Taking lithium-ion batteries to new extremes

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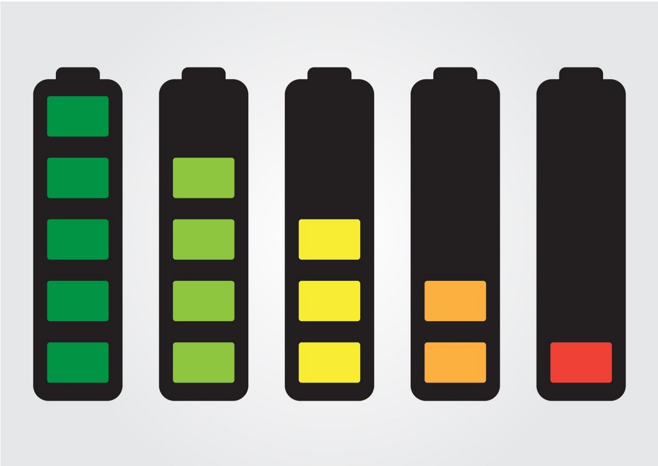

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Just like Goldilocks and her proverbial porridge, lithium-ion batteries (LIBs) perform best when the temperature range is just right—that is, neither too hot nor too cold. But this is a huge limiting factor when it comes to using LIBs in electric vehicles (EVs) in many locales where temperatures vary widely. LIBs perform poorly in extremes of heat or cold, and this is one roadblock preventing a transition to the wider use of EVs. As the authors of the study to follow note, "out of the 51 metropolitan areas in the United States, 20 areas normally experience extreme cold days below –18° C (0° F) while the summertime temperatures in 11 areas (including overlaps with the former 20) routinely exceed 38° C (100° F)." Similar temperature variations certainly exist throughout major urban areas worldwide, and likewise represent a barrier to the uptake of EVs as a potential renewable energy transport solution.

In a recent paper published in *Nature Energy* however, a group of UC Berkeley researchers report a novel invention that promises to effectively mitigate the effects of thermal extremes when used with LIBs. Their paper, entitled "Efficient thermal management of Li-ion batteries with a passive interfacial thermal regulator based on a shape memory alloy," details the contemporary operational landscape of LIBs in relation to ambient temperature variations in various locales, but also with regard to other confounding factors, such as newer fast charging and discharing batteries, which further complicate heat management strategies. They note that traditional linear thermal components typically fail to manage both extremes of hot and cold, and other potential solutions, such as controlled fluid loops, do not provide a high enough ON/OFF contrast, not to mention cost and weight considerations when used with EVs. Their solution is "a fluid-free, passive thermal regulator that stabilizes battery temperature in both hot and cold extreme environments. Without any power supply or logic, the thermal regulator switches its thermal conductance according to the local battery temperature and delivers the desirable thermal functionality, retaining heat when it is cold and facilitating cooling when it is hot."

To achieve this effect, their passive thermal regulator design draws on two key nonlinear features from existing thermal regulator concepts. The first of these features, solid-state phase change, exhibits good abruptness in response to temperature change, but fails to achieve an adequately high switching ratio (SR)—that is, the ON/OFF state thermal conductance ratio—which is the prime performance metric for thermal regulators. The second feature, the opening and closing of a thermal interface, has a much higher SR but relies on the differential thermal expansion between two materials. When the interface gap between materials is closed, it exhibits strong nonlinear thermal conductance. However, because the thermal expansion effect is relatively weak here, this design requires an unduly large thermal regulator body to accomplish the opening and closing of the gap.

As complicated as the preceding examples may sound, their solution—which embodies aspects of both solid-state phase change and interfacial thermal contact conductance—is remarkably simple.

To achieve their design goals, the study authors rely on a shape memory alloy (SMA) made from Nitinol, a flexible nickel /titatnium alloy wire which is routed around the periphery of a top thermal regulator plate, on which sit the LIBs. The ends of the SMA wire, one corresponding to each corner of the thermal regulator, connect with a bottom heat-sinking plate, known as a thermal interface material (TIM). The top and bottom plates are held in opposition by a set of four bias springs, which create a 0.5 mm air gap between the top and bottom plates and also hold the SMA wire in a state of tension. This defines the thermal-insulative OFF state.

As the battery heats up, the SMA, due to a undergoing phase transformation, begins to contract and pull the two plates closer. Thermal conductance is very low until the two plates touch, at which point the force of the contracting wire is greater than the opposing force of the bias spring, and the TIM plate (bottom) contacts the thermal regulator plate holding the batteries (top), and begins dissipating heat; this situation defines the ON state. The prototypal model described here encapuslates the essence of the passive interfacial thermal regulator.

To validate the fundamentals of this concept with regard to the SMA wire and the bias springs, the study authors built a model and tested it in a vacuum chamber, using two thermocoupled stainless steel bars as a heat source and a heat sink—these corresponding to the top and bottom plates here, respectively. In the experiment, thermal isolation in the OFF state proved to be excellent, as confirmed by the very large temperature discontinuity at the interface and the small temperature gradients measured in each of the stainless steel bars. However, when the upper bar temperature exceeded the SMA transition temperature, the gap closed and the TIM (the lower bar) began to heat up considerably. The authors note that the switch process here ocurred rapidly, within about 10 seconds, and that a record SR was achieved at 2,070:1. They point out that the Nitinol SMA wires had to first be pre-conditioned under higher stress loads before they could be relied upon to produce a stable, repeatable response through many cycles.

With the proof-of-concept established, the researchers moved on to demonstrating the concept in practice with two Panasonic 18650PF LIBs sandwiched between aluminum plates, tested in an environmental chamber. The design here used a similar thermal regulator design modified to fit the dimensions of the batteries in their holder, which callled for longer SMA wire lengths and a gap of around 1 mm between the top and bottom plates. Also, to meet a high level of performance, it was crucial to insulate the parallel thermal pathways of the wires and the springs and the LIBs themselves with an aerogel blanket. To compare performance, the researchers also provided two standard linear models, "always OFF" and "always ON," which involved replacing the SMA with stainless steel wires configured for a constant gap or constant contact between the two plates, respectively.

Under experimental conditions ranging from –20° C (–4° F; very cold) to 45° C (114° F; very hot), the thermal regulator performed well, warming quickly from –20° C (–4° F) to around 20° C (68° F) due to heat from the battery retained by the air gap and increasing the uable factor of the battery by a factor of three. At the opposite extreme, the thermal regulator also performed admirably, transitioning to the ON state at around 45° C (113° F) whereafter the temperature rise in the LIBs was limited to 5° C (9° F). After testing this thermal regulator set-up through 1,000 ON/OFF cycles, the investigators found the OFF state performance to be just slightly degraded (an 8.5% battery capacity reduction at –20 ° C [–4° F]) whereas the ON state performance remained unchanged.

As the study authors note, the costs of their thermal regulator are minimal when used with the standard "always ON" thermal management approach, which would already include a TIM heat sink. The additoinal mass of the SMA and bias springs is less than a gram, and the cost of the Nitinol wire is around $6. "Demonstration with a battery module consisting of commercial 18650 lithium-ion cells shows that this thermal regulator increases cold weather capacity by more than three-fold simply by retaining the battery's self-generated heat...while also keeping the module from overheating in hot environments even at high 2C discharge rate," the researchers conclude.

More information: Menglong Hao et al. Efficient thermal management of Li-ion batteries with a passive interfacial thermal regulator based on a shape memory alloy, *Nature Energy* (2018). DOI: 10.1038/s41560-018-0243-8

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