li-Po accumulator discharge characteristics. Lithium-Polymer accumulators are currently the most used energy source in electromotor driven unmanned aerial vehicles. Especially because this type of propulsion and power source combination is very user-friendly.

A comparison between Li-Po accumulators and other energy sources for electric motors can be found in Tab. 1. As we can see, energy density and specific energy of Li-Po accumulators is the best among compared energy sources.

Table 1: energy density and specific energy of electromotor energy. Source: (Buchmann, 2018), (Engineering ToolBox, 2001), (AA Portable Power Corp, 2008), (Engineering ToolBox, 2001b), (Eaton, 2017).

Energy source	Energy density [MJ/m³]	Specific energy [MJ/kg]
Li-Po accumulator	1 440 – 2 628	0.54 – 0.936
NiMH accumulator	720	0.216 – 0.432
Pb accumulator	100 – 900	0.04 – 0.140
Supercapacitor	50 – 60	0.01 – 0.036

As we can see in Tab. 1, there is no justification to use any other accumulator than a lithium based one. NiMH (nickel metal hydride) accumulators are good substitute in case if a price is a bigger factor than energy density. We can also observe, that lead (Pb) accumulators are absolutely not appropriate for use in applications, where weight and dimensions are limited. Supercapacitors have high energy density in comparison with normal capacitors, but they can not be compared to Li-Po or even NiMH accumulators. Their utilization belongs mostly in combined systems as energy storage with capability to discharge large currents. For example, in combination with proton exchange membrane fuel cells as main energy source.

Of course, energy density and specific energy are not the only parameters that make Li-Po accumulators the most widely used ones. They have comparatively big nominal cell voltage of 3.7 V, no memory effect, low self-discharge, easy state of charge indication through voltage (almost linear voltage decreases with discharging) and they are not dangerous to the environment (no lead or cadmium content). There is wide variety of Li-Po accumulator types. Each with specific advantages and shortcomings (Buchmann, 2018).

It is important to note difference between lithium ion and lithium polymer accumulators. Li-Ion use liquid electrolyte and the Li-Po ones use polymer electrolyte. Li-Po are also more expensive, but they are lighter and do not need hard shell. They can be manufactured in many different shapes.

It is important to know limits of technology, that is to be used, because then we can choose correctly according to our application needs. The objectives of practical measurements can be summarized as follows:

- How does the ambient temperature affect discharge characteristics and energy density?
- Does age and accumulator wear affect these characteristics?

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2. Materials and methods

The measurements were carried out in cooperation with the non-destructive testing and diagnostics laboratory (NDT) and the calibration of flight recorders of the Department of Air Transport of Faculty of Transportation Sciences Czech Technical University in Prague.

For the measurements were used accumulators PECKA-POWER LiPo – 3S 2200 mAh 11.1 V 3S1P 35 C. Thus, these accumulators have 3 cells connected in series with nominal voltage of 11.1 V and the indicated capacity of 2200 mAh which is 24.42 Wh (as indicated on packaging).

$$I\,[A] = Cr * C\,[Ah] \qquad (1)$$

where I is current in Amperes, Cr is the given value C of accumulator and is electric charge of the accumulator in Ampere hours (or in other words accumulator capacity). The accumulator manufacturer specifies a maximum continuous discharge current of 35 C and a maximum peak current of 50 C. This corresponds to a current of 77 A and 110 A respectively for peak load according to (1). It is therefore suitable for most UAVs used for recreational or commercial purposes. The maximum charge current is listed as 1 C, i.e. 2.2 A. The accumulator dimensions are 105 x 35 x 23 mm and its weight is 190.6 g, including packaging and cables (both power and balance ones). However, the weight and size thus given complicates the calculation of energy density and specific energy which values are then lower.

$$E\,[J] = 3600 * E\,[Wh] \qquad (2)$$

where E is the energy in Joules and Watt hours. The stated energy of the 24.42 Wh can be converted using equation (2) to 87 912 J. This value can then be adjusted to 0.087912 MJ. Using this value, weight and dimensions of accumulator, we obtain a specific energy of 0.46124 MJ/kg and an energy density of 1040.07 MJ/m3. These values are considerably lower than those indicated in Tab. 1. This may be due to the packaging of the particular manufacturer and to the aforementioned cables. Balance cables allow protection against discharge below recommended voltage and to charge to higher than recommended voltage (both cases would lead to significant reduction of accumulator useful cycles and possibly to destruction). However, this depends on the settings of the charger or appliance. Balance cables will only get information about voltage of each individual cell to the charger or appliance. Manufacturer of our accumulator does not know and does not mention the sub-type of Li-Po accumulator.

Two accumulators were used. One brand new and one few years old and quite worn. The old accumulator has already suffered from inflation, which indicates considerable degradation. This wear condition also indicates that the accumulator was not ideally handled (in terms of charging, discharging and storing). Such considerably different accumulators allowed us to compare well observed characteristics.

For charging and discharging was used Robbe Power Peak I4 EQ-BID 8507. Charger is able to charge 1 to 12 Li-Po cells with current from 0.1 to 10 A (maximum 210 W) and discharge them from 0.1 to 5 A (maximum 50 W). It also has the option of connecting a battery balancer, ensuring even charge of individual cells. During charging and discharging it can discontinue when pre-set voltage limit is reached (low or high) by any of the cells. Charging of Li-Po cells works automatically on the principle of constant current – constant voltage method (CC-CV). Using this method, the accumulator is first charged with a constant maximum possible current (CC), which is adjustable (determined by the C parameter of the accumulator). At the same time voltage increases. When the voltage reaches the maximum cell voltage, which is pre-set for Li-Po cells to 4.2 V/cell and is also generally accepted voltage as maximum possible, charging switches to constant voltage mode (CV). In this mode, the charger outputs this maximum voltage and gradually decreases the current. As soon as any cell reaches 4.2 V, the charger discharges this cell by several hundredths of V using balancing cables and then continues charging the entire battery. This process may take a long time (a maximum current of 300 mA is used during balancing), especially for older and worn accumulators, that have a significant cell voltage difference. Once the voltage of all cells is within range, charging is terminated. The charger and accumulator connection have been accomplished with appropriate connectors of sufficient length to allow for safe placement of the charger. The temperature measurement function with an external sensor connected to the charger was not used due to the low temperature range it can sense.

The charger also has a USB mini port. With this port, the charger was connected to a personal computer with Microsoft Windows 10 operating system. The installed Logview software enabled monitoring of current accumulator parameters such as: individual cell voltage, total voltage, charging or discharging current, transmitted energy and time. Logview can export these values to .csv format. The data was then processed in Microsoft Excel.

The charger required an input voltage if 11 to 15 V DC. For this purpose was used a switched power supply Power X-40 supplying 13.8 V and a maximum of 40 A (approximately 550 W).

Initially, a series of charging and discharging cycles with both old and new accumulators was conducted. These test measurements were used to gain experience and resolve any process deficiencies.

During the measurement, the main observed parameters were total voltage, cell voltage and transferred energy converted to the capacity given in mAh. The accumulators were left for a few hours at rest, room temperature and charged before each experiment. The first step in the measurement was to ensure that the accumulator was fully charged (4.2 V/cell) by plugging it into charge and turning on the charging process. Once the charging process was complete, the accumulator was left for 10 minutes. This is due to the internal temperature of the accumulator, which may increase during charging. This time was chosen because during the last charging phase, the temperature in the accumulator is basically not rising, due to the very small charging currents (the charger is balancing the cells). After this, the charger was set to start the discharging program with setting to discharge at 48 to 50 W and a maximum of 5 A. Thus, only with a C value of about 2.27, which is safely below the maximum value of the accumulator. Discharging was automatically stopped as soon as any cell of the accumulator reached 3 V. After 5 minutes, charging to a maximum cell voltage of 4.2 V was initiated. Data were exported in Logview and saved to .csv format.

Measurements were conducted in following temperatures:

- 60°C
- 50°C
- Room temperature (circa 22°C)
- 5°C
- -18°C

60°C and 50°C was achieved with a water bath. Since water could cause a short circuit and therefore damage to accumulators or injury, it was necessary to test this procedure carefully before using accumulators themselves. A pot was used as a container. In order to create a sufficient gap between the bottom of the pot, the heat source and accumulator, a stand was used to allow the accumulator to stand at a sufficient distance from the bottom. Sealed plastic containers filled with water have been used to prevent the accumulators form moving and slipping in the bath. Various packaging materials have been experimented with for the accumulator itself to isolate it from water. Therefore, a latex case of suitable shape was finally used, which kept the moisture out of the accumulator without any problems. It was very thin and had a high thermal permeability. After satisfactory tests, the measurements were carried out at these temperatures. The accumulators were left in the bath for 10 minutes before discharge was started. Temperature was maintained by means of gas burner under the pot. Burner was manually controlled. The temperature was read from a mercury thermometer with a range of up to 200°C and a scale of 1°C. The temperature was maintained at ± 3°C from the target during all experiments.

Measurement at room temperature was conducted as described in the general description above.

5°C was reached using a kitchen refrigerator that maintains this temperature. The accumulator was placed in the refrigerator for about 2 hours. Then the accumulator was connected to the charger, the refrigerator door closed again, and the discharge program was started. Good refrigerator sealing provided no or negligible entry of warm air, which was compensated for without problem.

Stable -18°C was achieved by inserting the accumulator into kitchen freezer that maintains this temperature steadily. Due to the physical properties of the Li-Po accumulators, it can not be completely frozen and expected to function. The chemical reaction inside the cells would stop and the accumulator would virtually lose all capacity. Of course, in real conditions, it is not possible to use Li-Po accumulators whose internal temperature is so low. They must be warmed up before use. The aim of this measurement was to find out how would accumulators be affected with a certain amount of time spent in such a freezing environment. This simulates a real example of using accumulators that are normally carried in a pocket, a car, or placed in a different environment where temperatures are not so low and are inserted into the appliance just before use. Therefore, these experiments aim to find out how much must the user rush to start using appliance after exposing accumulators to low temperatures. Assumption was, that after the current was drawn from accumulators, the internal resistance would start to heat them up and low temperatures would not compromise function. The accumulator was inserted into the freezer with cables and after specified time has elapsed, the discharging program was started.

Further measurements were taken at a room temperature after individual experiments at temperatures other than room. Mainly due to the need to verify that these extreme temperatures had no impact on further measurements and thus on the long-term capacity of the accumulators.

3. Results

Here will be presented results of measurements.

Table 2: capacity of accumulators during individual measurements. Source: Authors.

Measurement	Capacity [mAh] Old accum.	Capacity [mAh] New accum.
50°C	1516	2257
60°C	1530	2250
room temperature second time	1479	2249
room temperature after 50°C	1378	2245
room temperature	1599	2236
room temperature after 5°C	1556	2230
room temperature after 60°C	1288	2230
room temperature after -18°C for 25 minutes	1291	2223
room temperature after -18°C	1230	2223
room temperature after -18°C for 20 minutes	1368	2222
5°C	1465	2172
-18°C	963	2134
-18°C for 10 minutes	1134	2126
-18°C for 25 minutes	17	2111
-18°C for 25 minutes second time	802	2106
-18°C for 20 minutes	974	2103
-18°C second time	950	-
-18°C for 30 minutes	3	-
room temperature after -18°C for 10 minutes	1420	-
room temperature after -18°C for 30 minutes	1309	-

In Tab. 2 we can see a summary of the old and new accumulators capacities for each measurement. The old accumulator had more measurements because it was measured first, and some results had to be verified by a second attempt to make sure the experiment was correct.

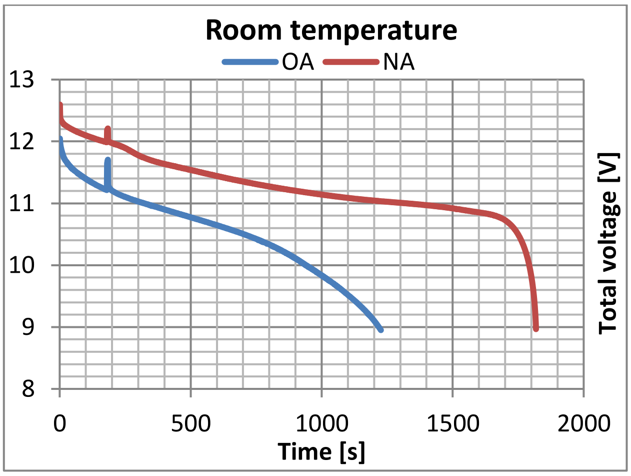

Figure 1: voltage drop over time at room temperature. Source: Authors.

In Fig. 1 we can observe the total accumulator voltage in V in dependence on time in seconds at room temperature (circa 22°C). The abbreviation OA stands for old accumulator and the abbreviation NA stands for new accumulator. These abbreviations will also be used in all of the following figures. Between 180 and 200 s we can see a short abrupt increase in voltage. This occurs in all experiments and is the result of the accumulator discharging process of charger.

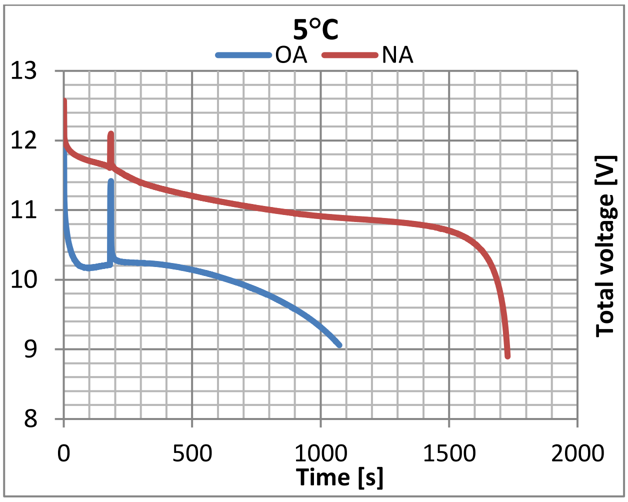

Figure 2: voltage drop over time at 5°C. Source: Authors.

Figure 2 depicts drop in voltage over time at stable 5°C.

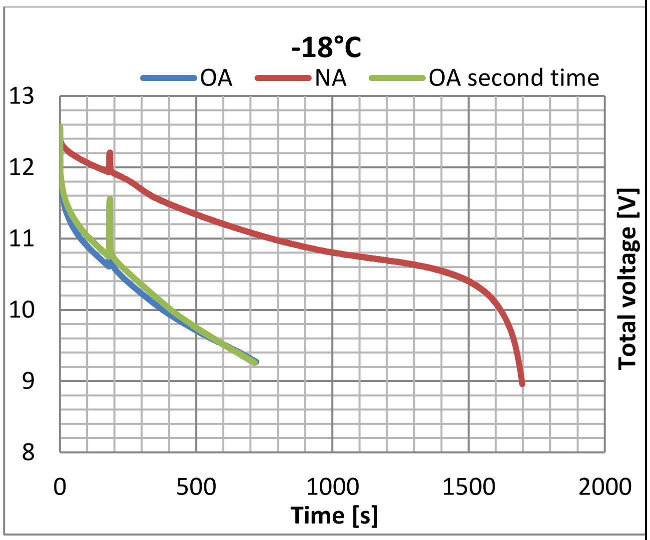

Figure 3: voltage drop over time at -18°C. Source: Authors.

In Fig. 3, we can see the same dependence at -18°C, when discharging took place immediately after insertion of accumulators into this environment.

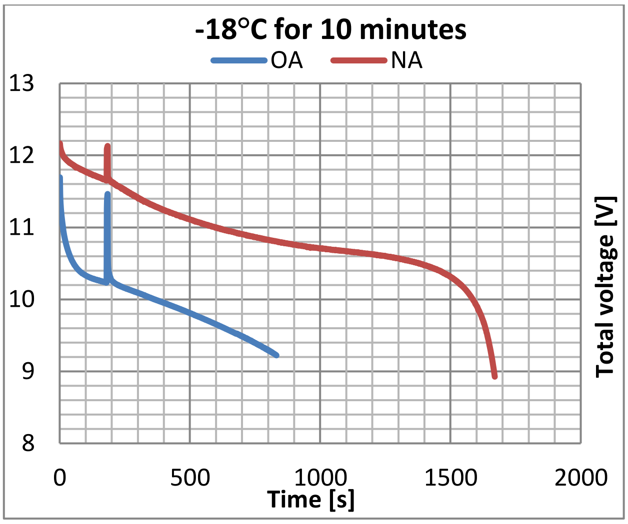

Figure 4: voltage drop over time at -18°C (inserted 10 minutes before discharge). Source: Authors

For measurements shown in Fig. 4, the accumulators were inserted into -18°C environment and after 10 minutes, the discharge program was initiated (as described in previous chapter).

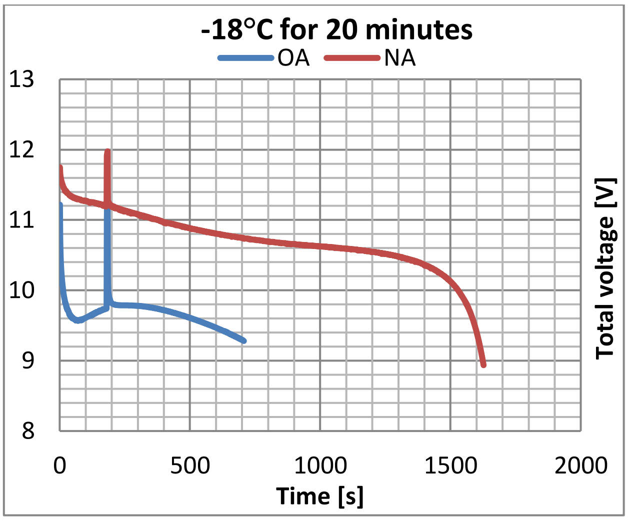

Figure 5: voltage drop over time at -18°C (inserted 20 minutes before discharge). Source: Authors.

Figure 5 shows the same kind of experiment, except that the accumulators were inserted for 20 minutes before discharge.

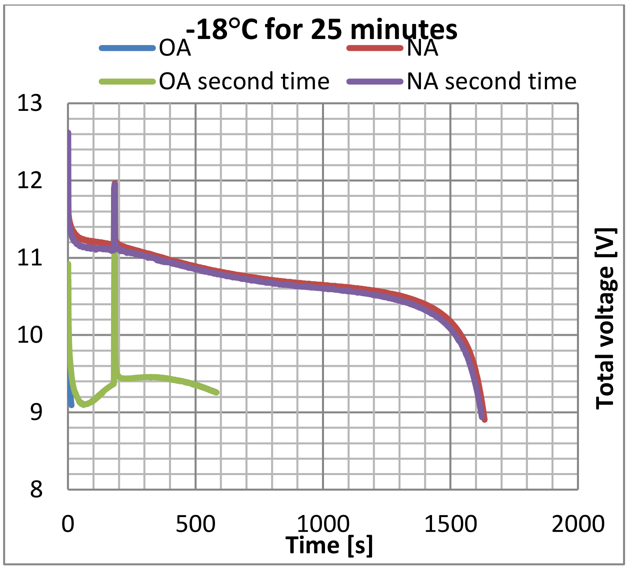

Figure 6: voltage drop over time at -18°C (inserted 25 minutes before discharge). Source: Authors.

In Fig. 6, we can see four measurements at -18°C with accumulators inserted into this temperature 25 minutes before the discharge. Two measurements were made for each accumulator.

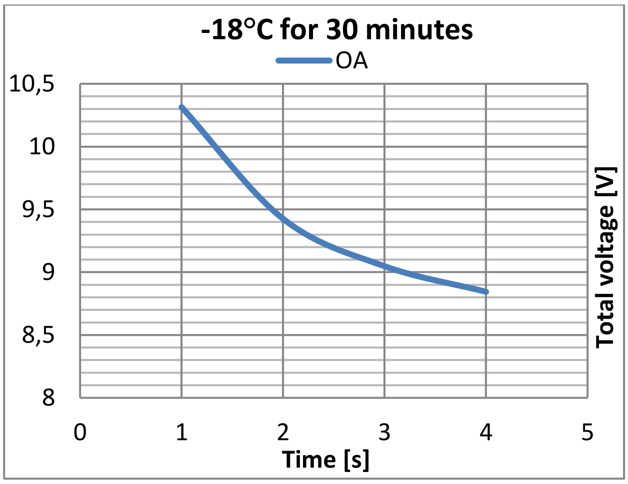

Figure 7: voltage drop over time at -18°C (inserted 30 minutes before discharge). Source: Authors.

Figure 7 contains only the data measured when discharging the old accumulator inserted to -18°C 30 minutes before discharge. During these repeated attempts with old accumulator, was found that the voltage drops immediately below the selected limit. Therefore, the new accumulator was not measured. The main reason was the need to preserve its relatively good condition for further use by the department.

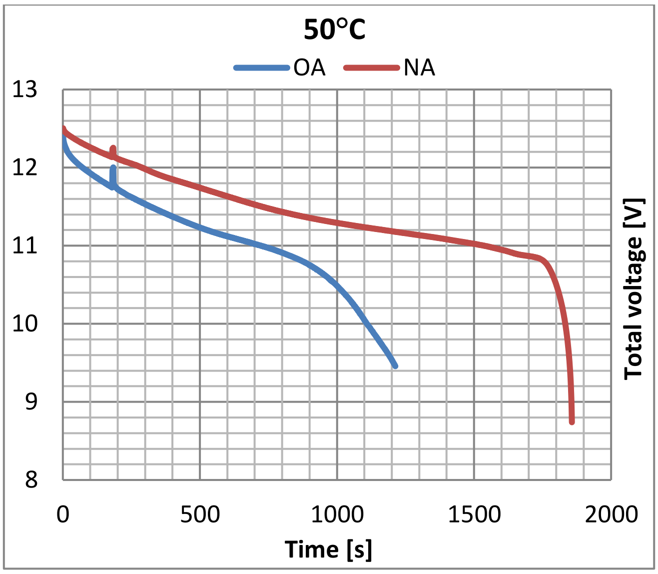

Figure 10: voltage drop over time at 50°C. Source: Authors.

Figure 8 presents the voltage drop at 50°C as described in the previous chapter.

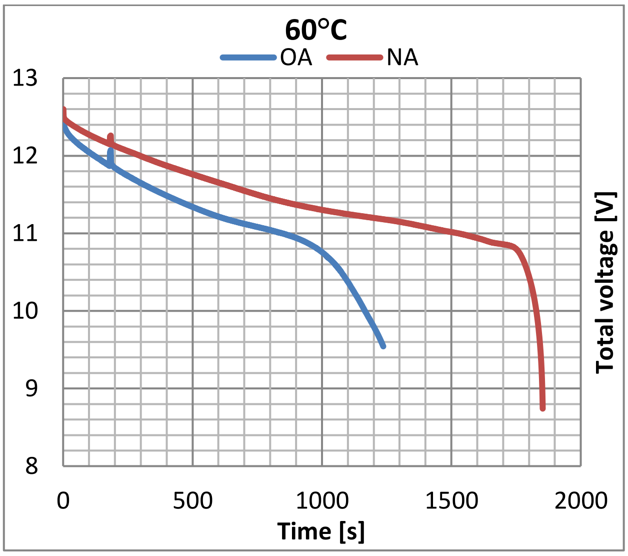

Figure 9: voltage drop over time at 60°C. Source: Authors.

Figure 9 displays measurement at 60°C.

Measurements made after each selected temperature measurement are not shown here but can be found in authors thesis.

4. Discussion

The difference between the new and the old accumulator is obvious from Tab. 2 at first glance. The capacity of the new one is around its declared capacity of 2200 mAh. While the old and already worn accumulator has actual capacity at room temperature of about 1500 mAh during the first measurements, which is only about 68% of the declared capacity. This result was expected.

The capacity of the old accumulator has been decreasing as measurements have been made. Table which shows measurements sorted as they were made is not shown here but can be found in authors thesis. Staying in extreme conditions was degrading for it. The effect of degradation will be further discussed for the individual results, that have been affected. On the other hand, the new accumulator retained its declared capacity at room temperature even after extreme temperatures. These results indicate that the age and wear of the accumulator has a significant impact on its ability to withstand extreme environments without consequences for future use. Conversely, a new accumulator will survive a limited number of cycles in these environments without further consequences.

The discharge characteristics themselves can be observed very well on Fig. 1. There is a distinct difference between the new and the old accumulator. The new one has a nearly linear drop in voltage over time to the point where the voltage starts to drop steeply. Therefore, for a longer accumulator life, it is preferable to set a higher discharge cell voltage limit than 3 V used in the experiments. With such a steep drop in voltage at the end of the curve, there is a risk of exceeding the 3 V threshold and degrading the cells. If we would end the discharge at the beginning of this severe voltage drop, at about 10.7 V and thus about 3.56 V/cell, the capacity used would be 2088 mAh at that time. This capacity is equal to 94.9% of the declared 2200 mAh capacity and 93.4% of the actual 2236 mAh capacity obtained in this experiment. For only 5.1 to 6.6% capacity, such a low threshold does not pay off and at least 3.5 V limit for normal use can be recommended. This will reduce wear on the accumulator, which is prone to undercharge and thus the service life increases. It should be remembered, that this limit varies according to the type of Li-Po accumulator. However, this applies only to the new accumulator. As we see on the second curve of Fig. 1 belonging to the old accumulator, 10.7 V is achieved very quickly. The accumulator has no significant drop at the end of the curve, but we see a steeper almost linear decline. For older and worn accumulators, it is worth setting a lower cell voltage limit when discharging. Apart from the obvious reason for the very low capacity at the higher limit, also for the economic reasons. The accumulator should be replaced (in normal use case) ion foreseeable future (inflation risk, loss of capacity). Lower capacity may prevent use for the purpose for which it was originally intended. The lower limit will therefore help us to use it a little longer for this purpose. As the accumulator capacity begins to drop significantly, it is advisable to gradually reduce the cell voltage limit for discharge. This general rule can work well with any Li-Po accumulator type.

Measuring at 5°C a result with a slightly lower available capacity was expected. Figure 2 and Tab. 2 show this decrease in units of percentage. Approximately 1.3% for the new accumulator compared to the declared capacity and 2.8% when compared to measured actual capacity (for further will be used as reference). At room temperature. 8.4% is then the capacity drop of old accumulator compared to measured capacity at room temperature. By comparing Fig. 1 and Fig. 2 we can observe a fundamental difference at the beginning of the curves. Here for the new accumulator, the voltage quickly dropped to 11.8 V compared to 12.2 V at room temperature after the start of the discharge process. The old accumulator drop is even more pronounced, reaching down to 10.2 V opposed to 11.5 V at room temperature. This decline can be expected to be much more distinct at lower temperatures (as will be seen in discussion later). Interestingly, the capacity difference is no more than 8.4% for the old accumulator despite a significant initial voltage drop. The explanation can be found in the next section of the curve. This decrease is followed by a slight increase in voltage despite the continuous discharge. The increase in voltage is caused by the heat generation inside the accumulators due to internal resistance. This internal resistance is a generally undesirable phenomenon that manufacturers are trying to minimize because it reduces the efficiency of accumulator energy transfer. But here it helps to warm up the accumulator and thus increase its usable capacity. If the effect did not exist, we could expect a similar or steeper curve than at room temperature measurement. Here we can see a significant difference between the new and old accumulators in the ability to withstand lower temperatures. The temperature increase inside the new accumulator cannot be detected on the curve. Thus, the internal heating provided us with similar curve as in the room temperature measurement case. The capacity reduction can be seen on the curve in the initial voltage drop. After discharging was complete, the accumulators were subjectively warm (as well as after room temperature measurements). It can therefore be said that this heating alone reduces the effect of an ambient temperature of 5°C.

When evaluating Fig. 3, which depicts the measurement at -18°C, it is necessary to emphasize the difference from the measurement at 5°C. Into -18°C (Fig. 3), the accumulators were inserted, and the discharge program was initiated immediately. In contrast, accumulators were put into 5°C temperature for several hours to allow them to reach this temperature fully. We can see a further decrease in available capacities. It is only 4.6% for the new accumulator, but 35.8% for the old accumulator from the room temperature reference measurements. This result again demonstrates the new accumulator’s high ability to withstand adverse temperature conditions. The worn accumulator had a very significant drop in accumulator in capacity. On the curve of the new accumulator we can see a steeper course than on the Fig. 1. However, the shape of the curve remains similar. We may also notice, that there has not been a sharp initial drop in voltage. Thus, if there is no hypothermia of the accumulator and the discharge process starts immediately after the transition to low temperatures, we can expect such good results. There were two measurements with the old accumulator in this experiment. There is no significant initial drop in in voltage as in Fig. 2, but it is nevertheless larger than at room temperature (Fig. 1). Of course, there is a noticeable steep decrease in voltage across the curve. The curve misses the characteristic arc seen in the previous figures. The measurement of the old accumulator was conducted as the 14th and 16th respectively and is affected by the degradation of the accumulator (as stated in the beginning of the paper).

Figure 4 shows the measurement when the accumulators were inserted into -18°C for 10 minutes before discharging. New accumulator has registered a 5% drop in capacity and the old 25% drop of reference value. The capacity drop for the new accumulator was not significant compared to the Fig. 3. We can explain this again by looking at the curve. We can see a rapid initial voltage drop to approximately 11.9 V. However, the next course of curve is very similar to the 5°C measurement apart from its steeper profile resulting in a shorter discharge time and lower capacity. The old accumulator also experienced a rapid initial voltage drop to 10.4 V. The initial voltage drop of both the old and the new accumulators compared to a drop of 5°C suggests that the accumulators did not cool down sufficiently in these 10 minutes at -18°C. However, it is clear from the further comparison of the curves, why the total capacity is lower. The reason for this is the inability of the heat generated by the internal resistance to compensate for the continuous residence at lower temperature. The curves are therefore steeper, and the capacity is lower. Especially in the case of the old accumulator curve we can observe the absence of voltage increase during the discharge (after initial drop), which is present in the Fig. 2. In Fig. 4, the curve after the initial decrease is rather linear.

Figure 5 shows measurement at -18°C with the accumulators inserted 20 minutes before the start of discharge. We can see a further reduction in capacity of both accumulators in Tab. 2. 6% for the new and 35% drop (from the reference values) for the old accumulator. Again, a significant initial voltage drop can be observed. For new accumulator to 11.3 V and for the old even to 9.6 V. After this drop, the new accumulator's curve is similar to other measurements at -18°C. The old accumulator has a significant increase in voltage after approximately 0.2 V and the curve is like that in Fig. 2 (5°C). Here again, the contribution of internal resistance can be emphasized. 20 minutes was enough time to cool the accumulators to display a significant drop in voltage. Thus, caution is needed when using older accumulators at high currents, which could drop voltage below set limit.

Figure 6 depicts the discharge od the accumulators kept at -18°C for 25 minutes before initiation. In this case, both accumulators were measured twice. For the new one, there was a decrease from the reference capacity of 5.6 and 5.8%. For the old then 98.9 and 46.5%. It is again confirmed, that the new accumulator is well resistant to low temperatures. 5 minutes more than the previous attempt, it did not reduce its useful capacity. We can observe the standard curve we expect here at -18°C. An initial voltage drop of approximately 11.2 V was expected. The old one had even worse results with these additional 5 minutes in the freezing environment. In one of these two measurements, the old accumulator's voltage dropped below the set limit and had essentially zero capacity. The drop in the second measurement was to about 9.1 V. Which is similar to one, where cell voltage limit was reached. However, none of the cells crossed the limit value here, but one went down to 3.002 V. Only another 2 mV away from reaching the limit before the voltage began to rise. In both experiments, the voltage is so close to this limit that it would be enough to increase the current draw and the cell voltage limit would surely be exceeded. The second attempt with the old accumulator is again marked by a significant increase in voltage after the initial drop, caused by internal resistance and heat generation. This time it the increase is by about 0.4 V. It is interesting to observe that the total voltage in time of end of discharge (when some cell drops below limit) is higher than during the initial drop.

Table 3: voltage limit values of old accumulator during -18°C for 25 minutes discharge measurement. Source: Authors.

	Total voltage [V]	Cell 1 voltage [V]	Cell 2 voltage [V]	Cell 3 voltage [V]
Initial drop	9,116	3,009	3,21	3,002
Discharge end	9,258	3	3,357	3,007

As we can see in Tab. 3, this phenomenon is due to the higher voltage of cell 2. This cell is in better condition than the other two and has better performance at this temperature. However, this is irrelevant for the total accumulator capacity. The whole accumulator depends on the properties of the worst (or weakest) cell. It can be assumed that cell 2 is in the center of the accumulator between cells 1 and 3. Thus, it is much more heated during discharging. We can mark this time of stay at -18°C as the limit for the older accumulator and it cannot be recommended for real environment usage at all. Higher temperature or shorter time should reduce the effect. But any temperature below 0°C should be treated with respect. Especially for the effect of initial voltage drop. If we do not draw sufficient current from the beginning of use, the accumulator will not heat up, and this will virtually prolong time spent in the freezing environment. Conversely, if we take too much current, there is an immediate drop below the set limit. It is therefore necessary to find a compromise and start discharging as soon as possible, but gradually. This will reduce accumulator wear and increase usable capacity. The older the accumulator is, more worn it is or more "inflated" it is, the more it will be prone to the phenomena described.

Figure 7 displays a measurement with an old accumulator at -18°C stored there for 30 minutes before beginning of discharge. For the reasons described in the previous chapter, only the old accumulator has been tested. As we can see, the voltage dropped immediately below the limit value and discharge was terminated. The capacity was almost nonexistent.

In Fig. 8 we can observe the curves for measurement at 50°C. Capacity increases were expected from measurements at higher temperatures. The new accumulator showed an increase of 0.94% from the reference value and 2.6% from declared value. The old accumulator then had increased capacity by 1%. From the reference value. However, it is important to note that this measurement of the old accumulator was done when some degradation was already noted. If we take, as a reference for the older accumulator, the value of the last measurement at room temperature, then the increase is 10.8%. The first thing that can catch our attention on the curves is their greater similarity to room temperature ones. The curve of the new accumulator is steeper at the end and therefore hold the voltage at the nominal level longer. The old accumulator has a more pronounced drop in voltage at the end of the curve and is more alike new accumulator curve (not observed in lower temperature measurements). Of course, as we can see, the accumulator did not maintain the voltage as long as the new one. But it can be seen that, the higher temperature was positive for the discharge process. The initial voltage drop we observed in previous measurements Is also present, but its effect is considerably smaller. Even smaller than at room temperature. For the new accumulator drop is to only 12.4 V and for the old one to 12.15 V. So, there is no risk of crossing the limit value for end of discharge even for older accumulator and with strong initial load.

The last Fig. 9 shows the measurement at 60°C. As in the previous case, there was an increase in capacity. For the new accumulator this increase was 0.6% form reference value and 2.6% from the declared value. 2% was the increase in capacity of the old accumulator. However, since the last measurement at room temperature, the increase is 11%. The difference between 50 and 60°C is therefore not so pronounced. Both curves are similar in shape to 50°C ones. There is almost imperceptible drop in voltage at the beginning of the discharge. For the new accumulator, the voltage dropped to approximately 12.45 V and for the old to about 12.25 V, which are better values than for room temperature measurements.

5. Conclusion

In general, we can say, that higher temperatures improve chemical reactions inside cells and in particular help older accumulators to increase their useful capacity. However, they do not have such great effect on newer accumulators. Nevertheless, periodically exposing Li-Po accumulators to high temperatures for which they are not designed, reduces life time. Even at 45°C there is a reduction of cycles by up to 50% compared to usage at 20°C (Buchmann, 2018c).

Conversely, in case of low temperatures, chemical reactions inside the accumulators slow down and internal resistance increases as well. Increased internal resistance reduces energy transfer efficiency, but also causes the cells to heat up significantly. As we saw, the cell voltage also increases at that moment, although discharging has been underway. The effect of heating is reduced internal resistance, which in turn increases the efficiency of the energy transfer. During longer stays at low temperatures, the accumulators suffered a rapid voltage drop at the beginning of the discharge, which was very pronounced for the old accumulator. Measurements before which we kept the accumulators cold for a longer period of time resulted in the old accumulator no longer showing any available capacity, because the voltage dropped below the set limit immediately after the start of the discharge. Thus, the older accumulator is generally sensitive to extreme temperatures and the new one is much more tolerant.

This paper serves as overview of environment temperature effects on Li-Po accumulators. Also, it shows how older and new ones react to different temperatures. This could prove to be beneficent for users of UAVs, who are relying on these accumulators. Using information gathered form this paper would help them use Li-Po accumulators more efficiently and save money on new ones because of increased life time. Further measurements could be made in one chosen temperature with more accumulators, to have more statistical background.

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