

THE EFFECT OF PHEV AND HEV DUTY CYCLES ON BATTERY AND BATTERY PACK PERFORMANCE

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ABSTRACT

Comparing different cars and [electric bike batteries](#) or different battery chemistries for real life duty cycles is an onerous process and requires each battery to undergo cycling for each specific duty cycle. The present paper is a first step towards simplifying this process by developing a metric for describing how a duty cycle current profile deviates from the constant current state. This quantity, the duty cycle eccentricity, is then utilized to compare the efficiencies of commercial NiCd, NiMH and Li-ion power tool batteries. Li-ion battery efficiency was found to be higher than that of NiMH and NiCd batteries.

KEYWORDS

[E-bike Li-ion batteries](#), duty cycles, efficiency, HEV, PHEV, [E-bike batteries](#)

INTRODUCTION

Coulombic efficiency can be seen as a measure of how much of the electric charge that is used for the intended purpose of an electrical device. Non-aqueous battery chemistries tend to run very small side reaction currents, hence achieving near 100% coulombic efficiency, even for real life duty cycles as seen in power tools or electric vehicles. The energy efficiency is the fraction of the total stored energy in a cell that is measurable as electrical energy. No battery chemistry can obtain 100% energy efficiency, for the simple reason that there will always be energy dissipated as heat through internal impedances. Generally, the efficiency drops as the current is increased because the rate dependent component of electrode overpotentials and the formation of concentration gradients will consume energy. In order to effectively design and utilize batteries for real life, power-demanding applications, some understanding of how the heat to electrical energy ratio varies with current and duty cycle is required.

The aim of the present paper is to demonstrate a methodology for adequately comparing different batteries or different battery chemistries for real life type of duty cycles without having to deal with the exact details of such duty cycles

Duty cycles are often defined in terms of their average current I ; however, this is insufficient to characterize pulsed duty cycles that may contain numerous steps. The standard deviation σ gives a representation of the departure from the constant current

state. To make it more universally applicable and to enable scaling we define the duty cycle eccentricity (DCE) as a unitless quantity given by

$$DCE = \frac{\sigma}{I} = \frac{I - I_{avg}}{I_{avg}}$$

If we then choose duty cycles such that the mean current remains constant in all cases, we can measure the cell efficiency as the duty cycle eccentricity grows.

Ignoring concentration gradients and assuming constant temperature, the cell will exhibit ohmic behavior: the voltage drop will be exactly proportional to the current. We use this theoretical behaviour to estimate the net contribution from temperature changes and concentration gradients and to determine whether they are positive or negative by extrapolating a least squares fit of energy efficiency vs DCE at low currents.

Selecting current profiles

For pulsed current testing involving different cell chemistries, selection of the current profile becomes non-trivial since the coulombic efficiency must be kept as close to unity as possible for the charge step when characterizing the discharge step and vice versa when characterizing the charge step. This is relatively straightforward for Li-ion batteries as long as the temperature is kept around room temperature or lower, and provided the recommended voltage range is not exceeded. This is possible because side reactions are virtually absent for the aforementioned conditions.

For aqueous chemistries, the situation is quite different, particularly for the charging reaction since the reversible hydrogen evolution potential is 1.23V (Aylward and Findlay 1974). This means that at any voltage exceeding 1.23V, some hydrogen evolution will occur. The rate of the hydrogen evolution will be dependent on the voltage difference between the electrodes.

EXPERIMENTAL

Standard E-One Moli Energy IMR26700A cells using LiMn₂O₄ based positive electrodes were employed for all tests with Li-ion batteries. Nickel-Cadmium (NiCd) batteries were obtained from an 18V 2.4Ah power tool pack. Nickel-Metal hydride (NiMH) cells were obtained from a 19.2V, 2.6Ah power tool pack.

High current measurements were performed using an E-One Moli Energy charger system or a Maccor Series 4000 battery cyler. Calorimetric measurements were performed using a Columbia Scientific Industries Accelerating Rate Calorimeter (ARC) and a Kikusui PLZ 700W electronic load.

For characterizing pulsed discharge, Li-ion batteries were charged using a constant current/constant voltage regime, starting with a current of 1C, switching to a constant voltage once 4.2V was reached. Charge was terminated when the combined charge time reached 90min. This 100% state-of-charge (SOC) was chosen as a reference state for the Li-ion cells.

NiMH batteries were first tested for coulombic efficiency using a charge current of C/10. It was found that the coulombic efficiency was near 100% up to a SOC of 90% using this current. The fully charged, reference state was therefore defined as 90% SOC for the

NiMH batteries. For the NiCd batteries, the charge efficiency was somewhat lower using C/10 as a charge current and 80% SOC was chosen as the fully charged, reference state.

For all cells, a charge approximately equal to 10% of the battery capacity was removed during the pulsed discharge step. The cells were then charged up replacing an equal amount of charge compared to what was removed during the discharge step. For the NiMH and the NiCd batteries, a charge current of C/10 was selected whereas the Li-ion batteries could sustain 1C charge current without the coulombic efficiency dropping. To compensate for limitations in the testing equipment, some of the tests were conducted using NiMH and NiCd 3 cell series packs.

For characterizing pulsed charge, a lower cutoff voltage was selected and used to define the discharged state. For NiCd and NiMH, discharged state was defined as a C/10 discharge to 0.9V. For Li-ion, the cells were discharged to a lower cutoff voltage of 2.5V using a C-rate current. This was defined as the fully discharged reference state. After every pulsed charge an equal amount of charge was removed before the next charge was initiated.

RESULTS AND DISCUSSION

Figures 1, 2, and 3 show the coulombic efficiencies for the three battery types using a C/10 constant charge current.

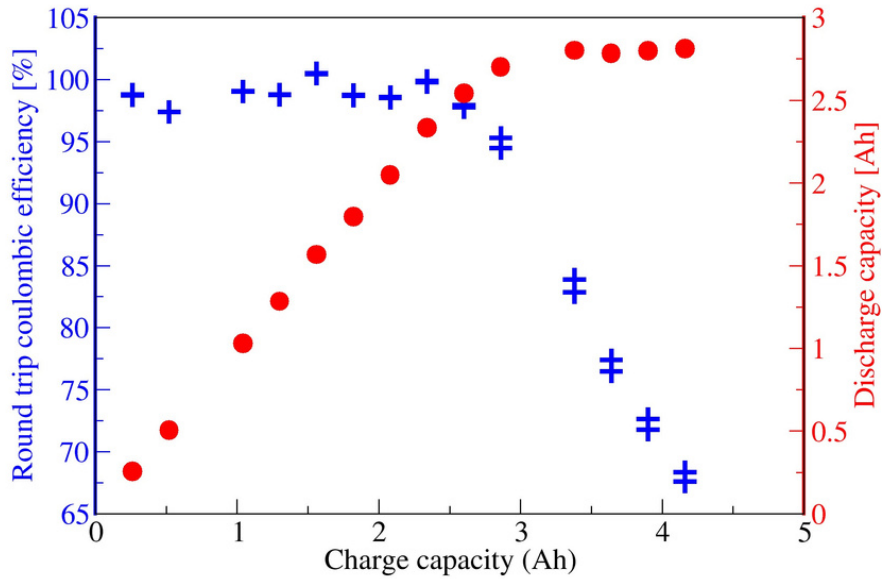


Figure 1: NiMH Round trip coulombic efficiency and discharge capacity as a function of charged capacity for C/10 currents.

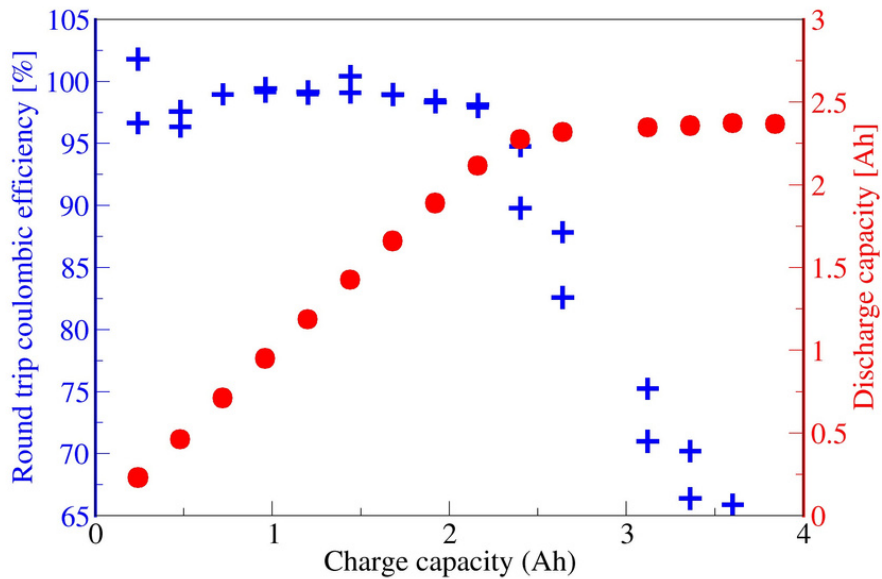


Figure 2: NiCd Round trip coulombic efficiency and discharge capacity as a function of charged capacity for C/10 currents.

It can be observed that both full efficiency and full discharge capacity are unobtainable even for this relatively low current. In particular for NiMH (Figure 1) and NiCd (Figure 2) cells the discharge efficiency drops rapidly as the cell approaches its fully charged state. The onset of this efficiency loss was chosen as the fully charged reference state for energy efficiency tests. This corresponds to approximately 90% of the maximum discharge capacity for the NiMH cell and 80% for the NiCd cells.

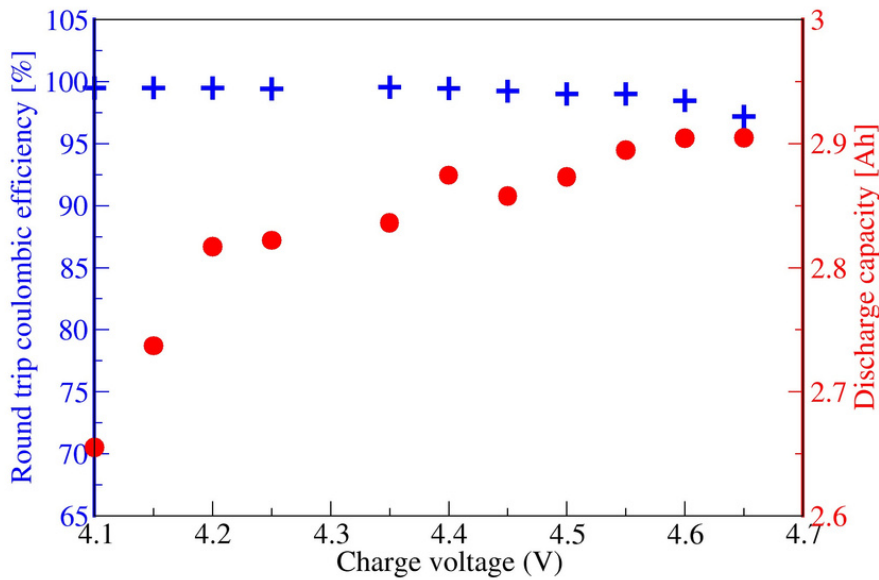


Figure 3: Li-ion Round trip coulombic efficiency and discharge capacity as a function of charge voltage for C/10 currents. Unlike NiMH and NiCd Li-ion batteries are charged using a CC-CV charging routine. This makes it easier to avoid cells being overcharged using a simple charger with no temperature monitoring

For the lithium ion cells, the coulombic efficiency is voltage determined. This is due to the constant voltage charge method. The fully charged state for a Li-ion cell is typically 4.2V, and the coulombic efficiency is very close to 100% at this point. As the voltage increases beyond 4.7V the efficiency does start to drop since electrolyte decomposition starts to take effect.

There will be some voltage threshold for all battery chemistries beyond which this electrolyte decomposition starts to happen. However, there is a fundamental difference between NiCd/NiMH and Li-ion since this electrolyte decomposition is mostly reversible for the former, whereas for the latter electrolyte decomposition is irreversible (Besenhard, 1998).

In Figure 4, the measured round-trip efficiency as a function of the duty cycle eccentricity is shown. In all tests the average current was kept to 3.3C (10A). For the tests with variable current on charge, the discharge current was kept constant at 1C and for the tests with variable current on discharge; the charge current was kept constant at 1C.

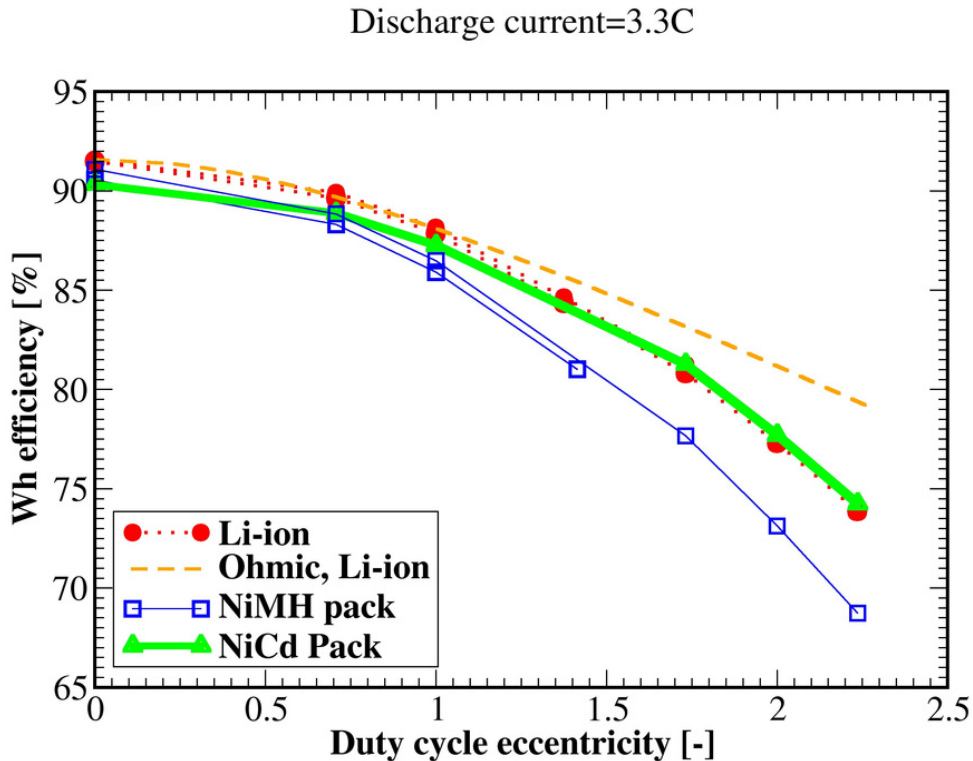


Figure 4: Measured round-trip charge and discharge efficiencies as a function of duty cycle eccentricity for 3.3C (10A) discharges.

For constant current, Li-ion shows a higher efficiency than NiMH and NiCd. As the duty cycle eccentricity increases the energy efficiency drops for all chemistries tested. The NiMH packs drops off faster than NiCd and Li-ion. As previously described, we can predict an ideal curve for efficiency vs. duty cycle eccentricity, denoted ‘ohmic’ in the plot. It can also be observed that the discharge efficiency deviates from predicted ohmic behavior once the eccentricity is greater than one. This is an indication that non-ohmic processes, such as diffusion or reaction kinetics, start to significantly influence the cell performance above that point.

From Figure 4, it can be observed that as the duty cycle eccentricity of the current profile increases, the efficiency decreases for all the battery systems tested. The efficiency for the Li-ion batteries is higher than for the NiMH and the NiCd batteries for the constant current discharge. The NiMH batteries showed a higher decline in efficiency compared to the Li-ion and the NiCd batteries whereas the latter were comparable. It is also

worthwhile to observe that the measurements performed using 3 cell series packs for NiCd and NiMH cells yielded the same efficiencies as the measurements performed for single cell tests.

Since the coulombic efficiency is very close to 1 for Li-ion batteries, it is also possible to analyze the efficiency as a function of duty cycle eccentricity for the charge current in a very straightforward, simple way. This is shown in Figure 5.

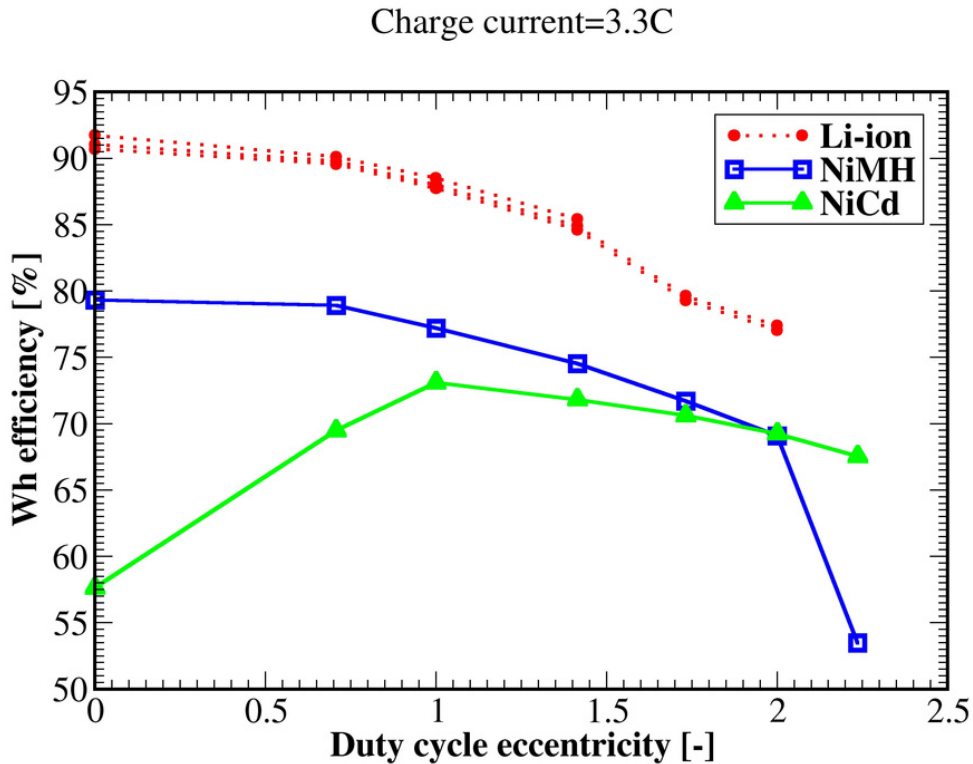


Figure 5: Measured charge efficiencies as a function of ratio of duty cycle eccentricity for NiCd, NiMH and Li-ion batteries

From Figure 5 it can be observed that the behavior is fundamentally different for the different battery chemistries. Li-ion has a very high charge efficiency, decreasing slightly as the duty cycle eccentricity increases. For the NiCd batteries, the charge efficiency is substantially lower. The NiCd efficiency shows a peak for an intermediate duty cycle eccentricity. For constant current, the coulombic efficiency is quite low, increasing with increasing duty cycle eccentricity of the current profile. However, as the duty cycle eccentricity increases, the heat production increases and offsets the gain in coulombic efficiency.

The importance of the findings presented in Figure 5 are of less importance for a battery charged using abundant power from the grid than for a battery charged from a limited energy source such as recaptured energy from regenerative braking. For a plug-in hybrid or electric vehicle, this will impact the all-electric-range (AER) and dependent on the

AER extension provided by the regenerative braking significantly contribute to which battery chemistry would constitute the ideal selection for such vehicles.

In Figure 6, the efficiency as a function of the depth of discharge (DOD) is given. The heat production is measured using the accelerated rate calorimetry (ARC) technique.

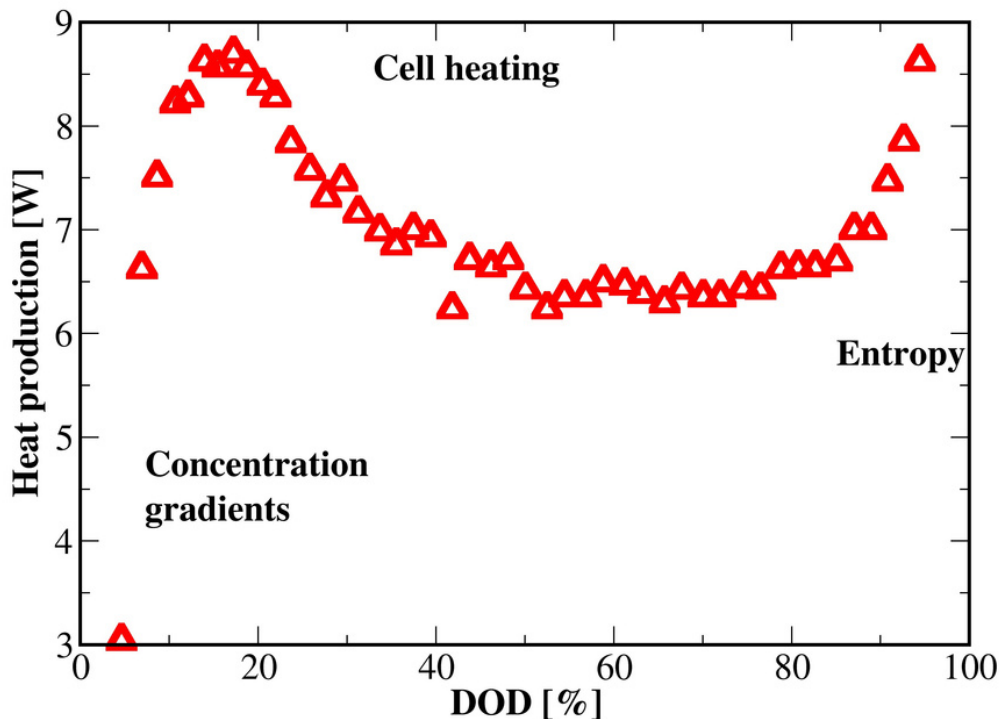


Figure 6: Heat production as a function of discharged capacity for a 6.7C(20A) discharge for a Li-ion battery

As can be seen from Figure 6, the heat production starts out low and increases while internal concentration gradients are building. This peaks when approximately 20% of the cell capacity has been utilized. The heat production then decreases and stays low until the end of discharge where it increases rapidly as heat is produced from entropy effects towards the end of the discharge.

CONCLUSION

In the present paper, a methodology for comparing different batteries, including different battery chemistries for real life parameters is presented. Average current was found to be insufficient for characterizing real life duty cycles. The performance of any battery is highly dependent on the duty cycle and knowledge of the power profile is crucial for battery and battery pack design. Development of standard tools for characterizing and grouping together duty cycles is important to be able to design optimal batteries and battery packs.

It is also shown that the charge and discharge efficiencies decrease as the duty cycle eccentricity of the current profile is increasing. This holds for all three battery chemistries tested. The energy efficiency of Moli IMR26700A LiMn₂O₄ based batteries remained remarkably high under all test conditions. This indicates the excellent viability of Li-ion batteries in applications requiring high efficiency.

Heat production for a constant current discharge was found to increase rapidly in the beginning of the discharge, and then decrease as the cell temperature escalated due to self-heating. At the end of the discharge, increased entropy production again increases the heat production.

References

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