Cool metric for lithium-ion batteries could spur progress

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A new measure for the rate of heat removal from battery packs gives manufacturers a simple way to compare products.

Lithium-ion batteries get hot, and it is hard to keep them cool. Industry has paid too little attention to this problem for the past decade. The focus has been elsewhere: on cutting costs and on boosting the amount of energy a single cell in a battery can store (energy density). This strategy has, for example, increased the longevity and capabilities of mobile phones. Future applications, such as electric vehicles and smart grids, need thousands of cells in a battery pack. These are prone to overheating.

Manufacturers of large, high-energy battery packs must design complicated systems to manage heat. The battery pack in electric-vehicle maker Tesla’s Model 3 car, for example, holds more energy than 6,000 iPhone 11 handsets. Coolant fluid is pumped through a network of channels to carry heat away from the individual cells. But these cumbersome additions make the battery pack heavy and drain its energy[1]. Developers are wasting time and money on these inefficient designs. Heat-removal strategies must be improved to make battery packs both light and powerful. Why this lack of attention? One reason is that there is no standard way of judging the thermal performance of battery packs. Manufacturers of single cells compete by chasing ever greater energy density. Their product-specification sheets do not cover how easy it is to remove heat from a cell. Designers of battery packs thus cannot know in advance how much heat a single cell will generate. They find out too late, after investing time and money in a design. The lithium-ion battery industry is expected to triple in size in the coming decade[2]. A step change is urgently needed in thermal management. It can be achieved quickly using proven technology.

The first step is for the battery industry to report routinely on thermal management. We have developed a standardized performance metric for this purpose[3,4]. It compares different electrochemical cells and can be measured using equipment that is readily available in battery laboratories. Including this metric on each battery specification sheet would drive competition and thus lead to improvements in single-cell designs and battery pack performance.

Thermal management

Leading car companies are investing heavily in developing better battery packs. BMW alone has put US$230 million into its battery research centre, which opened last year near Munich

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[1] Hunt, I. A., Zhao, Y., Patel, Y. & Offer, G. J. *J. Electrochem. Soc*. **163**, A1846–A1852 (2016).

[2] Choudhary, A. & Prasad, E. *Lithium-ion Battery Market by Component, End-use Industry and Automotive, and Industrial: Global Opportunity Analysis and Industry Forecast, 2019–*2027 (Allied Market Research, 2020)

[3] Hales, A. *et al. J. Electrochem. Soc.* **166**, A2383–A2395 (2019).

[4] Hales, A., Marzook, M. W., Bravo Diaz, L., Patel, Y. & Offer, G. *J. Electrochem. Soc.* **167**, 020524 (2020)

in Germany (see go.nature.com/2asxytj). Each company is using a different cell design and pursuing its own cooling strategy.

Broadly, there are three kinds of thermal management systems.

Air cooling. In the batteries of the Renault ZOE and Nissan LEAF car models, air is blown over the surface to remove heat. This method might be sufficient for stationary energy storage, such as for batteries that power homes, but it removes heat at a low rate. The battery packs of future electric vehicles, long-distance haulage and heavy-duty off-road vehicles will require that heat is removed faster as their performance improves year on year.

Liquid cooling. A certain volume of liquid has the capacity to remove heat about 1,000 times better than the same volume of air[5]. Cells can be immersed in flowing fluid or cooled indirectly by liquid that flows through channels wrapped around the cell. Immersion is most effective, but expensive dielectric fluids are needed to reduce the risk of a short circuit in the battery pack. Therefore, electric vehicles tend to use the cooling-channel method. Tesla wraps tubes containing liquid propylene glycol around its cylindrical cells[6]. Both immersion and cooling-channel methods drain power because of the need to pump the coolant around the battery fast enough.

Phase-change cooling. Some materials, such as the Novec fluids made by US technology company 3M, are designed to absorb heat when they change phase — from solid to liquid or from liquid to gas — without themselves getting hotter. Cells can be immersed in or coated with such materials to absorb heat. This method is the subject of considerable research, because it uses less power and withdraws heat more evenly than do air or liquid cooling[7]. However, there is a fundamental limitation. Phase-change materials do not channel away the heat; they simply store it. Therefore, all phase-change designs require an extra cooling system to carry the heat out of the battery pack.

Design challenge

Designers need to pick the best cooling method for their application and deploy it correctly. If they do not, the battery pack will be inefficient, supply less useful energy and degrade faster. Choosing which region of a cell to cool is the most difficult decision.

All cells are made up of layers of different materials: electrodes, an electrolyte, a separator and current collectors. The layers can be sandwiched together, as they are in pouch cells, or curled into a ‘jelly roll’, as in cylindrical and prismatic cells (see ‘Keep it cool’).

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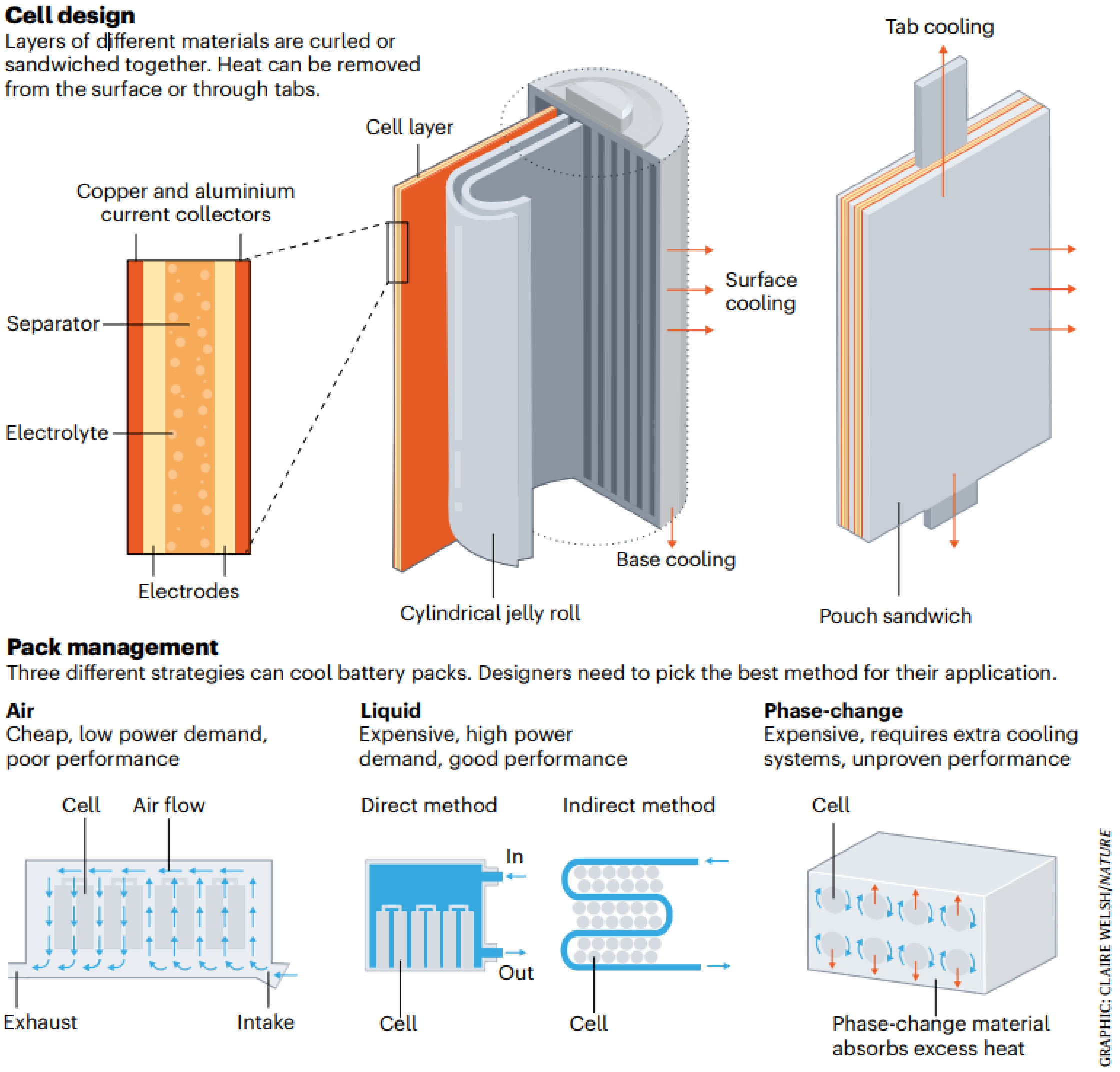
[5] Rogers, G. & Mayhew, Y. *Engineering Thermodynamics: Work and Heat Transfer* (Longman Scientific & Technical, 1992)

[6] Adams, D. T. *et al.* Battery Pack Thermal Management System. US patent 20090023056A1 (2009).

[7] Ianniciello, L., Biwolé, P. H. & Achard, P. *J. Power Sources* **378**, 383–403 (2018)



KEEP IT COOL

Lithium-ion batteries are prone to overheating. A metric that compares the heat removal rates of individual cells in a battery (top) could reduce the need for complicated cooling systems at the pack level (bottom).

Cell design

Layers of different materials are curled or sandwiched together. Heat can be removed from the surface or through tabs.

Pack management

Three different strategies can cool battery packs. Designers need to pick the best method for their application.

Air
Cheap, low power demand, poor performance

Liquid
Expensive, high power demand, good performance

Phase-change
Expensive, requires extra cooling systems, unproven performance

GRAPHIC: CLAIRE WELSH/*NATURE*

Electric current flows in and out of the cell through current collectors, which are joined to the cell's positive and negative terminals, or 'tabs'. Current collectors are made from metals which conduct heat very easily. But heat transfers slowly between the layers of the cell, because the electrodes, electrolyte and separator are thermal insulators. In other words, heat transfer parallel to the layers is faster than heat transfer across them[1].

The electrochemical performance of a cell is sensitive to temperature; at high temperatures, resistance to current flow is much lower. Thus, for the cell to be effective and stable, each layer should be exposed to identical thermal conditions. A temperature gradient between one layer and the next means that each operates slightly differently. Less energy can be taken from the cell because the hotter layer runs out of energy more quickly; some energy is left in the colder layer. The cell degrades more quickly when each layer is exposed to different rates of current flow[1,8].

Identical thermal conditions are possible only when heat is removed at the same rate from each layer. Surface cooling cannot achieve this, because it creates a temperature gradient[1].

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[8] Zhao, Y., Patel, Y., Zhang, T. & Offer, G. J. *J. Electrochem. Soc*. **165**, A3169–A3178 (2018).

Removing heat through the tabs — which are connected to each layer — can cool the whole cell evenly[1,8]. Unfortunately, tab cooling is not possible in today's lithium-ion cells. Tabs are often too close to one another and too small and thin to remove enough heat from each layer. As a result, cells that are cooled through their tabs can still get dangerously hot.

Key metric

The biggest problem is more mundane. There is no thermal performance metric for electrochemical cells that is easily reproducible anywhere in the world, and that does not reveal commercially sensitive information about how a cell is designed or manufactured.

There is no good or universal method to measure cell thermal performance in the battery industry. Heat-transfer specialists favour the Biot number, which describes a body's capability to pass and dissipate heat. Mechanical engineers prefer definitions of thermal conductance and thermal conductivity; these define the rate of heat transfer that can be achieved through a material for a given temperature gradient.

None of these methods can calculate the temperature gradient across a cell when it is in operation, because electrochemical cells generate their own heat throughout their volume. If the temperature gradient across one cell is not known, it is impossible to design a thermal management system for a battery pack containing 1,000 cells.

We have developed a metric called the cell cooling coefficient[3,4]. It can be used to describe the temperature gradient across a cell in operation in watts per kelvin ($W.K^{-1}$). A cell will have a different value for surface cooling and for tab cooling, because each method results in a different temperature gradient. Such a coefficient would tell a designer how difficult it will be to manage heat in the selected cells in a pack.

Our cooling coefficient is straightforward to measure in the lab. Researchers can create electrochemical heat in a cell and then determine the temperature gradient across it using temperature sensors. Heat loss from the cell can be measured using heat-flux sensors. For surface cooling, where one side of the cell is cooled and the other remains hot, the cell cooling coefficient could be calculated by dividing the rate of heat loss by the temperature gradient from the hot side to the cold side.

A large cell cooling coefficient is desirable. It means that more heat can be removed and there is a small temperature gradient inside the cell. Of the cells we have investigated, large pouch cells, such as the ones in the Nissan LEAF, seem to perform best and have a cell cooling coefficient close to 5 $W.K^{-1}$ [9]. Small cylindrical cells, such as the ones in the Tesla Model 3, perform less well, with a cell cooling coefficient of less than 0.5 $W.K^{-1}$ (unpublished results).

Some cell manufacturers might oppose using thermal performance metrics if their products fare poorly compared to those of their competitors. Some will object that adding another variable will complicate protocols for optimizing cell designs, adding time and costs. But we estimate that this should take only an extra two hours of tests on top of the days typically spent characterizing different types of cell. And those manufacturers that embrace the metric could gain a competitive advantage.

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[9] Dondelewski, O. et al. *eTransportation* (in the press).

Next steps

We call on researchers and engineers to measure and report the cell cooling coefficient routinely. Our metric should be included in publications alongside other typically reported metrics for cells, such as energy capacity and discharge rate.

Designers should evaluate thermal performance, alongside energy densities and power capabilities, to determine which cell is best suited for their battery pack. They should do this at an early stage, before designs are locked in. Computer simulations might be helpful for assessing the potential of cells. Knowing the cell cooling coefficient will help designers to evaluate trade-offs between thermal management and energy density, improving the working performance of the whole pack.

With such fierce competition in the battery industry, manufacturers who can keep their cells cool will have the brightest future.

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