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Nano-batteries in a carry fluid as power supply: Freeform geometry, superfast refilling, and heat self-dissipation

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This letter proposes and analyzes a system composed of many micro- or nano-scale batteries. Each battery is a self-contained Li-ion micro-battery enclosed in an insulating shell, and can charge/discharge wirelessly or through contacts. Thousands of such batteries are carried by an inert fluid to form a power fluid to drive an electric vehicle. This power fluid can be stored in the tank and replaced easily with a fully charged fluid by refilling once its energy is depleted. The system can provide better energy density, higher power density, and extremely fast "charging" within minutes. The architecture eliminates the large over-capacity design in the current battery packs, significantly reducing the weight and cost. It would also enable progressive improvements of vehicle performance by replacing the micro-batteries. The battery system has flexible geometry, and therefore can essentially go into a storage space of any geometry, allowing uniform design of battery configurations for diverse applications. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4904994]

Advanced battery technology is critical for vehicle electrification. The performance of current Li-ion batteries faces several significant challenges in capacity, charging time, cycling life, and cost. The United States Advanced Battery Council (USABC) has requested that a battery pack in electrical vehicles (EVs) should be able to support for a driving range of 400 miles, 80% of capacity retention after 1000 cycles, and product quality guarantee of 15 calendar years.[1] These standards, although pursued diligently by researchers, are difficult to reach for many battery chemistries with the current pack design. To compensate the capacity drop in severe temperature weather conditions and capacity loss associated with charge/discharge cycling, battery packs in current EVs are designed with up to 50% over-capacity, which significantly increases the weight and reduces the driving range per charge. Meanwhile, current battery packs usually take hours to be fully charged. For example, it takes 9.5 h for a Tesla 85 kwh battery pack to be charged with a 240 V single charger to provide a driving distance of about 300 miles. Battery cost is a critical factor that hinders the popularization of EVs. Taking the Tesla as an example, customers need to pay an additional $10 000 simply to upgrade the default 60 kwh battery to an 85 kwh one.[2]

The high battery cost is partly due to the fact that battery packs need intensive re-engineering of customized size and shape to fit in the different vehicle model and demand sophisticated cooling systems. In addition, it is very expensive to take advantage of new battery chemistries during the 8–10 yr service time of a battery pack since it requires changing the entire back. To address these challenges, we propose an innovative fluidic battery system composed of many micro batteries for EV and other energy storage applications.

As shown in Fig. 1, each micro battery is a self-contained Li-ion battery enclosed in an insulating shell, and can charge/discharge wirelessly or through contacts. Unlike the traditional "flow battery," which requires two active chemical components dissolved in liquids and charge/discharge through a membrane and redox reactions, the micro battery is each solid-state and self-contained. Thus, it does not have the challenges associated with the tradition flow battery such as low energy density, corrosion, need of a secondary containment vessel, and relatively complicated controls for flow and mixing. At the same time, the architecture

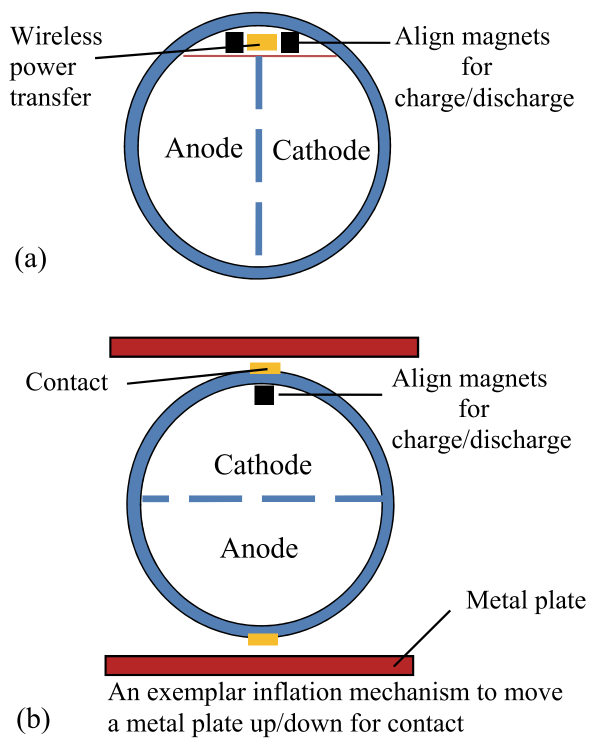

FIG. 1. Schematic of a micro battery. Each micro battery is a self-contained Li-ion battery enclosed in an insulating shell, and can charge/discharge (a) wirelessly or (b) through contacts.

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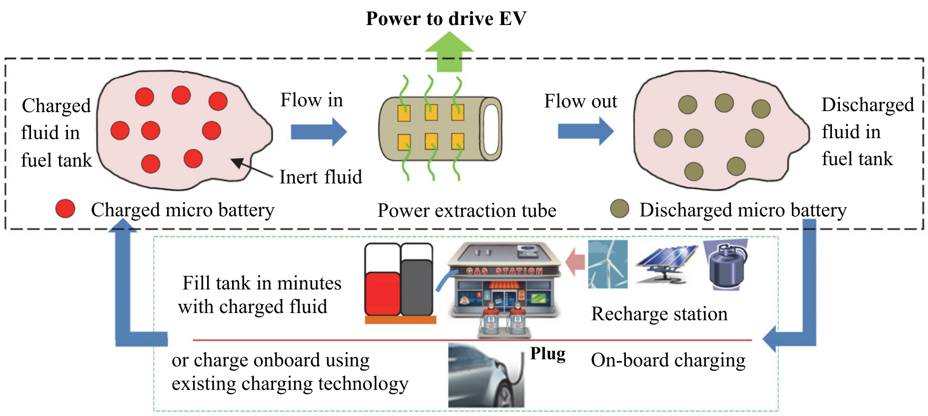

FIG. 2. Micro batteries are carried by an inert fluid to form a power fluid, which can be charged by the grid or renewable energy sources such as solar and wind at the charge station. An operator refills the car tank with charged fluid (many charged micro batteries) and sucks the discharged fluid (discharged micro batteries) into the charge station to be charged and reused. The process only takes a few minutes.

can offer high energy density, power density, and performance of a Li-ion battery.

Thousands of such micro batteries are carried by an inert fluid to form a power fluid, as shown in Fig. 2. The fluid can be charged by the grid or renewable energy sources such as solar and wind at the charge station. In fact, the charge station can use the current gas station infrastructure. An operator refills the car just like with petrol. He fills the car tank with charged fluid (many charged micro batteries) and sucks the discharged fluid (discharged micro batteries) into the charge station to be charged and reused. The process only takes a few minutes. Some key advantages of the proposed micro battery system include: (1) Battery scaling with vehicle life. An average vehicle lasts 10 yr. As it ages, the range extends as battery capacity grows with advances in the micro batteries. The proposed micro battery technique would enable progressive improvements of vehicle performance instead of fixed by a production date. (2) Efficient battery operation. The micro battery eliminates the large overcapacity design in the current battery packs, significantly reducing the weight and cost. (3) Ongoing battery recycling. Instead of waiting for the scrap yard, the battery is changed regularly either in refueling or in the maintenance process. (4) Reduced copper wiring. With the cells wireless and mobile, the amount of copper wiring needed for the assembly should drop. (5) Heat self-dissipation. Carry fluid acts as the heat dissipation mechanism, eliminating the need for separate battery temperature cooling fluid. (6) Onboard charging. The battery can also be charged onboard using existing battery charging technology. (7) Flexible geometry. The micro battery can essentially go into a storage space of any geometry, allowing uniform design of battery configurations for diverse applications. (8) Ultra-high safety. Each micro battery is contained in an insulating shell. When an accident happens and damages the system, the micro battery automatically disengages from output. Even if a micro battery itself is severely damaged, the damage is contained within itself and has minimum impact on other micro batteries or the overall operation.

In the following, we focus on analyzing several key characteristics of the micro battery system to evaluate its potential benefit and physical limitations. The first question is whether such a micro battery system can provide sufficient energy density since the carry fluid will take space. The volumetric energy density of the system can be estimated by the packing density of micro batteries. Each micro battery is a sphere with a radius r. It is widely known that the close packing density, η, of mono-sized spheres is $\pi/3\sqrt{2} = 0.74$. This is also the maximum possible packing density among mono-sized spheres.[3] The packing density of identical ellipsoids can reach 0.75, which is even higher.[4] When two sizes of spherical micro batteries are used, the smaller spheres can fill in the gap between the larger ones, increasing the overall packing density up to 0.93.[5]

The lower bound of the packing density can be calculated from random packing.[6,7] For a system compose of spheres of two given radii r_1 and r_2, the volume ratio of the two spheres affects the packing density. With the appropriate volume ratio, the random packing density reaches an optimized value for a given r_2/r_1 ratio. For random packing of micro batteries of two different sizes, our study gives the optimized packing densities for various r_2/r_1 ratios, as shown in Fig. 3. By choosing the appropriate radius ratio, the random packing density can easily go over 0.8. These results suggest that even with random packing, the energy density of the system can easily surpass the convention battery pack with over capacity. With appropriate fluid pressure and flow control, the system can achieve states near close packing, allowing even more efficient use of the space.

The conventional battery packs are designed with significant overcapacity. For example, the 35% overcapacity of the Volt battery packs, although is already quite impressive in industry, is still a large amount of unused volume or mass.

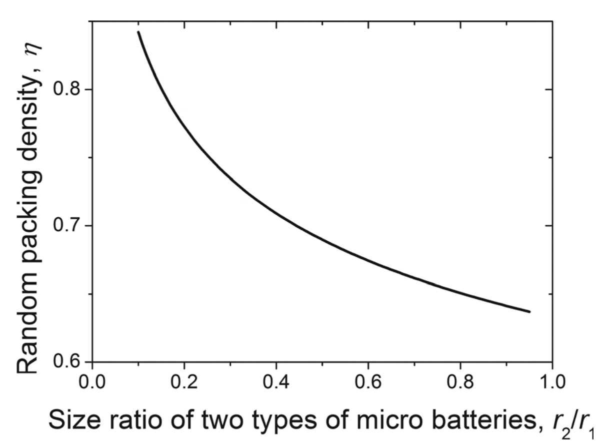

FIG. 3. Random packing density of a system with two types of micro batteries of different sizes. Their size ratio affects the random packing density.

This overcapacity alone translates to an effective packing density of 0.65 without considering other system overhead such as the cooling system, which further reduces the system level energy density. Thus, the micro battery system can achieve volumetric energy density higher than the conventional battery pack using the same battery chemistry.

The next question is whether the micro battery system can provide sufficient specific energy density. We will show that the specific energy density or energy per unit mass of the micro battery system will be significantly higher in comparison to the conventional battery pack. Denote the mass densities of the micro battery and the carry fluid by ρ_b and ρ_f, respectively. The mass packing density of the micro battery system, λ, defined as the ratio between the mass of the energy storage material and the mass of the system, is given by

$$\lambda = \frac{\rho_b}{\rho_b + (1/\eta - 1)\rho_f}. \quad (1)$$

The mass density of the carry fluid is smaller than that of the battery, making $\lambda > \eta$. Take a battery with $LiMn_2O_4$ (LMO) cathode and graphite anode as an example. The capacity ratio of LMO cathode/graphite anode in a battery cell is typically 0.9. Based on the theoretical capacities of LMO and graphite, which are 148 mAh/g and 372 mAh/g, respectively, their mass ratio is 2.26 in a battery cell. The densities of Mn_2O_4 and graphite are about 3.25 g/cm^3 and 2.2 g/cm^3, respectively. These quantities give an effective $\rho_b = 2.83$ g/cm^3. If the carry liquid is water with $\rho_f = 1$ g/cm^3 and the packing density is $\eta = 0.75$, Eq. (1) gives $\lambda = 0.9$. In other words, 90% of the system mass is used for energy storage.

The micro battery system can be maintained at a uniform operation temperature without sophisticated cooling systems due to the small battery size and each battery being fully surrounded by the inert fluid. While in conventional battery packs, dedicated cooling components are needed, yet still resulting in temperature gradient and associated thermal stress and electrode dissolution, and both can cause severe battery degradation. To evaluate the potential weight reduction from the micro battery system, we take the Volt battery pack as an example. The Volt's T-shaped battery pack consists of 288 individual cells arranged into nine modules. Plastic frames hold pairs of lithium-ion cells that sandwich an aluminum cooling fin. The design and construction of these aluminum plates are critical to ensuring an even temperature distribution with no hot or cool spots across the flat, rectangular cell. The approximate weight of them is 86.7 kg, taking 44% of the weight of the whole battery pack.[8] The proposed micro battery system, however, can make use of the surrounding inert fluid as a coolant at the same time, thus, saving the space and weight of the cooling components of the conventional battery packs, making it remarkably efficient in terms of specific energy density and thermal control. With 35% overcapacity and 44% cooling system overhead, the overall effective mass packing density of the conventional battery pack is about 0.36. The micro battery system can achieve a mass packing density of up to 0.9 for mono-sized micro batteries, which translates to a system weight of only 40% of the conventional battery pack. The weight reduction is even higher for a two-sized micro battery system.

Now, we analyze whether the micro battery system can provide sufficient power density. Here, we assume that electricity will be extracted from a cross-section of the micro battery system parallel to a collecting plate. This will provide a conservative estimation since the collecting plate can be in a three dimensional form to access more micro batteries at the same time. In this cross-section, micro batteries essentially form a two dimensional circle packing. The close packing density is $\pi/2\sqrt{3} = 0.91$, while the random packing density is 0.84. Therefore, the power density will be 80%–90% of that can be provided by a battery cell in terms of volume. The specific power will be higher since $\lambda > \eta$. At

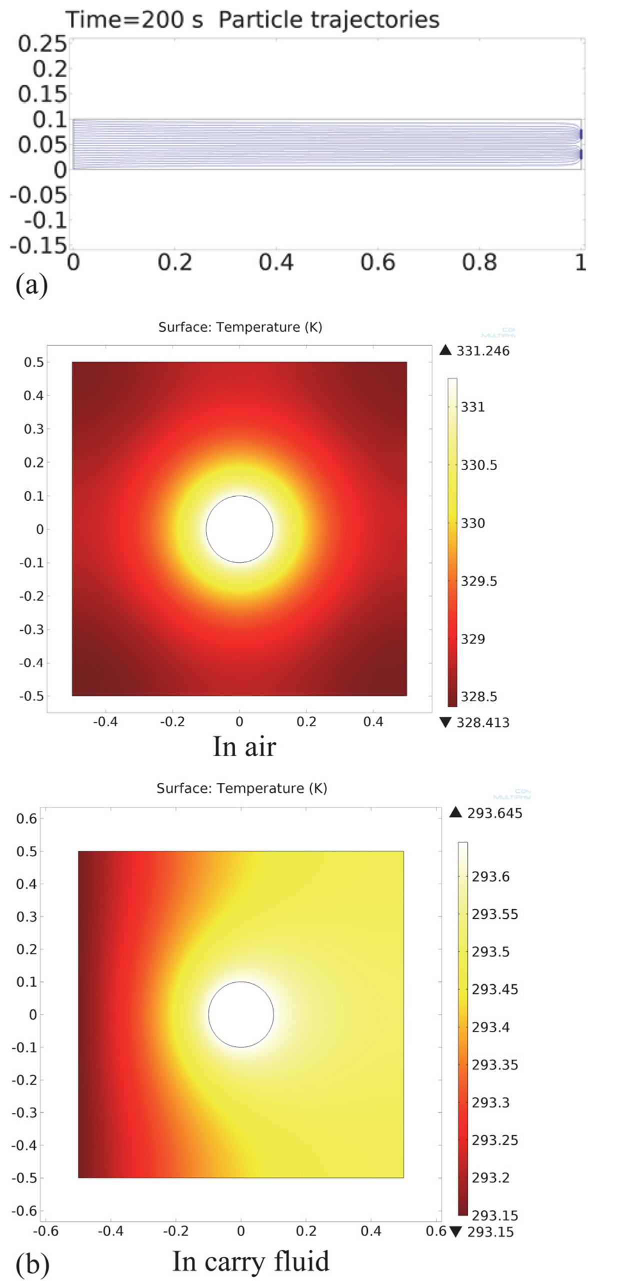

FIG. 4. (a) Flow of carry liquid between two plates. Micro batteries concentrate spontaneously at the two holes on the right end. (b) Temperature distribution of a battery cell in the air (upper graph) and in the carry fluid with a flow velocity of 0.1 mm/s (lower graph). The battery temperature rises 38 °C in air but less than 0.5 °C with the carry fluid.

the system level, a conventional battery pack has 35%–50% overcapacity, leading to an effective 0.65–0.5 packing density or 65%–50% of the power that can be provided by a battery cell. Considering the 44% cooling system overhead, the overall effective mass packing density of the conventional battery pack is about 0.36–0.28. In other words, the system level specific power is about 28%–36% of that can be provided by a battery cell. Therefore, the micro battery system has the capability to provide power density or specific power better than the current battery pack. In addition, the small size of each micro battery offers other benefits. Studies have shown an inverse relationship between the power density and size.[9] In a battery cell, factors such as phase transition, polarization, and fracturing of the electrodes can limit the power density. Multiple mechanisms have been reported to cause battery degradation.[10–12] The micro battery architecture offers opportunities to improve the battery performance in these areas.

With COMSOL multi-physics, we performed several numerical studies on the interaction between the carry fluid and the micro batteries. Figure 4(a) shows the flow of carry fluid with many micro batteries between two parallel plates. There are two holes at the right end for the fluid to exit. The micro batteries concentrate and pack spontaneously around the exit region. The simulations suggest the possibility of using a burst of flow to control the arrangement of micro batteries for charging/discharging. Figure 4(b) demonstrates heat self-dissipation of the system. The environmental temperature is 20 °C. Operating in the air, the battery temperature rises to 58 °C, an increase of 38 °C. With carry fluid moving even at a very low velocity of 0.1 mm/s, the temperature rise of the battery is less than 0.5 °C. The simulations suggest that the carry fluid is very effective in dissipating heat and maintaining a constant operating temperature. We find that the flow for moving micro batteries and for dissipating heat can work at quite different velocity zones. This de-coupling would provide a significant degree of freedom in experimental control.

In summary, the micro battery system discussed in this letter can potentially resolve several major challenges in the conventional battery pack. Our analysis suggests that it can provide higher energy and power density, while at the same time it provides unique capabilities such as battery scaling with vehicle life, superfast refilling or "charging," efficient battery operation, ongoing battery recycling, heat self-dissipation, and flexible geometry.

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