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All-Climate Battery Technology for Electric Vehicles

Inching closer to the mainstream adoption of automated driving.

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THE YEAR 2017 WAS WHEN ELECTRIC VEHICLES (EVs) CAME OF AGE. EV sales, according to Macquarie Bank, climbed from 740,000 vehicles in 2016 to 1.1 million, an increase of 51%. In terms of market shares, EVs accounted for 1.7% of new car sales in 2017, up from 1.1% in 2016. Although still small in the grand scheme of things, the growth rate was exceptional. All market movers are now taking EVs seriously, as evidenced by a flurry of announcements last year about the plans of major automakers for the EV market. Should these plans come to fruition, we are foreseeing roughly 400 models and 25 million sales of EVs by 2025.

Range anxiety has long been recognized as the key reason that discourages consumers from acquiring EVs, compounded by the fact that recharging an EV takes a much longer time than refueling an internal combustion engine vehicle (ICEV). To tackle the barrier of range anxiety, automakers are now targeting high battery capacities of more than 60 kWh that can provide a driving range of approximately 200 mi/charge. In the meantime, an exciting race is going on around the world to build fast charging stations with charging power up to 350 kW, capable of charging a 60-kWh battery in roughly 10 min.

A critical challenge to both driving range and fast charging is cold weather. The driving range of a Chevrolet Bolt per single charge, for instance, can be 240 mi in warm weather but it drops by more than 100 mi in cold weather, according to a recent article from *The Washington Post*. Likewise, a Nissan Leaf can be charged to 80% full in 30 min in an ideal temperature, but it would take more than 90 min to recharge in freezing temperatures. Therefore, when talking about driving range and fast charging, there is a strong need to establish criteria like all-climate range and all-climate recharge rate to evaluate EVs. To be truly competitive with ICEVs, EVs should be region and weather independent. Even in an extreme case like the historic bomb cyclone that covered the entire East Coast of the United States in

Digital Object Identifier 10.1109/MELE.2018.2889545
Date of publication: 4 March 2019

2325-5987/19©2019IEEE

January 2018, EVs should have a driving range and recharge rate similar to those in the warmer climate of Southern California.

The linchpin to making EVs weather independent is the innovation of battery technology. In 2016, our team at the Electrochemical Engine Center (ECEC) of Pennsylvania State University, along with EC Power LLC, reported a new battery structure, a self-heating lithium-ion battery (LiB) that can rapidly warm up from ambient to room temperatures in only tens of seconds. As such, the cell always works in a so-called greenhouse no matter how cold the ambient temperature is, eliminating temperature restrictions on battery performance. The self-heating battery structure has been patented by EC Power and incorporated into its All-Climate Battery (ACB) products. In only two years, this new technology has advanced from prototyping to mass production, and it is going to be widely used in real-world applications, such as for 10,000 EVs to serve the 2022 Winter Olympic Games. In this article, we present an overview of the ACB technology, from its working principle to its capability of boosting driving range and enabling all-climate fast charging, and its current status of commercialization.

Structure and Working Principle of the ACB

The structure of an LiB, including the three main components—the anode, cathode, and electrolyte—has remained unchanged since it was first reported in the 1970s. The ACB attempts to change the LiB structure by introducing a fourth component, a thin nickel (Ni) foil, inside the cell. The structure of an ACB cell is given in Figure 1 along with a current diagram showing its working principle. The Ni foil is coated with thin backing materials on both sides for electrical insulation and sandwiched

between two single-sided anode layers; the three-layer assembly is then stacked at the center of the cell. One end of the Ni foil is welded with the tabs of anode layers and connected to the negative terminal; the other end of the Ni foil extends outside. Hence, an ACB cell has three terminals: positive and negative terminals, as in conventional cells, and a third one named the *activation* (ACT) terminal. In addition, a switch is added in between the positive and ACT terminals.

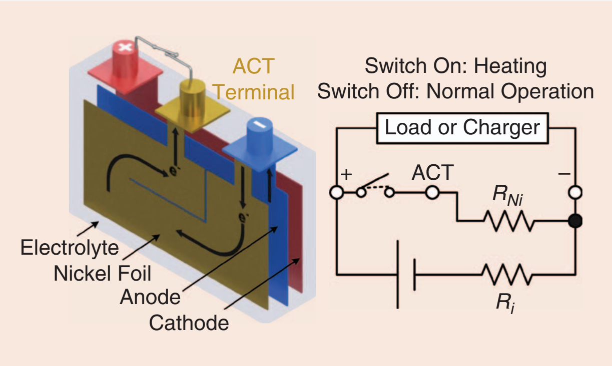

Figure 1. The structure and working principle of the ACB.

Rapid and Uniform Internal Heating

The working principle of an ACB cell is simple. When heating is needed, the switch between positive and ACT terminals is closed. As such, all current generated by the cell goes into the Ni foil, creating immense heat that rapidly warms up the cell. Figure 2 gives an example of self-heating from –20 °C ambient temperature. The cell was a 10-Ah pouch cell having a graphite anode and $LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$ cathode with an energy density of 170 Wh/kg. Prior to the test, the cell was soaked in an environmental chamber overnight to reach equilibrium with the –20 °C ambient temperature. The switch between positive and ACT terminals was closed to initiate self-heating. It can be seen from Figure 2(a) that cell voltage, the voltage difference between positive and negative terminals, remained above 2.5 V in the heating process, indicating that the battery materials do not suffer potential degradation. In the meantime, a large current up to roughly 8 C (1 C equals 10 A) was

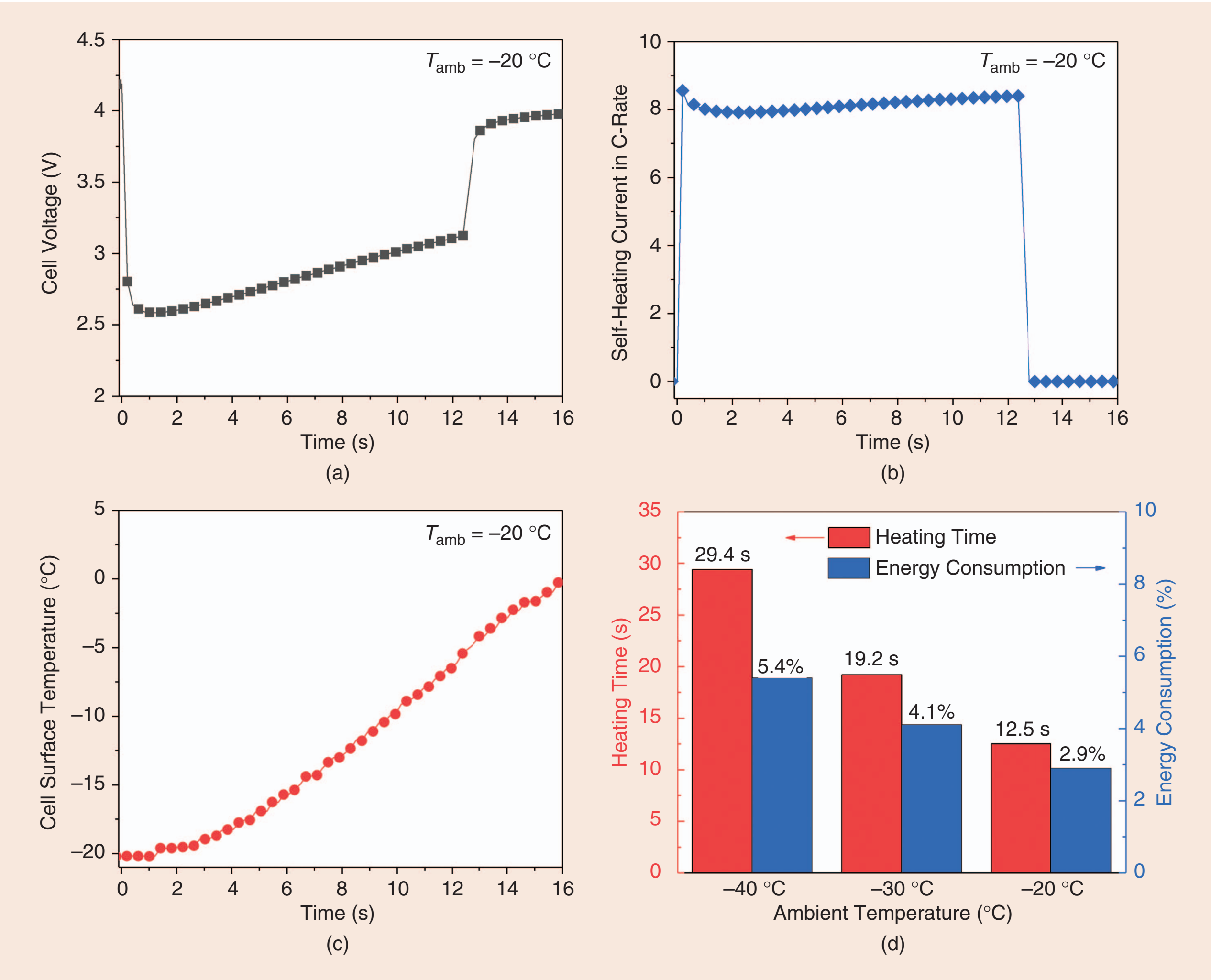

Figure 2. The evolution of (a) cell voltage. The (b) current and (c) surface temperature during self-heating from –20 °C. (d) A summary of the heating time and energy consumption at different temperatures.

generated and went through the Ni foil [Figure 2(b)], creating immense heat that rapidly warmed the cell [Figure 2(c)]. When the cell surface temperature reached –5 °C, the heating process was completed by opening the switch. After relaxation of a few seconds, the surface temperature rose to 0 °C [Figure 2(c)].

Figure 2(d) summarizes the heating speed and battery energy consumed for heating in the tests at different ambient temperatures. Even in the extreme temperature of –40 °C, it took only 29.4 s to heat the cell to –5 °C, representing a heating speed of 1.2 °C/s. As will be discussed later, conventional battery heating methods using external heaters are restricted by an intrinsic conflict between heating speed and uniformity, and, thus, their heating speed is typically below 1 °C/min, more than 60 times slower than the ACB cell. Figure 3 shows infrared thermography images of the ACB cell heated from –20 °C. Six images are presented, and the rectangle box in each image, which is 120 × 69 mm^2, represents the area covering the electrode active materials. It can be seen from this figure that temperature distribution is uniform throughout the rapid heating process, indicating that the Ni foil is well designed to ensure uniform internal heating.

A great feature of the ACB technology is that it enables the rapid restoration of battery energy and, thus, boosts the driving range of an EV in cold weather.

Furthermore, EV makers are now targeting a larger capacity of single cells to reduce the manufacturing cost, which makes EV batteries much thicker. The 94-Ah single cells used in the latest BMW i3 have a thickness of 45 mm, approximately five times that of the last generation of EV batteries. The increase of cell thickness poses a greater challenge to external heating, as the temperature difference across the cell is even larger, and, thus, the heating speed shall be further reduced to prevent localized overheating.

Here lies the inherent superiority of the ACB cell. No matter how thick the cell is, the issue of temperature nonuniformity can be resolved by inserting more pieces of Ni foil into the cell, which divides the total heat source into different locations along the thickness and enables rapid and uniform heating. As shown in Figure 4(c), an ACB cell with 34-mm thickness can be heated from –30 to 0 °C (surface temperature) in 26.8 s while maintaining the maximum temperature below 10 °C by inserting eight Ni foils. Therefore, there are no concerns of overheating in ACB cells. Furthermore, by reducing the temperature nonuniformity with more Ni foil, the energy consumed for heating is also reduced, as shown in Figure 4(d). On the contrary, the method of external heating is not only slow in

The ACB Versus External Heating Methods

Most EVs today utilize either positive temperature coefficient heaters or thermal management systems to heat the battery externally. A critical issue of external heating is that the heating speed is restricted to prevent localized overheating near the cell surface. Heating power is increased to accelerate the heating process [Figure 4(a)], whereas higher heating power leads to a larger temperature difference across cell thickness [Figure 4(b)] due to the poor through-plane thermal conductivity of LiBs (<0.5 W/mK). Hence, there is an intrinsic conflict between heating speed and cell safety for external heating; that is, the increase of heating power makes the cell more prone to localized overheating, as can be noted from Figure 4(c). Therefore, the speed of external heating is pretty slow, typically below 1 °C/min.

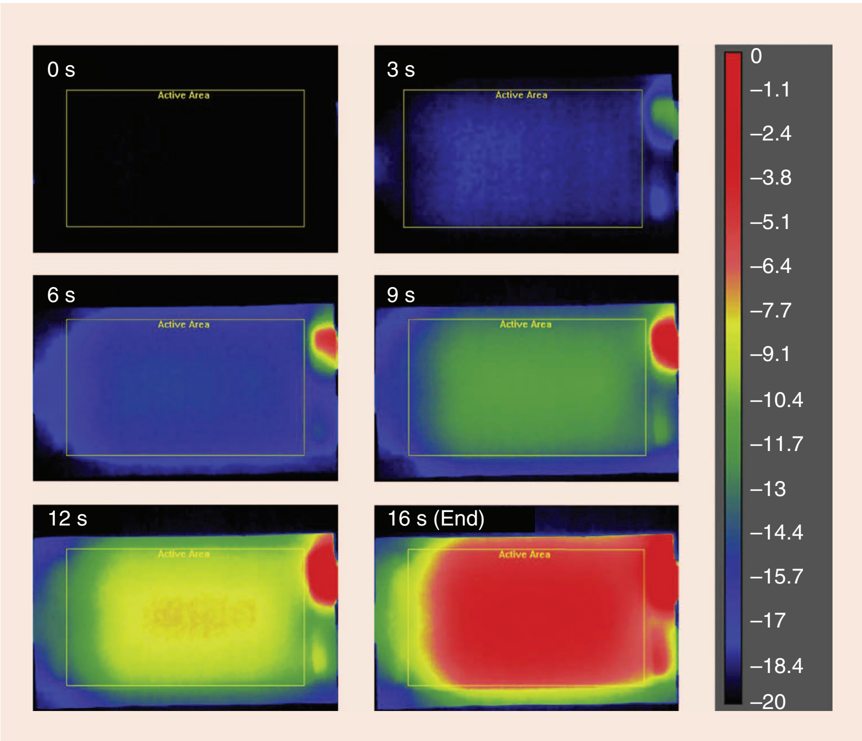

Figure 3. Time-sequential images from the infrared thermography of a 10-Ah self-heating Li-ion cell activated from –20 °C.

speed but also consumes more energy, especially when the cell is not perfectly insulated.

Boost of Driving Range in Cold Weather

A great feature of the ACB technology is that it enables the rapid restoration of battery energy and, thus, boosts the driving range of an EV in cold weather. A major reason for the loss of EV driving range in cold weather is that regenerative braking energy, which accounts for more than 20% of the total driving range per charge, cannot be harvested at low temperatures because LiBs are not allowed to be charged at low temperatures to prevent Li plating. A general solution is to heat the battery prior to or during driving but, given the low speed of external heating, it would take tens of minutes to warm up the battery before regenerative braking energy can be recovered.

We have developed an active control strategy based on the ACB structure that enables the rapid restoration of battery energy while the vehicle is driven, which eliminates any need to wait for preheating. Figure 5(a) shows the principle of the self-heating-while-driving (SHWD) strategy. A real-world driving profile of an EV can be categorized into three regimes: battery discharge for vehicle driving, battery charge for recovering braking energy, and battery rest when the vehicle is stopped. The key to the SHWD strategy is that when the battery temperature is low while it is either in the regenerative braking regime or rest regime, as sketched in Figure 5(a), the switch connecting positive and ACT terminals is closed to heat up the cell. Figure 5(b) and (c) gives an example of the SHWD protocol under the US06 driving cycle. The black line in Figure 5(b) is the actual profile of

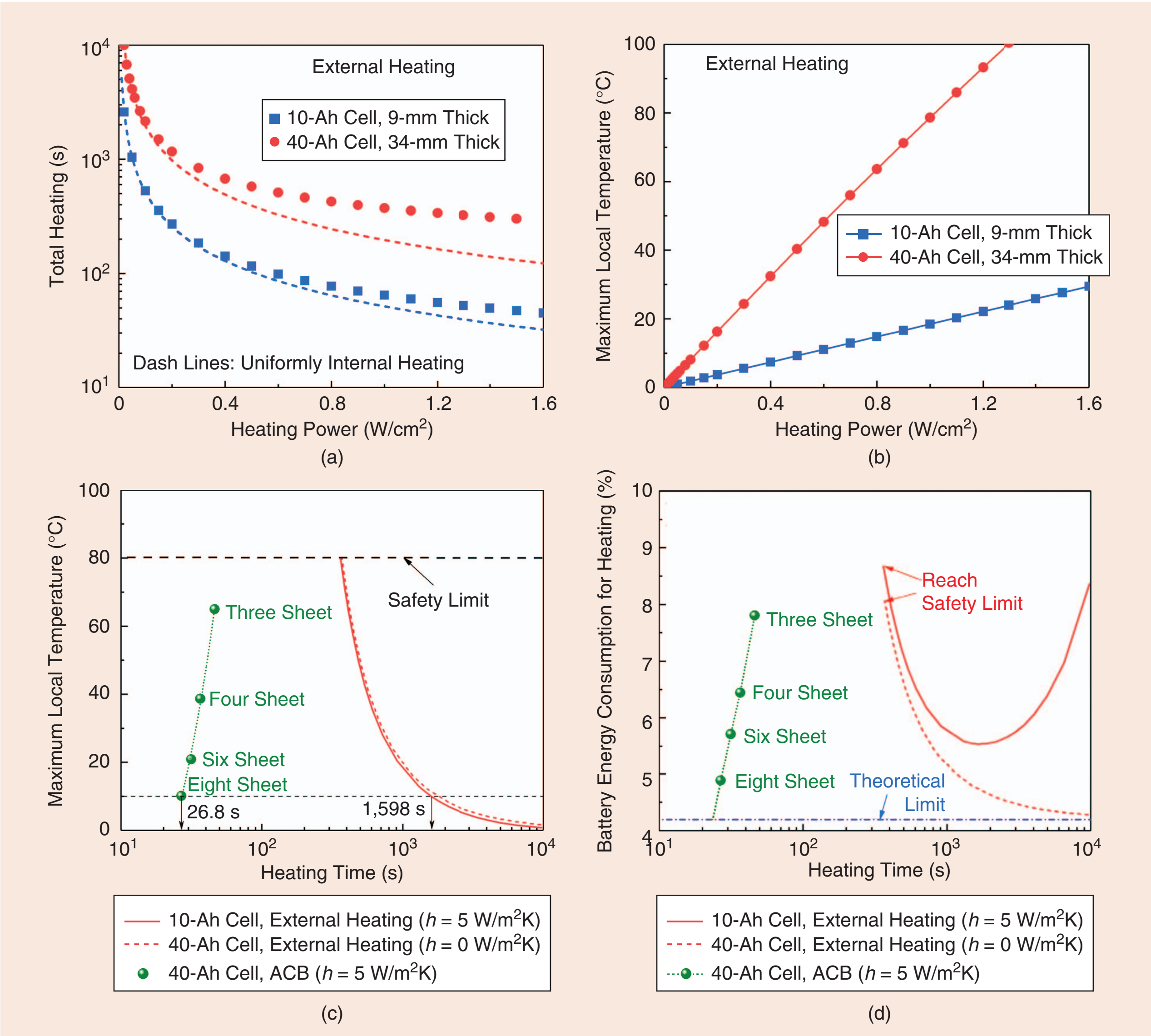

Figure 4. Variations of the (a) total heating time and (b) maximum local temperature with heating power for external heating. A comparison of the ACB with external heating in terms of the (c) maximum local temperature and (d) total battery energy consumption against the heating time.

the external current, while the blue line is the profile of the actual cell current. When the external current is negative (cell discharge), the cell acts as a conventional cell. When the external current is zero or positive (regenerative braking), the switch is closed, and the cell also discharges. During this period, both the input current recovered by braking and the discharge current of the cell flow into the Ni foil for heating. As such, the driver's behavior is not affected (i.e., there is no waiting time), and cell temperature quickly rises from –40 to 10 °C in 112 s [Figure 5(c)].

Figure 6 further compares the power profile of the ACB cell under the US06 driving cycle using the SHWD strategy with a baseline cell at –40 °C ambient temperature. As the baseline cell remains at low temperature, regenerative braking energy cannot be harvested (i.e., there is no positive value in the power profile of the baseline case). Figure 6(c) presents an energy breakdown analysis of the total battery energy of the ACB and baseline cells. The driving energy is significantly increased for the ACB cell with the SHWD strategy, which is 49% more than the baseline cell. The boost of driving energy can be ascribed to two reasons. First, the regenerative braking energy, which accounts for roughly 22% of the total energy for driving, is fully recovered. Second, the remaining battery energy at the end of the test (i.e., cell voltage reaches the cutoff limit) is only 0.7% of the ACB cell, indicating that all battery energy is discharged. On the contrary, 7.8% of the battery energy cannot be discharged for the baseline cell due to the poor performance at low temperatures.

> ***Another extraordinary capability of the ACB technology is that it enables fast charging in any ambient temperature without sacrificing cell life.***

Fast Charging From All Temperatures

Another extraordinary capability of the ACB technology is that it enables fast charging in any ambient temperature without sacrificing cell life. Most EV batteries use graphite as the anode material, which has an equilibrium potential within 100 mV versus Li/Li$^+$. In harsh charge conditions, such as a high charge rate or low temperatures or both, the large anode polarization can push the anode potential below a threshold that triggers the deposition of metallic Li on graphite surfaces, a behavior called *Li plating*. A major symptom of Li plating is a drastic capacity loss in addition to hazardous consequences. Therefore, Li plating shall be strictly prevented during charging, which is why today's EVs take a much longer time to charge the battery at low temperatures.

We have developed a novel charging strategy based on the ACB structure that enables fast and healthy charging in any temperature. The total charging process is divided

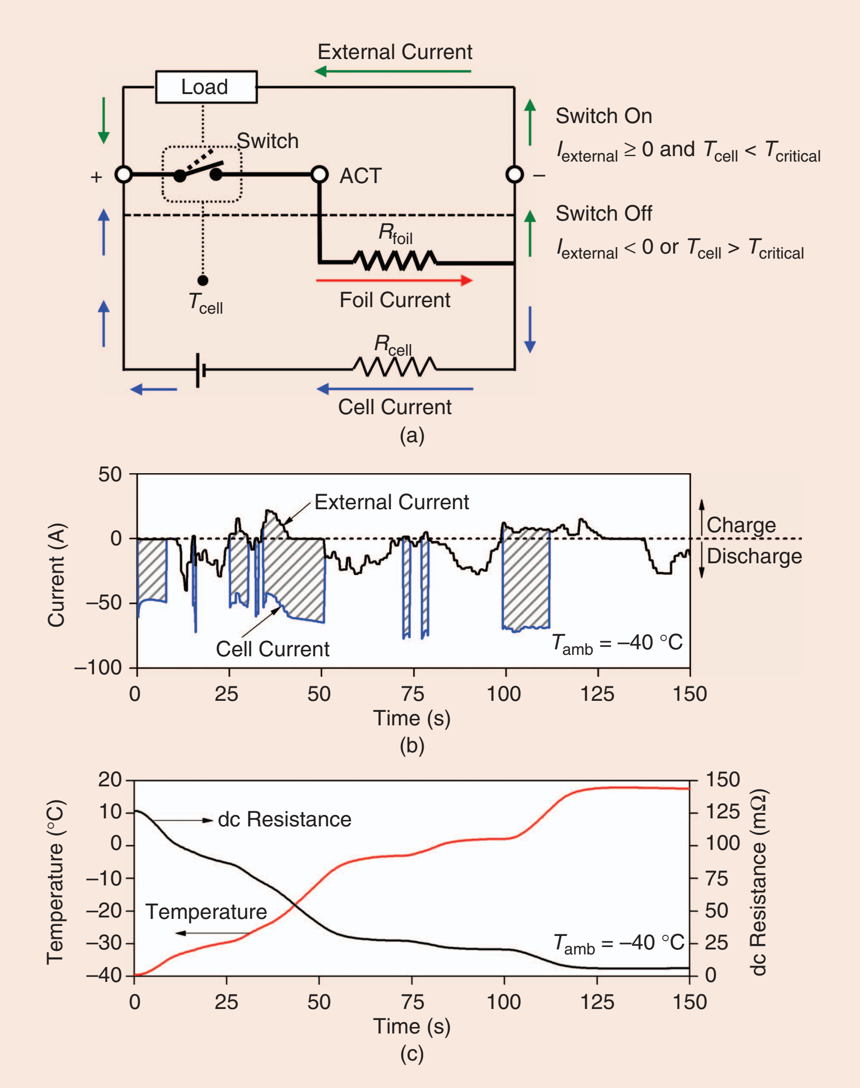

Figure 5. (a) The SHWD strategy. The evolution of the (b) cell current and external current and (c) cell temperature and internal resistance during power restoration while driving in a US06 driving cycle test at –40 °C.

into two steps: a rapid heating step to raise the cell temperature to a level that eliminates Li plating, followed by a fast-charging step. Figure 7(a) shows the voltage curves during 3.5-C charging of an ACB cell in different temperatures. The cell was a 9.5-Ah cell with an energy density of 170 Wh/kg, which was fully discharged prior to each test. A rapid heating step was performed at the beginning of each test by applying a constant voltage of 3.15 V (close to cell open-circuit voltage), along with closing the switch between the positive and ACT terminals. A large current [Figure 7(c)] was supplied from the charging source, and all of the input current went into the Ni foils without going into electrode materials (no Li plating) in the heating process, and, hence, cell temperature rapidly increased [Figure 7(d)]. Once the surface temperature reached 20 °C, the switch was opened to complete the heating step, and the cell was then charged using the constant current, constant voltage protocol with 3.5 C and 4.2 V until reaching 80% state of charge (SOC).

Figure 7(b) summarizes the total charging time, including heating and charging of all four tests, and we can learn that, even in the extreme case of –50 °C, which is already beyond the operation limit of the cell (i.e., the electrolyte ceases to work), the cell can be charged from 0 to 80% SOC in only 15 min. Furthermore, it can be noted from Figure 7(a) that the charging voltage curve at –50 °C is almost the same as that at 0 °C, indicating that the ACB enables a unified charging practice independent of ambient temperature, which can be extremely useful for EVs, as it can greatly simplify battery management systems and enhance the accuracy of battery state estimation.

ACB technology will be deployed in 10,000 vehicles, including cars and buses, to serve the 2022 Winter Olympic Games in Beijing.

Figure 7(e) further compares the cycle life of the ACB cell with a baseline cell. Both cells were put through a cycling test with a 3.5-C charge to 4.2 V followed by a 1-C discharge to 2.7 V in a freezing temperature of 0 °C. The baseline cell lost 20% capacity in only 50 cycles, while the ACB cell survived 4,500 such cycles, which is a 90 × boost compared with the baseline cell. Even if a driver performs one charge per day in such a freezing temperature, 4,500 cycles means a lifetime of 12.5 years. Most recently, we have partnered with the U.S. Department of Energy to develop an extreme fast-charging technique—10-min charging to 80% SOC—using the self-heating cell structure. Specifically, we shall achieve >220 Wh/kg (based on an NMC622 or NMC811 cathode and graphite anode) and >1,000 cycles of 6-C charging to an 80% SOC.

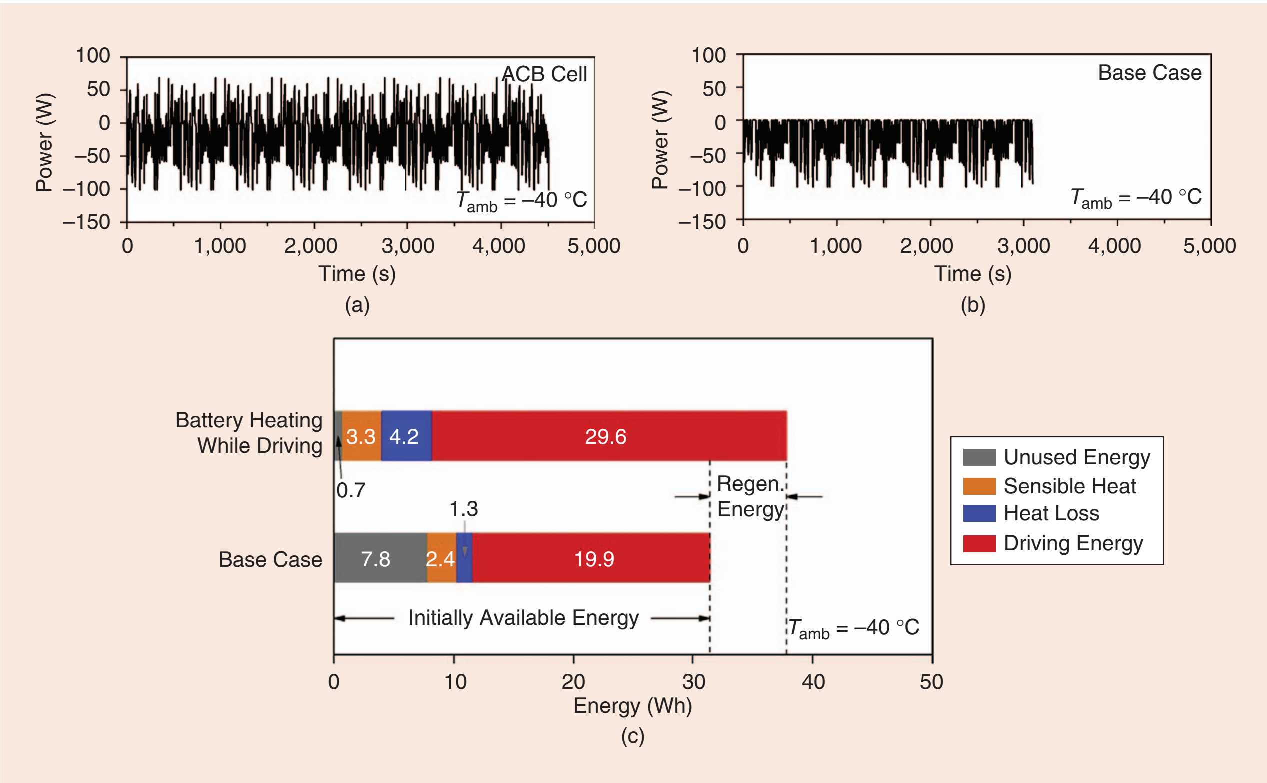

Figure 6. A comparison of the ACB cell using the SHWD strategy with a baseline case in a US06 driving cycle at –40 °C. (a)–(b) Power profiles. (c) A breakdown of the total energy delivered. Regen.: regenerative.

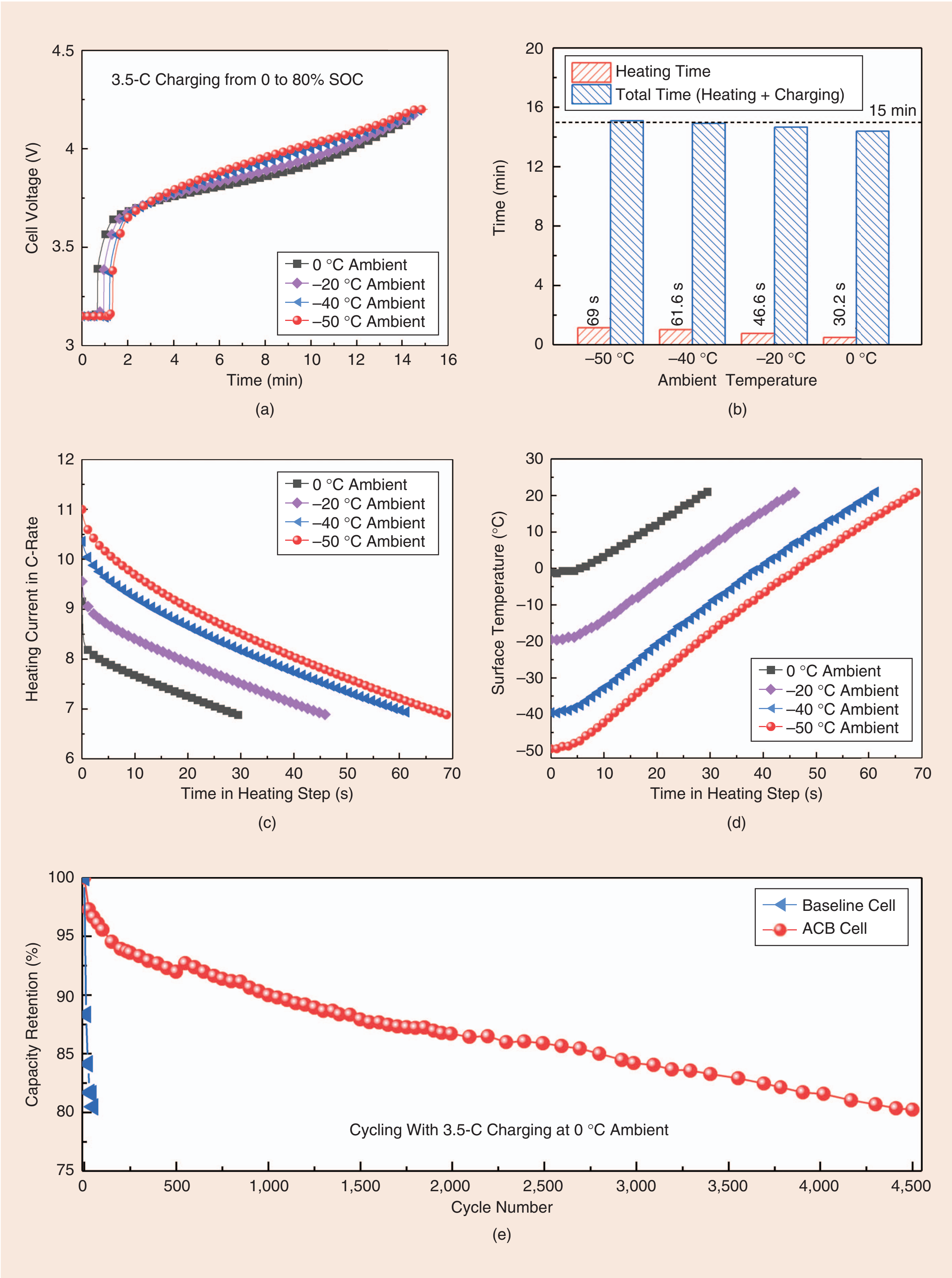

Figure 7. Fast charging of the ACB in different ambient temperatures. (a) The charge voltage curve in 3.5-C charging. (b) A summary of the total charge time. (c)–(d) The evolution of the heating current and surface temperature during the rapid heating step. (e) A comparison of cycle life during 3.5-C charging at 0 °C.

Commercialization of ACB Technology

The ACB technology has received global attention in the past two years and is already widely commercialized. For example, in September 2017, the 2022 Winter Olympic Committee announced that ACB technology will be deployed in 10,000 vehicles, including cars and buses, to serve the 2022 Winter Olympic Games in Beijing (Figure 8). Significant progress has been made by the team led by Prof. Fengchun Sun of the Beijing Institute of Technology along with industry partners in the last year. ACB cells and packs have been mass produced by Citic Guoan MGL Power Sources Technology Company Ltd. and utilized in three types of EVs, including an electric sedan manufactured by BAIC-BJEV, a 7-m-long coaster-type electric minibus by Yutong Bus, and a 12-m-long electric bus by Foton Bus. In March 2018, all of these EVs were tested in the Hailar Winter Test Center, located in northeastern Inner Mongolia of China close to the China–Russia border, where the ambient temperature is approximately –40 °C. The testing criteria required all vehicles to be left in the –40 °C ambient temperature for 72 h and then given 10 min to reach their normal performance. With the ACB technology, all three vehicles were quickly heated up at a speed of roughly 10 °C/min and successfully passed the test. In January 2018, BMW Group publicly announced a partnership with EC Power by executing an intellectual property agreement that allows the BMW Group to use the ACB technology in their EVs. Examples of BMW's ACB cells and packs are shown in Figure 9.

ACB technology is capable of making EVs truly region and weather independent.

Summary

Increasing driving range and reducing charging time are the keys to enabling the mainstream adoption of EVs. A critical issue that shall not be neglected is temperature effect, as either the driving range or charging speed drops substantially in low temperatures. The ACB

(a)

(b)

Figure 8. (a) Three types of EVs powered by ACB technology to serve the 2022 Winter Olympics games. (b) The testing team of the three ACB-powered EVs in the Hailar Winter Test Center.

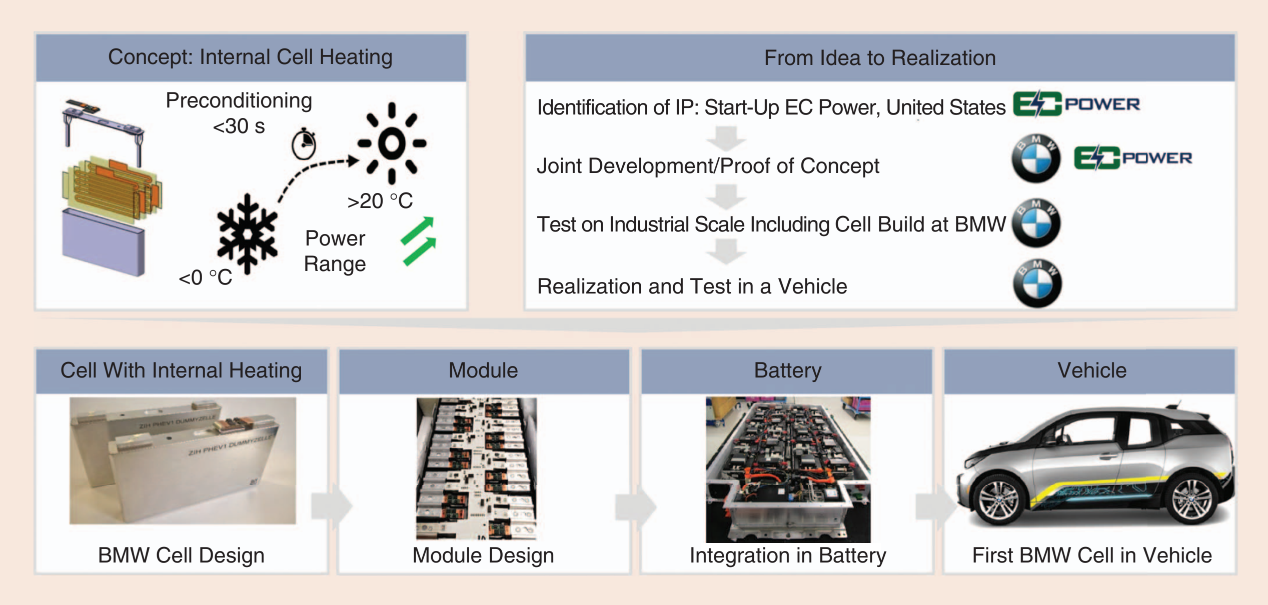

Figure 9. The ACB cells and packs utilized in BMW EVs. The internal cell heating to improve low temperature battery performance is an example of BMW innovation (BMW Group 2017).

technology offers a simple yet powerful approach to tackle the low-temperature issues. Through rapid heating in a matter of seconds, the ACB cells are able to work under optimal conditions no matter how cold the ambient temperature is. Therefore, ACB technology is capable of making EVs truly region and weather independent.

For Further Reading

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