



A Review on Thermal Behaviors and Thermal Management Systems for Supercapacitors

Wei Zhou ^{1,2}, Zhien Liu ², Wan Chen ^{2,*}, Xianzhong Sun ^{1,2,3,4,*}, Maji Luo ², Xiaohu Zhang ^{1,4}, Chen Li ^{1,4}, Yabin An ^{1,3,4}, Shuang Song ^{1,3,4}, Kai Wang ^{1,3,4} and Xiong Zhang ^{1,3,4,*}

- ¹ Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing 100190, China ² Uk hei Kerr Libertheme (Advanced Technology (in Automation Commonweak) Weber L
 - Hubei Key Laboratory of Advanced Technology for Automotive Components, Wuhan University of Technology, Wuhan 430070, China
- ³ University of Chinse Academy of Sciences, Beijing 100049, China
- ⁴ Institute of Electrical Engineering and Advanced Electromagnetic Drive Technology, Qilu Zhongke, Jinan 250013, China
- * Correspondence: wch@whut.edu.cn (W.C.); xzsun@mail.iee.ac.cn (X.S.); zhangxiong@mail.iee.ac.cn (X.Z.)

Abstract: As a representative electrochemical energy storage device, supercapacitors (SCs) feature higher energy density than traditional capacitors and better power density and cycle life compared to lithium-ion batteries, which explains why they are extensively applied in the field of energy storage. While the available reviews are mainly concerned with component materials, state estimation, and industrial applications, there is a shortage of understanding of thermal behaviors and thermal management systems of SCs, which makes this review a timely aide for fulfilling this gap. This review introduces the energy storage mechanisms of SCs, followed by descriptions of current investigations of thermal behaviors. This covers the aspects of heat generation rates for electric double-layer capacitors (EDLCs) and hybrid supercapacitors (HSCs), together with reviewing existing experimental methods to measure and estimate heat generation rates, as well as comparative assessments of multiple heat generation rate models and research on thermal runaway. In addition, there are also overviews of current efforts by researchers in air cooling systems, liquid cooling systems, phase change material cooling systems, and heat pipe cooling systems. Finally, an in-depth discussion is provided regarding the challenges and future work directions for SCs in thermal behaviors and thermal management systems.

Keywords: supercapacitor; energy storage mechanism; heat generation rate; thermal management system

1. Introduction

The enormous amounts of fossil energy as a result of accelerated economic development have led to a series of environmental problems [1,2]. To tackle these challenges, China has launched carbon peaking and carbon neutrality targets to offset the increasing emission of greenhouse gases [3,4]. Renewable energy sources, such as tidal, wind, and solar energy, represent an important solution for this goal [5,6]. However, all these suffer from geographical shortcomings, intermittent uncontrollable nature, and uncertainty; thus, they rely more on the power grid for coupling [7,8]. Thus, it is particularly imperative to devise an alternative technique for clean energy storage with both reliability and flexibility [9,10]. Electrochemical energy storage with superior portability and durability has been widely recognized as a promising candidate [11,12].

At present, lithium-ion batteries (LIBs) and supercapacitors (SCs) are the two most extensively employed energy storage devices [13]. LIBs rely on redox reactions to store electrical energy, but the reaction rate is controlled by electrolyte diffusion or intercalation [14,15]. This results in low power density, large temperature variations during charging and discharging processes, and a limited number of repeatable cycles [16,17]. On the other



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Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). hand, SCs store energy at the electrode interface to provide a higher energy density than conventional capacitors and much better power density, energy efficiency, cycle life, and safety than LIBs [18,19]. SCs have potential large-scale industrial applications in a variety of fields, including military transportation and power grid systems [20].

As a vital operating parameter for SCs, temperature has a remarkable effect on overall performance, including capacity, charging and discharging efficiency, reliability, and durability [21,22]. When the temperature is beyond a certain threshold, irreversible thermal stress is caused on the electrode during charging and discharging, leading to the oxidation of the carbon surface and partial damage of the activated carbon (AC). As a consequence, the performance and lifetime of capacitors is markedly deteriorated and safety concerns arise in the case of long-time exposure to high temperatures [23,24]. Because of the slow ion transport in the electrodes and electrolyte at low temperature, capacitors are susceptible to high polarization and irreversible capacity loss, which causes poor energy density and power density [25,26]. It is therefore essential to understand and precisely model the heat generation rate inside the capacitor by properly adjusting its internal temperature under various operating conditions for system integration in energy storage applications. Besides, inappropriate temperature distribution between capacitors may also trigger thermal runaway, which implies that as heat is accumulated, capacitors may generate emissions or even explode, with severe impacts on the security of automobiles and passengers [27,28]. There is a great need for cost-effective thermal management systems to keep the temperature of capacitor cells and modules within the appropriate range [29,30].

A state-of-the-art review of recent literature in this field has been conducted for the purpose of understanding the advanced technology and latest achievements of SCs. The existing review papers on SCs are primarily focused on the following aspects: electrode materials and electrolytes [31,32], state of estimation [33], fractional-order models [34], industrial applications [35,36], and reliability [37–39]. The number of review papers available on thermal modeling and thermal management systems for SCs is very limited. Sakka et al. [40] presented a relatively comprehensive paper in 2009. However, this review article does not include the advances that have been made in recent years. Zhang et al. [33] in 2018 and Naseri et al. [41] in 2022 described some of the thermal modeling advances for SCs. In 2022, Rashidi et al. [42] briefly mentioned the content of thermal management systems with regard to SCs. In general, there is still a lack of comprehensive review papers on thermal behaviors and thermal management systems in the field of SCs.

The goal of this paper is to provide a comprehensive review of thermal behaviors and thermal management systems for SCs, appropriately filling the gap in this area. Since there are relatively few reviews on thermal behaviors and thermal management systems for SCs, the following points distinguish this review from existing review articles. First, as several types of SCs have distinct electrochemical reaction mechanisms, the different temperature characteristics between them are compared, and the heat generation mechanisms are further discussed separately. Second, existing thermal models and experimental measurements for different types of SCs are review, with a further discussion of the effect of temperature on SC materials. Finally, a comprehensive review of the efforts is made by the researchers in developing thermal management systems in the SC field.

Figure 1 shows the key structures of this review paper. The details are listed as follows: Section 2 presents an initial overview of the fundamental working principles of SCs. Section 3 discusses and summarizes the thermal behaviors of SCs in detail. Section 4 presents the development of thermal management systems for SCs. Section 5 presents an outlook on future research challenges and opportunities for heat generation rate models and thermal management systems. The conclusions are described in Section 6.



Figure 1. The outline map for this paper.

2. Energy Storage Mechanisms of Supercapacitors

SCs can be classified into the following categories with respect to their physical and chemical energy storage mechanisms: electric double-layer capacitor (EDLC), pseudocapacitor, and hybrid supercapacitor (HSC) [43,44].

2.1. Electric Double-Layer Capacitor

Their architecture features two active electrodes, an electrolyte and the porous separator, as shown in Figure 2a [45]. The electrodes of SC are separated by separators saturated with electrolyte [46]. As the electrode materials of an EDLC are predominantly diverse carbon materials, the energy storage mechanism is electric double-layer energy storage [47].

Figure 2b shows that the charging layer consists of two layers at the electrode material interface, with one layer on the electrode side of the interface and the other on the electrolyte side of the interface. So, it is referred to as the electric double-layer, i.e., the diffuse layer and Helmholtz layer [41]. Based on the electric double-layer energy storage principle, SCs store energy as a physical energy storage mechanism without a redox reaction [48]. While the capacitors are discharged, the electrons flow from the negative terminal to the positive terminal through the external circuit. The adsorbed cation and anion are released from the surface of the electrodes, and no charge transfer across the electrode-electrolyte interface occurs throughout the entire charge/discharge cycle [49].



Figure 2. (a) Schematics of various types of capacitors. (b) Charge and discharge energy storage principles of an EDLC where black arrows represent ions in the electrolyte and red arrows reflect the direction of ion movement [45], open access.

The capacitance of the EDLC is normally determined using Equation (1) [50,51]:

$$C = \frac{\varepsilon_0 \varepsilon_r A}{D} \tag{1}$$

where ε_r is the dielectric constant with respect to the electrolyte utilized, ε_o is the dielectric constant of the vacuum, A is the surface area of the electrode material approachable by the electrolyte ions, and D is the effective thickness between the electric double-layer (charge separation distance).

In light of the physical electrostatic process, there is a strong determination of the formation of the electric double-layer by the effective surface area of polarizable electrode material, together with the nanoscale charge separation distance. There are various materials among carbon-based porous materials, such as AC [52], graphene [53,54], and carbon nanotubes (CNTs) [55]. They have a high specific surface area, promising electrical conductivity, superior electrochemical characteristics, and thermo-stability, which are extensively applied in the SC field [56].

Equation (2) demonstrates that energy *E* and power *P* are intimately related to voltage [38,57]:

$$E = 0.5CV^2 \tag{2}$$

$$P = \frac{V^2}{4R_{\rm ESR}} \tag{3}$$

where *C* denotes the device capacitance, *V* is defined as the device working voltage, and R_{ESR} is the equivalent series internal resistance of the internal elements of the device. There has been extensive research worldwide to develop stable electrode materials and high-voltage electrolytes to increase the energy density and power density of SCs [52,58].

2.2. Pseudocapacitor

For the purpose of accumulating energy, pseudocapacitors basically depend on the rapid and reversible faradaic reaction occurring at the electrode/electrolyte interface, with several variations of the reaction mechanism, as indicated in Figure 3 [59]. When the voltage is imposed externally, the redox reaction occurs on the surface of the electrode, yielding the faradic current, which resembles the charging and discharging procedure of the battery. In the presence of an external electric field during charging, ions in the electrolyte diffuse from the solution to the surface and near the surface of the electrode active material [60]. The reversible reaction occurs in the process of discharging, where the ions of the electrode material again return to the electrolyte by releasing the stored charge through the external circuit. Pseudocapacitors normally exhibit relatively high energy densities, as the storage process also includes electrical energy storage in the electric double-layer resulting from electrostatic adsorption, which increases their capacity to store charge [61]. Despite the higher energy density of the pseudocapacitor compared to the EDLC, the faradaic reaction rate is somewhat slower than the electric double-layer formation process, thus reducing its power density and cycling stability [62,63].

Redox-active Redox-active Noble Metal Electrolyte Electrolyte Electrolyte Materials Materials (\pm) Œ Current Collector Current Collector Current Collecto (+)(+)(+)(+)(+) \oplus Absorbed Atoms Cations Li⁺ ion Ions in electrolyte

Underpotential Deposition | Redox Pseudocapacitance | Intercalation Pseudocapacitance



Some of the currently researched pseudocapacitor materials include noble oxides [64,65], conducting polymers [66], and transition metal oxides [35,67]. However, the majority of pseudocapacitor materials suffer from relatively inferior cycling stability and are usually formed into composites with carbon materials to improve cycle life and charge/discharge performance [68,69].

2.3. Hybrid Supercapacitor

The LIC cell is an important type of HSC. It is conventionally manufactured from capacitive electrodes coupled with pre-lithiated battery electrodes, as demonstrated in Figure 4a [11]. The lithium salt LiPF_6 is mixed with an organic solvent to constitute the

electrolyte. The capacitive electrodes contribute high power, while the battery electrodes feature high energy, so as to ensure optimum equilibrium between power density, energy density, and cycle life [70,71]. During the operation of LICs, there are separate stages for the anions and cations in the electrolyte: the intercalation/de-intercalation of Li⁺ occurs at the negative electrode, whereas the adsorption/desorption of Li⁺ and PF_6^- ions can take place at the positive electrode [72,73]. Because of the mixed electrochemical energy storage configurations in LICs, there are two completely diverse working mechanisms in terms of open-circuit voltage [74,75].



Figure 4. (a) Comparison of the working principles of the LIC with the LIB and EDLC, reproduced with permission from [11]. Copyright 2020, Elsevier.(b) Charge transfer profiles of the positive electrode (AC) and negative electrode (pre–lithiated hard carbon) of the LIC, reproduced with permission from [74]. Copyright 2016, American Chemical Society. (c) Illustration of the pre-lithiation process, reproduced with permission from [76]. Copyright 2021, IOP Publishing.

Figure 4b describes the charging and discharging curves of both electrodes for an LIC. In the first stage (I–II) of the charging process from the open-circuit voltage to the maximum voltage, PF_6^- transports towards the positive electrode and adsorbs into the surface of the AC electrode, while Li⁺ transfers towards the negative electrode and inserts itself into the negative electrode material, in which the concentration of Li⁺ in the negative electrode is constantly increasing and the ion concentration in the electrolyte is decreasing [77]. For the second stage (II-III), from the peak voltage for discharging to the open-circuit voltage, there is an increase in the concentration of Li^+ and PF_6^- in the LIC electrolyte. Li^+ is de-intercalated from the negative electrode, with PF_6^- being desorbed from the positive electrode [78]. In the third stage (III–IV), from open-circuit voltage discharging to cut-off voltage, the PF_6^- does not participate in the reaction process in which the average concentration in its electrolyte remains constant. Li⁺ is removed from the negative electrode, while it is adsorbed into the AC electrode [79]. As a result, there is a steady average concentration of Li^+ as well as PF_6^- in the electrolyte throughout the voltage range of the third stage. In the last stage (IV–V), the charging process is completely contrary to the discharging process in the third stage (III–IV). From the above analysis, it is evident that the charging and discharging work mechanism of an LIC as a whole can be categorized into the electrolyte depletion process and the Li⁺ intercalation/de-intercalation process of the pre-lithiated electrode [80].

The pre-lithiation process, which is depicted in Figure 4c, is essential for LICs. In this configuration, a three-electrode cell is applied, which consists of an anode, a cathode, and a lithium foil electrode. The tab of the anode is connected to lithium foil electrode tabs using ultrasonic spot welding technology. The anode electrode is separated from the lithium foil electrode through a separator. During the process of discharge, the lithium foil is dissolved in the electrolyte and Li⁺ is intercalated into the anode electrode material. The potential of the lithium storage electrode can be reduced so that it improves the operating voltage and energy density of the device. Meanwhile, the formation of the solid electrolyte interphase (SEI) film on the negative electrode surface is used to eliminate the irreversible capacity as well as the consumption of lithium to the maximum extent possible [76,81].

In summary, Table 1 contains an overview of the electrode materials and energy storage mechanisms of several common types of SCs, with various materials serving different working principles. Many manufacturers currently adopt organic electrolytes and AC-based electrode materials to produce SCs. Table 2 introduces some commercial SCs that have representative energy and power densities from an application point of view, so that the performance characteristics can be more comprehensively observed.

Table 1. Summary of various SC electrode materials and energy storage mechanisms, reproduced with permission from [37]. Copyright 2020, Elsevier.

Туре	Electrode Material	Mechanism of Energy Storage
EDLC	AC, CNT, graphene, porous carbon, etc.	non-faradaic process
Pseudocapacitor	Metal oxides (e.g., RuO ₂ , MnO ₂), p-doped conductive polymers; intercalation host material (e.g., Nb ₂ O ₅)	faradaic process
HSC	One metal-ion insertion/desertion electrode (e.g., Li-ion, Na-ion, Si-C), and one capacitive electrode	battery-type electrode: bulk redox reaction or displacement reaction; capacitive electrode: faradaic or non-faradaic process

 Table 2. Comparison of the performance characteristics of various commercial SCs, reproduced with permission from [82]. Copyright 2022, Elsevier.

Producer	Potential (V)	Capacitance (F)	ESR (mΩ)	Energy Density (Wh kg ⁻¹)	Power Density (W kg ⁻¹)
Maxwell	2.3	300	13	9.1	3000
Maxwell	2.7	3000	0.23	6.9	25,600
LS Cable	2.8	3200	3.7	3.7	12,400
BatScap	2.7	1680	4.2	4.2	18,255
Apowercap	2.7	590	5	5	23,275
Musashi					
Energy	3.8	1100	1.2	10	14,000
Solutions Co.					
Musashi					
Energy	3.8	2100	6.2	24	4000
Solutions Co.					

3. Thermal Behaviors of Supercapacitors

Since the SCs feature a range of internal resistance, they generate large amounts of heat inside the capacitor that leads to substantial temperature changes during high rates of charging and discharging processes [83,84]. This can have an essential impact on the parameters related to temperature-sensitive capacitors. The capacitance of the SC correspondingly increases with temperature, while the internal resistance decreases with temperature [85,86]. Moreover, temperature can have a detrimental influence on the self-discharge rate of capacitors [87]. Indeed, ions exhibit much greater migration at elevated temperatures, which results in high levels of ion release and self-discharge [88]. In addition, the electrolyte can decompose at

elevated temperatures to yield gas, which can create unusual pressure in the capacitor, thereby heightening the likelihood of explosion [89,90]. Likewise, this elevated temperature can facilitate faster decomposition reactions between the electrode and the electrolyte, producing byproducts that will stick to the electrode/electrolyte interface and thereby diminishing the effective active area of the cathode electrodes [91,92]. Therefore, it becomes crucial to have an accurate understanding of the thermal behaviors of capacitors.

3.1. Temperature Characteristics

It has been explained previously that for different operating principles of SCs, the mobility of ions performs an indispensable role. However, the majority of the literature is concerned with the energy storage principles of the materials and rarely pays attention to the differences in temperature properties of different categories of SCs.

Dandeville et al. [93,94] first devised and constructed a non-adiabatic calorimetric device to evaluate the capacitor heat generation rate by measuring the temperature variation and applying deconvolution analysis. As can be noticed from Figure 5a,c, the temperature profile of the hybrid pseudocapacitor (AC//MnO₂) during the charging and discharging cycles is in contrast to the temperature profile of the EDLC (AC//AC). The temperature drops during the charging process due to the heat absorption reaction, and the temperature rises during the discharging process when the exothermic reaction takes place. The authors further analyzed the heat generation rate of the two electrodes, as shown in Figure 5b,d. It considers that it is the same for the AC electrode of the EDLC and the AC electrode of the hybrid pseudocapacitor, where the heat generation rate of the AC electrode can be subtracted from the total heat generated by the hybrid pseudocapacitor to obtain the heat generation rate of the other MnO₂ electrode. The MnO₂ electrode is charged as an endothermic reaction and discharged as an exothermic reaction fue to the electrochemical reaction of the electroche and ion adsorption and desorption reactions [93].



Figure 5. (a) Surface temperature vs. time during charging and discharging process for AC//AC and (c) $AC//MnO_2$ cell, (b) reversible heat curves vs. time with respect to the AC electrode, and (d) the MnO_2 electrode, reproduced with permission from [93]. Copyright 2011, Elsevier.

Figure 6 presents the findings of our group with regard to the temperature variation of the LIC over time in the charging and discharging processes [95]. It shows that the temperature declines from ambient temperature as the charging voltage progresses from an initial voltage of 2.0 V to 3.47 V. The temperature starts to rebound from 3.47 V to the upper cut-off voltage, where the charging process is characterized by both endothermic and exothermic properties. In general, the overall temperature tends to increase over time when the discharge is in progress.



Figure 6. Temperature versus time during the charging and discharging process for an LIC with AC//SC (pre-lithiated soft carbon), reproduced with permission from [95]. Copyright 2019, Elsevier.

In summary, the properties of capacitors and temperature are tightly coupled, and the heat generation mechanisms of several types of SCs are radically not identical; thus, it is imperative to be aware of the thermal characteristics of capacitors. The next section will explore the heat generation mechanisms of each component in more detail.

3.2. Heat Generation Mechanism for Supercapacitors

3.2.1. Electric Double-Layer Capacitor

The thermal properties of the EDLC are governed by complicated internal responses and electro-thermal conversions. Figure 7a illustrates the increase in temperature over this period of time as an exothermic characteristic during charging of the EDLC as well as the drop in temperature over this period as an endothermic phenomenon during the discharging process. The heat generation rate of the EDLC primarily comprises two distinguishable parts: reversible heat and irreversible heat [96]. During normal EDLC operation, part of the heat generation rate is the ohmic losses caused by internal resistance. Similarly, it is possible to generate reversible heat due to the entropy change in the electric double-layer [41]. Some researchers have suggested that the heat generation rate stems from the Joule heat of the internal resistance of the EDLC, which is applied to simulate the temperature curves during the charging and discharging cycles of capacitors [97]. The heat generation rate is the product of the internal resistance and the square of the current. Although this method can roughly simulate the temperature evolution during the charging and discharging process, there is no clear explanation regarding the up and down fluctuations caused during the temperature rise. In fact, reversible heat is responsible for the temperature fluctuations, as shown in Figure 7b [98]. The dashed line accounts for reversible heat, which is relatively near the temperature oscillations achieved by the measurement.

In the course of charging, some ions are transformed from their disordered and random state to the aggregated state with the release of energy. Conversely, during the process of discharging, the ions in an aggregated state are removed from the electric double-layer at the solid/liquid interface to again be transformed into the stochastic state. Therefore, during the adsorption and desorption of ions, or in other state transitions, there is often some absorption and release of energy, part of which is referred to as reversible heat [99]. It is therefore valuable to deduce models for further profound analysis in light of temperature variations.



Figure 7. (a) Temperature versus time during the charging and discharging process for the EDLC with AC//AC; (b) temperature fluctuations with time for the EDLC with reversible heat during the charging and discharging cycles, reproduced with permission from [98]. Copyright 2016, Elsevier.

In the literature, there is some work that makes the problem easier by assuming a uniform heat generation rate for ease of calculation. Under the hypothesis of a uniform heat source, the irreversible heat generation rate Q_{irrev} is defined as follows [100,101]:

$$Q_{irrev} = I^2 R_{\rm ESR} \tag{4}$$

where *I* is the applied current during charging/discharging process. This is an exothermic reaction, which is always positive.

Another approach based on first-principles can better describe the physical phenomenon inside the EDLC, and the equation is presented as follows [102]:

(

$$Q_{irrev} = \frac{j^2}{\sigma} \tag{5}$$

$$i(r,t) = \sum_{i=1}^{2} z_i F N_i(r,t)$$
 (6)

$$\sigma(r,t) = \frac{Dz^2 F^2}{R_u T} [c_1(r,t) + c_2(r,t)]$$
(7)

where j(r,t) is the current density and $\sigma(r,t)$ is the electrical (ionic) conductivity, which is subject to concentration in electrolyte; z_i is the valency of ion species i, where i = 1and i = 2 indicate cations and anions; $N_i(r,t)$ is the local ion flux vector of species i at location r and time t; F is the Faraday constant; D is the diffusion coefficient of ions in the electrolyte; R_u is the universal gas constant; T is the local temperature, and c(r,t) is the ion concentration. This method of calculation reflects the internal mechanism in much detail than the preceding method, but many variables are not very available, which means that the calculation is more time-consuming [103].

It is clear from the previous diagram (Figure 7b) that the temperature rise of EDLC during the charging and discharging processes did not manifest a smooth curve, but rather superimposed fluctuations on the rise. In response to this wave of temperature fluctuations, Schiffer et al. [101] performed the first analysis of the EDLC's reversible heat. It is proposed that the reversible heat may be from the chemical reaction among the electrodes/electrolyte during the charging and discharging process, the Peltier effect, and the entropy change. As a result of the analysis, the presence of a minor electrochemical reaction on the surface of the EDLC electrode is deemed ignorable, and the Peltier effect also induces the temperature change to be of a very small order of magnitude, which therefore eliminated the first two possible causes, i.e., the chemical reaction and the Peltier effect [104]. The ions in the EDLC electrolyte again during the discharging process; consequently, the entropy may be explained as a measure of disorder, which tends to be a proper interpretation. The reversible heat generation rate Q_{rev} is given as follows:

$$Q_{rev} = -2\frac{T\kappa}{e}ln\left(\frac{V_H}{V_o}\right)i(t)$$
(8)

where *T* is the average EDLC temperature, κ is the Boltzmann's constant, *e* is the elementary charge, V_H is the volume of the Helmholtz layer, *i*(*t*) is the transient current, and V_o represents the volume of the EDLC electrolyte. This approach requires fewer parameters and has a certain level of precision.

In light of the surface Gibbs free energy for the electrolyte solution at the electrode/electrolyte phase interface and the use of energy conservation law, an alternative computational model is deduced for the reversible heat of the EDLC in the course of constant current charging and discharging processes as follows [98]:

$$Q_{rev} = -2\frac{T\kappa}{ze}\ln\left(\frac{a_{\pm 2}}{a_{\pm 1}}\right)i(t) \tag{9}$$

where *T* is the average EDLC temperature, κ is the Boltzmann's constant, *e* is the elementary charge, *z* represents the chemical valence of the anions and cations in the electrolyte, a_{\pm} is the mean activity of the electrolyte in the electric double-layer, where subscript 1 and 2 are various states, and *i*(*t*) is the transient current.

A comparison of Equations (8) and (9) reveals that the discrepancy comes from the logarithmic parameters of the equation. The former is for the ratio of the volume of the electric double-layer to the total volume of the electrolyte solution across the solid/liquid interface of the capacitor electrode. The latter is related to the ratio of the activity of the electrolyte in the electric double-layer at the electrode/electrolyte interface within the EDLC either before or after charging or discharging. The porous electrode and separator inside the EDLC can be estimated in terms of pore volume. The volume inside the capacitor is difficult to evaluate beyond the components, such as the electrodes and separator [105]. Indeed, the volume of the electrolyte solution at the solid/liquid interface double-layer on the electrode is likewise difficult to compute precisely. Equation (9) compares the ratio of activity before and after charging or discharging, where the volume at the electric double-layer can be approximately removed. It improves the precision of the calculated reversible heat values with respect to Schiffer's reversible heat equation.

Moreover, based on first principles, d'Entremont et al. [106] deduced the reversible thermal model on EDLC by taking into account ion adsorption during charging and discharging, ion diffusion that occurred in the desorption process, steric effects, and changes in mixing entropy related to other variables (such as temperature, electrochemical potential), as shown below:

$$Q_{rev} = q_{\rm E,d} + q_{\rm E,s} + q_{\rm s} \tag{10}$$

$$q_{E,d}(r,t) = \frac{DzF}{\sigma} j \cdot \nabla(c_1 - c_2)$$
(11)

$$q_{E,s}(r,t) = \frac{DzFa^3N_A(c_1 - c_2)}{\sigma[1 - a^3N_A(c_1 + c_2)]}j \cdot \nabla(c_1 + c_2)$$
(12)

$$q_s(r,t) = \sum_{i=0}^n N_i \nabla \left[T^2 R_u \frac{\partial ln \gamma_i}{\partial T} \right]$$
(13)

where $q_{E,d}$ is ion diffusion generated reversible heat, $q_{E,s}$ is the steric effect produced reversible heat, q_s is the heat of mixing, D is the ion diffusion coefficient in the electrolyte, z is the valency of ion species, F is the Faraday constant, σ is the electrical conductivity, j is the current density in electrolyte solution, a is the effective ion diameter, N_A is the Avogadro constant, N_i is the local flux of species i, R_u is the universal gas constant, T is the local temperature, and γ_i the activity coefficient of ion species i. This reversible heat calculation model is generally accurate, but this method is time-consuming and makes the calculation more complex because of some of the more relevant parameters considered.

In light of the intricate nature of practical porous electrode structures, it is found that the prediction of the temperature domain in real EDLC devices with Equation (10) above involves extensive amounts of computational expenditure. d'Entremont et al. [107] further explored the development of an uncomplicated thermal model to quickly determine the thermal performance of EDLC. Such models are employed with the lumped-capacitance parameter method and the relevant empirical equations to deduce the semi-empirical equation for the temperature fluctuations of the EDLC exposed to reversible heat, as shown below:

$$f(x) = \begin{cases} \pm \frac{\alpha I_s}{C_{th}} (t - n_c t_c), \ n_c t_c \le t \le (n_c + 0.5) t_c \\ \pm \frac{\alpha I_s}{C_{th}} [(n_c + 1)t - t], \ (n_c + 0.5) t_c \le t \le (n_c + 1) t_c \end{cases}$$
(14)

$$=2\frac{C_{th}\Delta T_{rev}}{I_s t_c} \tag{15}$$

where α represents a semi-empirical parameter with regard to a certain EDLC, I_s is the current, n_c is the quantity of charge/discharge cycles, C_{th} is the heat capacity of EDLC, and t_c the cycle period. The positive and negative signs refer to the charging or discharging phase. The bulk of the variables are quite accessible from the experiment, but the crucial parameter α is a semi-empirical parameter based on reversible heat and temperature evolution. The empirical values vary for different compositions of the electrolyte, so it cannot be widely available.

α

3.2.2. Pseudocapacitor

There are also irreversible heat generation rates and reversible heat generation rates in pseudocapacitors. Of these, irreversible heat generation rate is derived from the resistance of the electrodes, current collectors, and electrolyte, and reversible heat generation rate is induced by the ions' entropy change, faradaic reactions, and non-faradaic reactions. d'Entremont et al. [108] further extended the first-principles continuum thermal model to hybrid pseudocapacitors. It explains the partially reversible and irreversible heat generation rates induced by the formation of electric double-layer at the interface between the pseudocapacitor electrode and the electrolyte, redox reactions, and Joule heating. The irreversible heat generation rate can be expressed as:

$$Q_{irrev} = \frac{j^2}{\sigma_p} + \frac{j_F \eta}{H}$$
 in the pseudocapacitive electrode (16)

$$Q_{irrev} = \frac{j^2}{\sigma_E}$$
 in the electrolyte diffuse layer (17)

$$Q_{irrev} = \frac{j^2}{\sigma_c}$$
 in the carbon electrode (18)

where σ is the local electrical conductivity, j_F is the faradaic current density, H is the Stern layer thickness, and η is the surface overpotential.

The reversible heat generation rate can be expressed as:

$$Q_{rev} = \frac{j_F \Pi}{H}$$
 in the pseudocapacitive electrode (19)

$$Q_{rev} = q_{\rm E,d} + q_{\rm E,s} + q_{s,c} + q_{s,T} \text{ in the electrolyte diffuse layer}$$
(20)

where $q_{E,d}$ is ion diffusion generated reversible heat generation rate, $q_{E,s}$ is the steric effect produced reversible heat generation rate, $q_{s,c}$ and $q_{s,T}$ refer to the heat of mixing arising from concentration gradients and from temperature gradients, and Π is the Peltier coefficient. Moreover, the carbon electrode of the pseudocapacitor displayed identical thermal behavior to that of the EDLC carbon electrode, so that both the electric double-layer formation and faradaic reaction states were combined in the thermal model [93]. The irreversible faradic reaction and reversible electric double-layer heating dominate most of the heat generation rate at small current densities and slow charging, where the Joule heat accounts for the dominance in the capacitive state, which correlates to high current densities and fast charging. This is due to the faradaic reaction, which results in the asymmetric variation of ion concentration across the pseudocapacitor electrode [108].

3.2.3. Hybrid Supercapacitor

The thermal characteristics of LIC cells can also be attributed to complicated electrochemical processes and electro-thermal exchange back and forth [109]. The heat generation rate is composed of the following primary constituents: irreversible heat, reversible entropic heat, heat of side reaction, and heat of mixing. The irreversible heat is associated with the intrinsic resistance of the capacitor, which can be calculated using the EDLC method [110]. The reversible heat is predominantly linked to the adsorption/desorption of anions/cations from the electrolyte on the positive electrode surface and the intercalation/de-intercalation of Li⁺ into/from the negative electrode; therefore, it cannot be ignored. The side reaction heat is triggered by the aging of the capacitor, which can either be positive or negative. The mixing heat describes the variation in the concentration gradient of the internal ingredients, which is induced by the diffusion of the solid active substance into the porous electrode and the electrolyte. To facilitate much simpler simulations, a simplification of the model, based on the Bernardi equation, is shown below [111]:

$$Q = I(V - U_{ocv}) + IT \frac{\partial U_{ocv}}{\partial T}$$
(21)

where *V* is the cell operating voltage, U_{ocv} is the open-circuit voltage, *I* is the current, which is positive or negative, and *T* and $\partial U_{ocv}/\partial T$ represent, respectively, the temperature and the entropy coefficient, which relies on electrochemical reaction. While the model does not contain a detailed interpretation of the electrochemical phenomenon that occurs, it has found extensive application, as the parameters are fairly easy to measure. Zhou et al. [112] used this model to investigate the thermal characteristics of LIC pouch cells at transient high rates for 1C to 550C discharging. Figure 8a depicts the discharge curves of the LIC cell from 1C to 550C with various discharge rates. As the discharge rate increases, the discharge capacity retention rate is over 83% at 50C. When the discharge rate increases to 550C, the capacity retention rate drops directly to 17%. The temperature characteristics are illustrated in Figure 8b. Because of the limited discharge capacity at high discharge rates, the end of the discharge temperature curve exhibits a parabolic trend as the discharge rate increases from 1C to 550C at ambient temperature 23 °C, with a maximum value of 33.68 °C at the end of discharge for 200C. To further explain the temperature phenomenon, the heat generation characteristics of the cell at a variety of discharge rates are presented in Figure 8c. Total heat generation and irreversible heat generation show the same parabolic trend as the end of the discharge temperature. Figure 8d demonstrates the contribution of reversible heat, irreversible heat, and other heat to the total heat at different discharge rates. As the discharge rate increases, irreversible heat accounts for nearly 80% of the total heat at 550C. Moreover, since a significant percentage of the total heat generated at low rates is reversible, more than 50% of the reversible heat should not be neglected when computing the total heat of a cell. Finally, other heat below 10% should not be discarded at a high rate.



Figure 8. (a) Discharge voltage curves of LIC cells at different rates, (b) maximum temperature at the end of discharge as a function of C-rate, (c) heat generation of pouch cells at diverse discharge rates, and (d) the percentage contribution of each type of heat in the cell heat distribution, reproduced with permission from [112]. Copyright 2022, Elsevier.

In summary, Table 3 outlines the previous thermal model evaluation approaches for SCs. The selection of equations is essential for determining the thermal behavior of SCs. In the case of an inhomogeneous hypothetical heat generation rate, the internal electrochemical reaction rates can be better depicted by partial differential equations based on first-principles. However, this method is time-consuming, and the parameters are not readily available for detailed mechanism research. Under the assumption of a homogeneous heat generation rate, the electrical model is adopted to simplify heat generation as well as the measurement of parameters from experiments, which is more appropriate for research in the field of energy storage.

Type of SC	Heat Generation Mechanism	Equations	Advantages	Disadvantages	Ref.
		$I^2 R_{\rm ESR}$	Parameters easily accessible, low computation cost	Not enough precision	[100,101]
	Irreversible heat	j^2/σ	High precision, detailed description of heat generation rate	Parameters not easily available, high computation cost	[102,103]
EDLC		$-2rac{TK}{e}\ln\left(rac{V_{ m H}}{V_{ m o}} ight)i(t)$	Precision, low computation cost	Parameters not easily available	[101]
		$-2rac{Tk}{ze}\ln\Bigl(rac{a_{\pm 2}}{a_{\pm 1}}\Bigr)i(t)$	Precision, low computation cost	Parameters not easily available	[98]
	Reversible heat	$q_{\mathrm{E,d}} + q_{\mathrm{E,s}} + q_{\mathrm{s}}$	High precision, detailed description of heat generation rate	high computation cost, hard to obtain parameters	[106]
		$\pm rac{lpha I_{ m s}}{C_{ m th}}(t-n_{ m c}t_{ m c}) \ \pm rac{lpha I_{ m s}}{C_{ m th}}[(n_{ m c}+1)t-t]$	Parameters easily accessible	Not widely applicable	[107]
HSC	Irreversible heat	$I^{2}R_{\rm ESR}$ $I(V - U_{\rm ocv})$	Parameters easily accessible, low computation cost	Not enough precision	[113] [95]
	Reversible heat	$TT\partial U_{\rm ocv}/\partial T$	r		[110]

Table 3. Summary of thermal model equations for SCs.

3.3. Measurement Approaches

3.3.1. Heat Generation Rate Measurement

In order to obtain a more precise insight into the heat generation rate of capacitors, many researchers have investigated their heat generation rates by means of calorimetry [114]. Munteshari et al. [115,116] developed an isothermal calorimeter, as depicted in Figure 9a, to obtain valuable information about the complicated physicochemical phenomenon occurring at each electrode of the capacitor. They discovered that the positive electrodes generate heat in different ways during charging and discharging processes, as shown in Figure 9b. The reversible heat of the positive electrode during charging and discharging is exothermic and endothermic, respectively [114].



Figure 9. (a) Isothermal calorimetry apparatus disassembly diagram; (b) the reversible heat $Q_{rev,+}$ at the positive electrode vs. the dimensionless time for various cycles where Device 1 with 1 M LiPF₆ in ethylene carbonate: dimethyl carbonate with 1:1 volume, Device 2 with 1 M citric acid in deionized water, Device 3 with tetrabutylammonium tetrafluoroborate in acetonitrile solvent, reproduced with permission from [115]. Copyright 2017, Elsevier.

3.3.2. Temperature Measurement Techniques

In addition, in order to detect the spatial temperature in the capacitor, thermocouples and thermal imagers are available for precise measurements [40,117,118]. The surface temperature of the capacitor can be easily measured by arranging thermocouples on the surface of the capacitor, but obtaining the internal temperature of the capacitor is somewhat more challenging. Gualous et al. [117] reported the internal temperature of the capacitor with K-type thermocouples embedded in the capacitor, with the sensors located as shown in Figure 10a,b. Their findings indicate that the discrepancy between the inner and outer surface temperatures of the capacitor showed an increase trend over time, as seen in Figure 10c, due to the air cooling on the surface of the device reducing the outer temperature [40]. Indeed, there is a variation of 3 $^{\circ}$ C from the peak temperature of the capacitor to the minimum temperature during charge/discharge cycles, as a result of the heat accumulation of SCs during the charging and discharging processes, which causes this temperature to increase over time. Moreover, to achieve better comprehension of the temperature variations of the capacitor during operation, as illustrated in Figure 10d, thermal imaging can also be used to characterize the capacitor [118]. This allows the actual temperature distribution that occurs to be more perfectly described for studying the thermal characteristics of the capacitor [119].



Figure 10. (a) SC construction with embedded thermocouple, (b) geometric diagram of thermocouple positions, (c) plots of internal and external temperature of SC versus time, reproduced with permission from [117], copyright 2011, IEEE, and (d) thermal image of capacitor temperature change, reproduced with permission from [118]. Copyright 2016, Springer Nature.

3.4. Thermal Modeling of Supercapacitors

The drastic reactions that take place inside SCs during charging and discharging processes can have an influence on the thermal behavior of capacitors [120]. The mechanism of heat generation in capacitors is rather complex, with many researchers seeking to identify the reasons behind it and the relationship among the various components within their capacitors. The thermal models of SC can be classified into zero-dimensional (0D), one-dimensional (1D), and three-dimensional (3D) models based on their dimensions.

3.4.1. Zero-Dimensional Model

The 0D model treats SC as a point of mass equilibrium and presumes that its interior material is uniform and isotropic. This type of model is widely available in circuit models. The equivalent circuit model, without taking into account the internal physical reactions of SC units, offers a category of easy constructions to describe the input/output properties of SCs. It generally involves common electrical circuit variables (capacitance, impedance, and so on) to denote the electrical behavior of capacitors. A variety of models display different levels of accuracy, based on the electrical circuit profile and the number of components, where increasing the complexity of the circuit is beneficial for improving the precision of the model. It is necessary to couple the thermal model with the electrical model to produce a computationally productive electrical model. Soltani et al. [121] proposed an electro-thermal model for LIC cells that was suitable for an extended temperature range and high current situations, as shown in Figure 11a. In light of the fact that a first-order model is unable to simulate the voltage characteristics of LIC cells with two distinct electrodes and various energy storage mechanisms, a second-order model is necessary to perform electrical performance simulations [33]. The results demonstrate that the coupled secondorder electrical model and the thermal model are capable of exhibiting good precision for both concentration differentiation and electrochemical polarization, with errors in the model under 5% at high currents (300 to 500 A). Indeed, the lumped parameter thermal model is relatively straightforward and computationally more time-efficient than other



models [122]. In this type of model, when the SC is considered to be a lump body, it is identical in every direction in the process of heat transfer at a temperature.

Figure 11. (a) 0D electro-thermal model for an LIC cell, reproduced with permission from [121]. Copyright 2020, Elsevier. (b) Lumped parameter thermal model of SC string including several cells, reproduced with permission from [123]. Copyright 2020, IEEE.

Lystianingrum et al. [123] developed thermal models as shown in Figure 11b for multiple SC strings using this approach, which was verified experimentally. The identification of the thermal model variables is discussed, and a closed-loop observer is devised for assessing the temperature on the basis of the verified model. The findings confirm that a basic closed-loop observer can provide potentially reliable information on transient temperature estimation. In addition, other researchers have proposed some general thermal network models to analyze SC thermodynamics. Berrueta et al. [124] proposed a combination of electrical and thermal models to describe the thermal characteristics of SCs as governed by temperature in the case of equivalent circuits. The electrical model elaborately considers ionic variations in the electrolyte and the process kinetics within the pores of the electrode and the electric double-layer, and the thermal model assumes that heat is generated evenly throughout the process. The precision of the model is verified by an extensive series of experimental tests in a practical operating environment. Sarwar et al. [125] coupled a pseudo-3D thermal model with an electrical model to forecast the inner temperature and variation pattern of SC under high current charging/discharging processes. These pertinent data on the thermal gradient is then used to define the temperature-related electrical properties.

3.4.2. One-Dimensional Model

The electrochemical model starts from the explanation of the double charge layer at the electrode/electrolyte interface, constructing the corresponding interface model through the deduction of interfacial charge separation and the theory of idealized electrodes, which can accurately represent the reaction process occurring inside the capacitor [126,127].

On the basis of porous electrode theory, Kundu et al. [104] proposed a 1D electrochemical model, as illustrated in Figure 12. The model is constructed from porous electrodes and separators, as well as the 1D transportation of ions across the separator from the anode to the cathode electrode. This model reduces the number of dimensionless parameters by simulating the variation of the heat generation rate inside the capacitor over time during cycling in comparison to previous results. Li et al. [97] combined the 1D electrochemical model and the 3D thermal model to provide an entropy generation analysis of SC. In it, there is an accurate quantification of the irreversible factors caused by heat transfer, mass transfer, and ohmic losses for SC. The results of this model are in very good accordance with the experimental values, with an error of 0.159% under adiabatic conditions and 0.182% under natural convection conditions, respectively. Li et al. [128] further refined this type of model optimization to analyze the heat transfer irreversibility and fluid friction irreversibility of SC cells. They investigated the influence of physical variables such as structural geometry, cooling fluid, inlet temperature, current, and inlet water velocity on the SC blocks. It was observed that the SC module with larger longitudinal spacing results in lower entropy generation under the demand of compactness. In contrast, if the cooling requirements are satisfied, increasing the coolant inlet temperature leads to a decrease in entropy.



Figure 12. Electrochemical model of an SC, reproduced with permission from [104]. Copyright 2021, Elsevier.

3.4.3. Three-Dimensional Model

In order to gain a better visualization of the internal temperature distribution of SC over time, as shown in Figure 13, a 3D geometric model could be established with the finite element method, as well as solving the equations for the simulation to obtain the desired parameters [129,130]. Wang et al. [131] developed a 3D thermodynamic finite element model of stackable SCs and analyzed the temperature evolution of capacitors as well as the regularity of the internal temperature profile during cycling procedures. During operation, the maximum temperature of the capacitor is found at the core [132]. Moreover, the temperature rise of the capacitor is below 15 °C in the 3 A constant current charge-discharge cycles, which proves the robustness of the model for a more realistic response to the actual situation.



Figure 13. The temperature field distribution for an SC [129], open access.

Lee et al. [133] also investigated the influence of ambient temperature and service conditions on the thermal behavior of the 3500 F SC with the 3D model. It was found that the temperature of the SC consistently elevates for the first 50 cycles, thereafter attaining a stable value with higher capacitor temperatures as the ambient temperature increased. This type of approach facilitates a theoretical basis for the thermal management system, thus assuring that the entire system remains within a safe range [110,134]. Hamza et al. [135] presented a 3D multi-scale SC thermal model that precisely forecasts heat generation rate and temperature rise and provides a more detailed physical explanation of heat generation rates. The numerical heat generation and temperature curves are similar to the experimental findings, with an uncertainty of less than 15% in prediction. The temperature is consistent throughout the cell, but displays a primary decrease over the air gap.

Table 4 concisely summarizes the heat transfer modeling approaches mentioned above for SCs. In some cases, 0D models can be derived from experiments where the parameters are relatively simple to measure. In addition, their parameters have no physical expression, so there is no explicit internal information. However, they are extensively employed for their structural simplicity and adequate modeling precision. 1D models and 3D models allow for authentic reflection of the internal heat generation phenomenon, but many microscopic parameters need to be extracted, which consumes considerable computational resources.

Category	Variable Considered	Advantages	Disadvantages	Ref.
0D model	Current, voltage, resistance, capacitance	Parameters easily accessible, simple structure	No detailed dynamic information available	[121-125]
1D model	Mass charge, elec-trochemical kinetics	High precision, detailed descripti-on of the actual phenomenon	Heavy computation, model complexity	[104,108,126]
3D model	Physical structure, temperature locate-on dependent conv-ection and radiation	Good in temp-erature gradient depiction	Heavy computation, mesh size and boundary conditions sensitive	[129–133]

Table 4. Summary of various SC thermal modeling methods by researchers.

3.5. Effect of Temperature on Supercapacitors

The working temperature of SCs has a considerable impact on their components and performance properties. At ambient temperatures above 25 °C, the lifespan of SCs is

reduced by 50% for each 10 $^{\circ}$ C exceeded. As the temperature rises further, this leads to a decrease in the power and capacity of SCs. This section provides an overview of the effects of temperature on electrode materials.

3.5.1. Effect on Electrolyte

The electrolyte temperature range is usually from 233 to 343 K. As the temperature increases, the ions move more randomly, which increases the electrolyte's ionic conductivity. In addition, there is a reduction in the viscosity of the electrolyte as the temperature increases and an opposite relationship with ionic conductivity. Finally, the temperature also influences the reliability of the electrolyte. When the normal operating temperature range is exceeded, the electrolyte's ionic conductivity drops significantly or decomposition occurs in the electrolyte, inducing a degradation in electrochemical characteristics.

3.5.2. Effect on Separator

The separators are located between the anode and cathode electrodes and permit the rapid transportation of ions between them. It is prone to melting at higher temperatures, which require high stability. Besides, it also needs to have an automatic shutdown function. When the temperature exceeds a certain level, the separator melts, which blocks the ion transport path by eliminating pores and ultimately avoiding thermal runaway.

3.5.3. Effect on Electrodes

SCs operate at high temperatures, exacerbating the reaction of the interfacial film between electrolyte and electrode. The pores can be blocked by solid particles generated between the carbon electrode and the electrolyte, which can result in a reduction in capacity due to the loss of the active material. Moreover, it is possible to use carbon black and AC at elevated temperatures with no difficulties. Binders (usually PTFE) are relatively inert and pure fluoropolymers. Hence, the working temperature scope of the electrodes is restricted by the melting point of binders.

3.5.4. Thermal Runaway

The fact that excessive cell temperatures can result in disastrous fires or explosions has made thermal runaway a critical scientific concern in the study of battery safety [136,137]. Many studies have shown that the thermal runaway mechanism in cells is the result of a chain reaction induced by an uncontrollable elevation in temperature [138,139]. During regular operation, some heat is generated by electrochemical reactions within the cell. With time and external heat dissipation, cell heat generation will be gradually reduced so that the temperature will remain in a controlled range. If the cells are subjected to abnormal conditions (such as mechanical abuse, overcharge/over-discharge and thermal abuse), the internal temperature can increase significantly, which leads to the temperature rise of the cell at an uncontrolled rate and consequently to thermal runaway [140]. Smith et al. [141] assessed the thermal runaway behavior of LIC cells and the thermal properties of the elements using two types of calorimeters. The result, as shown in Figure 14a, indicates that the temperature profiles of the LIC cells with two distinct types of electrolyte exhibited similar trends. At temperatures of 90 °C to 100 °C, the LIC cells were subject to continuous chemical reactions in which the SEI film formed on the anode started to decompose. The sharp increase in cell temperature from 120 °C to 200 °C is attributed to the reaction of the pre-lithiated electrodes with the electrolyte and the binder, in which these reactions tend to yield gases. At 400 $^{\circ}$ C, the temperature of the LIC cells reached its peak. Figure 14b illustrates the temperature versus time curve for EDLC (1.2 Ah) in the Accelerated Rate Calorimeter (ARC). No exothermic reaction was found across the entire curve change. The calorimeter is the only heat source for the constantly rising temperature of the EDLC. At approximately 169.6 °C, the EDLC vented towards the outside with the pressure set in advance. Overall, it can be found that the EDLC does not show the same self-heating and thermal runaway as the LIC and LIB. Oca [142] evaluated the security of LIC cells under

overcharge and over-discharge situations in a post-mortem analysis. In the case of the over-discharged cell, there is no appreciable internal degradation, of which some bubbles occur in the separator as the only indication of degradation. By contrast, the overcharged cell suffers noticeable deterioration in all components, as shown in Figure 14c. Of these, there are small regions of separator meltdown, as well as a certain degree of degradation of the active substance of AC and graphite electrodes. In general, LIC cells are found to be safe under abuse conditions, with no dangerous cases of fire or explosion.



Figure 14. (a) The temperature vs. time curve for LIC pouch cells' thermal characteristics where lowercase letters a and b represent two distinct types of electrolyte, (b) the temperature vs. time curve for EDLC (1.2 Ah) pouch cells' thermal characteristics, reproduced with permission from [141]. Copyright 2021, Elsevier. (c) Inner constituents of LIC cells after the electrical abuse tests, reproduced with permission from [142], copyright 2019, Elsevier and (d) LIC nail-penetration test [143], open access.

Omonayo et al. [143] performed a related nail-penetration test on LIC pouch cells, and the experimental result is shown in Figure 14d. At the beginning when the nail starts pinning, the voltage transient drops as the conductive nail connects the positive and negative terminals with the internal short circuit. The temperature rises rapidly to 90 °C within 40 s, while the cell produces excessive gas. When the nail is removed, the cell temperature is dropped and no violent explosions occur because the nail provides the gap for the gas products to be released, thus reducing the pressure inside the cell.

4. Thermal Management System

4.1. The Necessity for Thermal Management

As some degree of electrochemical reactions constantly taking place is SCs, they are susceptible to their own temperature rise and temperature fluctuations caused by their own heat generation, besides the ambient temperature [144]. When the temperature rises, the electrolyte conductivity increases for a corresponding reduction in internal resistance [85]. A moderate increment in temperature has a certain virtue, but the electrolyte is essentially formulated from mixtures of organic solvents, of which evaporation begins at an ambient temperature of 20 °C, where higher temperatures have a tendency to induce gas yield [145,146]. At ambient temperatures above 25 °C, the lifespan of SCs is reduced by 50% for each 10 °C exceeded [101]. In addition, in the case of relatively elevated ambient conditions or high rate discharging, the irregular distribution of the internal temperature field in the SC modules for a long duration will consequently lead to the uneven performance of the modules and the individual units, especially in the area with high temperature distribution. The degradation

rate of capacitors will be markedly quicker than that of the low-temperature component. Consequently, with the accumulation of time, the physical differences among capacitors will be more apparent, which causes the coherency between capacitors to deteriorate even if premature failure occurs [109]. Therefore, it is necessary to ensure that the corresponding heat dissipation measures are taken together with the limitations of the charging and discharging power so as to control the temperature rise level. Otherwise, the capacitor may overheat to the extent that the performance deteriorates or even causes thermal runaway [40]. This is worth noting because the low temperature performance of SCs is relatively good and no supplementary heating system is available when the temperature falls below $-40 \,^{\circ}C$ [42].

Thermal management systems for SCs are adopted to keep the temperature in the appropriate range using technical methods [147,148]. Based on the available exterior energy to be consumed, thermal management systems are categorized into active cooling systems and passive cooling systems. Of these, there are active cooling systems that depend on the movement of pump- and fan-powered working fluids, which are normally seen in air and liquid cooling applications. In this regard, the impetus for the fans and pumps is determined by the interference of external energy, where there is mutually exclusive interaction between the cooling effect and the overall efficiency of the system [134]. As for passive cooling systems, specific configurations are placed on the surface of the device. The temperature is regulated by the intrinsic features of the component to facilitate the heat exchange on the device and the external environment, such as phase change material (PCM) cooling and heat pipe (HP) cooling [149]. There are external energy sources for thermal management systems with more sophisticated equipment and consume more energy to achieve more intense heat dissipation. Moreover, the thermal management system, which has no additional energy consumption, permits certain goals of balanced temperature dispersion and flexibility of response.

4.2. Air Cooling System

It appears that the air is not appropriate as one of the heat transfer intermediates in the thermal management system because of its low thermal conductivity. However, given the outstanding combination of ease of installation, economic efficiency, and design feasibility, the air cooling system has been successfully developed in the business field to some extent in Chinese and Japanese automakers' vehicles [150]. In this way, the modules are cooled through convection heat transfer with the surface of the capacitors as the air moves through the SC modules. There are two primary categories of air cooling systems: natural air convection and forced air convection.

A typical cooling strategy for the use of air as a heat transfer medium is the natural convection cooling method [151]. When air from the exterior environment or the electric vehicle accesses the flow channels of the thermal management system, it is in direct contact with the interface of the SC module. The objective of cooling the capacitor is accomplished by convection heat transfer from the air to the device, the device cabinet, and that of the thermal conductive constituents [29]. The convective heat transfer factor in this manner is smaller, as well as the natural convection movement being weaker, inducing the poor heat release efficiency of conventional natural cooling. Therefore, it is rather confined to actual implementation and investigations [152].

Forced air convection is the most accessible approach in this category, as it only involves fans to circulate the air [153]. The wind created by the movement removes the heat from the capacitors inside the cabinet through the exhaust fan. As air volume increases, the peak temperature decreases. The forced air convection system intensifies the convective heat transfer coefficient to regulate the temperature of the capacitors by means of enforced airflow. Forced convection is the more prevalent method of cooling capacitors as it is considerably better than natural convection in terms of reliability and considerably improved heat dissipation [150]. However, these systems are very exacting with regard to the design of air ducts, which appear to have difficulty in attaining a homogeneous flow field, giving rise to the usual issue of uneven temperatures between capacitors. In

order to tackle the discrepancies between capacitors, investigators in different countries have carried out various alternative paths to enhance temperature homogeneity, focusing primarily on such research as the spacing between capacitors [154], the direction of air conduction [27], and the position of fans [155].

Xia et al. [156] have developed cooling channels for capacitor packs that contain both parallel and series connections, as shown in Figure 15a. The capacitor packs consist of 6 modules, each of which is composed of 15 capacitor individuals, for an overall number of 90 individuals to be linked in series. The entrance to capacitors is positioned in the center of the top face of capacitors, while the exits are placed towards their left and right sides, with six capacitor blocks arranged symmetrically at the entrance. The heat dissipation structure with air intake in the center and air exhaust in both directions allowed sufficient air to pass over every single side of the capacitors to remove the heat produced by them [157]. Their results demonstrate that the largest temperature variation in capacitor packs could be limited to 5 °C, guaranteeing uniformity of capacitor operating temperatures. Hybrid cooling methods prevent the arrangement of too many devices in one row, as it is common to have several dozen units in electric vehicles. In addition, the temperature inhomogeneity problem can be mitigated due to the much shorter coolant movement routes. This is also noted in Ref. [158].



Figure 15. (a) Connection in series and parallel configuration diagram where red arrows represent the direction of gas flow [42], open access. (b) The SC's staggered layout, reproduced with permission from [154]. Copyright 2019, Elsevier.

Voicu et al. [29] devised the staggered layout of different horizontal and vertical distances in SC modules to achieve various degrees of compactness. At a particular ventilation power, it is indicated that a horizontal distance across two successive SCs offers

superior cooling properties at the equivalent of 1.25 times the diameter. This layout not only cuts down on spatial demands but also reduces the amount of power available to transfer the cooling air. Ionut et al. [154] further researched the thermal management of modules featuring air cooling with this capacitor arrangement, as indicated in Figure 15b. Forced air convection research is conducted on nine SCs arranged in a module for charging and discharging with 70 A current. Experimental and simulation results demonstrate the relatively good cooling performance of the second column, regardless of its position in the heart of the module. At inlet speeds up to 0.36 m s⁻¹, the first column is the least cooled, but its temperature is nearly the same as that of the last SC column. A minimum temperature in the second column relative to the first is due to the additional turbulence caused by the airflow passing through the first column. As a consequence, heat exchange is enhanced in the second column. There is less significant impact of incremental turbulence and partial heat transfer factor on the SC temperature in the third column, as the air elevates in temperature over the duration of its transit across the first two columns. There is also less cooling in the third column than in the second, as it is the last column of the module and lessens partial heat transfer. In other words, it is possible that the maximum surface temperature is situated in the last column of the SC module.

Zhang et al. [27] developed an innovative air cooling system, as illustrated in Figure 16a, for the SC cabin of an electric bus. The impact of exterior ventilation on the air circulation inside the cabin is taken into account by modifying the construction and placement of the cabin air exit, namely inserting a deflector at the front side of the air exit. In view of the aesthetic requirements of the vehicles, the deflectors are adopted for each surface area of 138 mm × 48 mm. Figure 16b presents the velocity vector diagram of the cooling air moving from the passenger cabin to the SC block cabin, which subsequently exhausts through the air vents positioned on the underside of the vehicle. The outcomes of this design demonstrate that at a speed of 30 km h⁻¹, the temperature of the components inside the modified capacitor cabin changed from 27 °C to 41 °C, which is a reduction of 10 °C [27]. This is an indication that the optimized capacitor module compartment is up to the high current working state.

Soltani et al. [155] conducted experimental and simulation research on the air cooling system of the LIC module, comprising 12 LIC cells coupled in series, as shown in Figure 17. To facilitate better precision of air cooling systems, achieve improvements in temperature homogeneity, reduce peak temperatures, and diminish energy expenditure, it is possible to combine a variety of functioning and designing variables, such as fan location, air speed, and interval between capacitors [109]. The results proved that in this layout, with the fan placed on the right and the air vent on the left part of the block, the air movement is relatively more in touch with the faces of the capacitors, since the air moved parallel to the largest part of the cells, which promotes greater heat transfer and cooling characteristics [159]. The balance between cooling efficiency and energy expenditure can be reached when the speed is 5 m s^{-1} and the capacitor interval is 5 mm. The simulation and experimental results match relatively well with an inaccuracy of under 2 °C that justifies this approach as the perfect proposal.



Figure 16. (**a**) Illustration of the optimization and (**b**) optimization of velocity vectors at the entrance and exit of the compartment, reproduced with permission from [27]. Copyright 2016, Elsevier.



Figure 17. Experimental configuration graphs of the LIC's air cooling system, reproduced with permission from [155]. Copyright 2019, Elsevier.

In summary, although SC modules have certain enhancements in the air cooling system, and they also have some shortcomings. In contrast to the liquid cooling systems with

identical flow velocities described next, there is difficulty eliminating the heat generation by air cooling at adequate flow rates. Besides, there should contain just a handful of capacitors in the capacitor pack for the wider clearances between capacitor groups, which are necessary to sustain active heat exchange via air cycling, which restricts the amount of energy available for storage in the capacitor groups. One further negative aspect of this system is that the several fans or blowers employed in electric automobiles can create much noise. These weaknesses constrain the availability of air cooling, as it severely hampers the reliability of capacitors as well as the range of electric automobiles. However, the equality of the forced air cooling system is dramatically constrained by exterior energy consumption, which in turn adversely impacts thermal management properties.

4.3. Liquid Cooling System

A liquid cooling system is a type of conventional active cooling system, typically employing mineral oil, water, and so on as the working medium [160]. What it does depends on the movement of the fluid in the surrounding cell to deliver heat. It is more efficient than air cooling as a result of the relatively strong coefficient of diffusion of heat from the liquid [161]. There are also categories of direct contact and indirect contact according to the contact pattern, as shown in Figure 18a,b [157,162]. This is the direct contact cooling of cells by submerging them completely into an excellent working solution with higher thermal conductivity, so that their heat is dissipated by the flow of the solution. The whole body face of the cell may be cooled in this way, which facilitates greater temperature homogeneity by reducing the partial heating impact of the positive and negative terminals [163]. In short, it is possible to obtain high thermal management capabilities with direct cooling applications because the surfaces of the cells have adequate exposure to the heat exchange fluid. Yet, the direct contact approach extends the expense of keeping the coolant and cell serviced, while the rigorous sealing and pressure demands impose extra complications on the structure, preventing such cooling from being implemented in practice. By means of indirect contact heat transfer, it is assumed that the heat produced by the cells is absorbed into the working medium through radiators, which are subsequently recycled by the working medium [164]. The thermally conductive components, such as liquid cooling plates and fins, are fabricated from aluminum or copper plates that have excellent heat exchange capabilities. This establishes an optimal heat flow route between the cell units and the cooling medium in cold plates to achieve the minimum necessary thermal resistance [134]. Moreover, if there is no flow rate constraint, it is advisable to opt for a liquid with superior thermal conductivity as well as better heat dissipation. For example, for prismatic SCs, their regular geometry and smooth faces permit the insertion of liquid cooling plates between successive units for heat dissipation.

Karimi et al. [165] conducted research on both cooling plates wrapped around the liquid cooling system for the LIC cell to probe factors that influence the capability of the thermal management system. Figure 18c illustrates the evolution of the LIC cell superficial temperature as a function of time under various cooling conditions. It is seen that the surface temperature of the LIC for the liquid cooling scenario is much lower than the other two air cooling scenarios. Therefore, the liquid cooling system is the optimum cooling option for the above three cooling scenarios. This is further explored in terms of inlet fluid velocity and the inlet cooling temperature of the liquid cooling process. The temperature profile of the LIC for a variety of coolant flow speeds is shown in Figure 18d, where it can be observed that the temperature of the cell is reduced with an increase in the inlet flow rate. The increased speed of the cooling medium induces corresponding growth in convective heat transfer, which in turn causes variations in cell temperature. In light of the nonlinear dependence of the coolant inlet velocity and pressure drop, the temperature could be regulated at the flow velocity of 100 mL min⁻¹. Furthermore, Figure 18e presents comparisons of the effect of various inlet liquid temperatures on the LIC cell temperature. The results indicate that the apparent temperature varies with the duration of discharge. As the secure functioning limit of LIC is below 40 °C, the ambient temperature above this

is prone to overheating influences, thus undermining performance [42]. As the relatively low intake temperature necessitated a vigorous radiator to keep it at a consistent threshold, it is opted for an approximate inlet temperature of 30 °C, which remains within the secure service range for the peak operating temperature.



Figure 18. (a) Direct contact liquid cooling system, reproduced with permission from [162], copyright 2014, IEEE, (b) indirect contact liquid cooling system, (c) graphs of temperature versus time under the following three laboratory tests: natural air convection (NC), forced air convection (FC), and liquid cooling (LC) for LICs, (d) temperature trends over time at various flow rates, and (e) temperature variation trends over time for a variety of inlet cooling medium temperatures, reproduced with permission from [165]. Copyright 2020, Elsevier.

In summary, despite widespread concern for liquid cooling systems, there are several underlying weaknesses that should be addressed. In contrast to air cooling systems, the overall system has become much more sophisticated as a result of extra parts (such as water pumps and radiators) and intricate flow channels. Moreover, it is important to create a compact construction to eliminate leaks as well as to facilitate the circulation of fluids, while also maintaining excellent heat conductivity and the absence of erosion of SCs. In light of these above potential parameters, it may be that liquid cooling is less investigated in the field of SCs.

4.4. Phase Change Material Cooling System and Heat Pipe Cooling System

The thermal management system employing air and liquid for the cooling transport medium involves extra equipment and the consumption of exterior energy so that the overall system becomes complex and entails relatively substantial expenditure on maintenance. However, there has been much discussion about the particular qualities of PCM as the solution for thermal management systems, in terms of its uncomplicated nature, ease of implementation, and superior temperature management features [166]. PCM is one type of material that can take part in the absorption or distribution of thermal resources for the system by means of its latent heat of phase change. In the course of its physical phase change, it can absorb heat from the exterior world or release power to the external surroundings in order to attain the objective of energy conversion to regulate the temperature of surroundings as well as the exploitation of energy [167]. When the PCM is applied to thermal management systems, the devices or units can be submerged immediately in the PCM, as depicted in Figure 19a. The latent heat feature of the PCM may be adapted to preserve the operating temperature of cells within the desired scope. The latent heat reserve is primarily based on the energy extraction and exhaustion of energy by the material in the context of phase change. It is common for PCM to shift from one phase regime to the other, while a significant volume of heat is simultaneously taken up or removed from the

surroundings when the temperature is elevated or dropped to a specific temperature [160]. Of the diverse PCMs, paraffin wax is extensively used in thermal management systems for the sake of its affordability, excellent chemical consistency, and durability. However, there is a principal drawback to the employment of paraffin waxes in view of some of their poor thermal properties [168]. To address these challenges, some researchers have carried out investigations on how to strengthen heat transfer.



Figure 19. (a) Diagram of the thermal management system with LIC units and PCM. (b) The LIC units covered by aluminum mesh. (c) The temperature versus time plots for the various tests below: forced convection, PCM, and the PCM and aluminum mesh (PCM-Al) for LICs, reproduced with permission from [169]. Copyright 2020, Elsevier. (d) The HP cooling system for the LIC cell [170], open access.

Joris et al. [171] investigated the employment of paraffin as the cooling medium for the PCM within a module made up of two LIC single cells for its thermal management system. To boost the heat conduction of the paraffin, extra constituents (such as aluminum mesh) are attached together with the LIC module to transfer the heat flow from the PCM towards the LIC module, as shown in Figure 19b. The experimental and simulation results are presented in Figure 19c, where the cooling system with paraffin and aluminum mesh (PCM-Al) in the LIC module is observed to be lower in temperature than the pure PCM cooling system. This suggests that the specially positioned aluminum mesh that surrounds the capacitor offers excellent electrical conductivity and suppresses the heat of the module very well. For the purpose of ensuring greater homogeneity and reducing system costs to some extent while simultaneously preserving the system's excellent heat distribution characteristics, Danial et al. [169] carried out the relevant adjustments to the LIC module with the identical research procedure. Through the optimization of the PCM with a range of thicknesses, the aim is to identify the perfect thickness to capture the heat generated as a result of the LIC module, as well as to retain the temperature inside a secure range. They discovered that the terminal temperature is rather high for relatively thin PCMs, which severely hampers the service life of the LIC. Although the greater thickness added to its expense and heaviness, the approximate thickness of 7 mm is rather desirable to accommodate these balances.

Furthermore, HP is one of the main metals with superior thermal conductivity, where the heat transfer process is facilitated through the phase change of the inner substance [172]. The HP cooling system for the LIC is shown in Figure 19d. While HP is in action, the liquid medium inside the pipe is subject to heat evaporation, with the liquid medium inside undertaking the phase change to become steam and absorbing the majority of the heat [157].

Afterwards, the steam enters the condenser side, where it condenses into the liquid through the phase change procedure. The heat is delivered to the external world through thermal convection to attain heat dissipation, and the liquid medium is eventually returned to the evaporator terminal under the function of gravity. In other words, the process of heat dissipation can be circulated to constantly transfer heat to the environment, thereby permitting the transfer of significant heat flow with minimal temperature fluctuations, thus decreasing the temperature of SCs. Karimi et al. [170] explored the influence of diverse environmental constraints on LIC cell performance in order to manage the LIC cell temperature with an HP cooling system. In the course of evaluating the temperature evolution of the LIC in the presence and absence of an HP cooling system, it was discovered that an HP cooling system could achieve temperature reductions of between 7.5% and 11.7%. Under an identical number of cycles, the capacity retention of the LIC is boosted by roughly 2.1% with an HP cooling system versus natural convection cooling. This is attributed to the HP cooling system consistently absorbing the heat generated, alongside the instant migration of such absorbed heat to the surroundings.

While the HP cooling system provides significant improvements in thermal conductivity and the absence of danger of leakage, it also suffers from the drawbacks of incompatible space configuration, service constraints, and particular demands on the cell shape [168]. For practical implementation, this is frequently integrated with PCM thermal management techniques as a way of eliminating the deficiencies of poor thermal conductivity and too much heat accumulation from the PCM [173]. A hybrid thermal management system (HTMS) is introduced for LIC cells that employs PCM and HPs, as shown in Figure 20a, to avoid heat damage and equilibrate the temperature homogeneity of cells over the cycle measurement period [174]. Their experimental and simulation findings reveal that there is a tremendous cooling system in the HTMS in that it achieved a 35% decrease in cell temperature as well as an 86% reduction in temperature deviation versus that of the research undertaken without the cooling system. This is attributed to the heat conversion process where the PCM and the HPs concurrently conduction the heat loss from the cell.



Figure 20. (a) Geometry of the hybrid thermal management system incorporating HPs and PCM where blue colors in figure represent flat heat pipes, positive tab and negative tab, reproduced with permission from [174], copyright 2021, Elsevier; (b) the heat sink for the LIC cell (unit in mm) [175], open access.

In the case of the PCM, there is a shortage of sufficient latent heat for high working temperatures or high power operation, which is supplemented by the incorporation of

active cooling methods [176]. It was designed by Karimi et al. as an innovative thermal management system containing the PCM and heat sink for the LIC cell [175]. The exterior configuration of the heat sink is illustrated in Figure 20b. The radiators enhance the heat flow away from the power supply by providing more surface area for the equipment. Not a promising option for high-performance systems when acting as a primary cooling source, the heat sinks exhibit excellent properties for secondary cooling. Their discovery also validated this, with a reduction of 16.4% relative to a simple PCM cooling system.

While the PCM cooling system is currently subject to investigation, as well as having to encounter certain technical challenges in actual use, for instance in terms of encapsulation and poor heat conduction, it possesses distinct benefits than other forms of thermal management systems [177]. For instance, in contrast to HP cooling systems, the costs are considerably cheaper, with much improved cell temperature evenness [178]. In addition, the PCM offers the merits of better efficiency and the absence of exterior power sources. Thus, there are very promising applications for cooling systems based on PCM medium.

In summary, Table 5 presents a summary of the benefits and drawbacks of passive and active thermal management systems for capacitors. Each of the above-mentioned types of thermal management systems has not yet achieved complete technical sophistication, so that a powerful modular thermal management system will be a mixed system, via the joint design of no less than two distinct thermal management systems, in the future evolution of a capacitor cooling system.

Thermal Management Systems	Types	Advantages	Disadvantages	Ref.
Active systems	Air cooling system	Simple configuration, ease of installation, light weight	Low efficiency, low specific heat	[27,29,154–156]
	Liquid cooling system	High efficiency, high thermal conductivity	Leakage possibility, complicated structures	[162,165]
Passive system	PCM cooling system	Uniform temperature distribution, high efficiency	Low thermal conductivity, Leakage problem	[169,171,173,178]
	Heat pipe cooling system	High thermal conductivity, no leakage	Expensive, difficult to maintain	[170]

Table 5. Advantages and disadvantages of various thermal management systems.

5. Discussion

The heat generation rate of SCs under various service conditions is of vital importance for project design and administration in the field of energy storage. Currently available SC models pay less regard to extended working environments and complicated operating conditions, for instance in electric truck-associated applications. Indeed, the heat generation rate models in existence appear to be either excessively simple or complex in terms of actual applications, while the accuracy of the simulation results is to some extent reliant on the measurement of material parameters. Future research into the modeling of heat generation from EDLCs and HSCs in real situations must particularly focus on how to develop models that capture the principles of heat generation and heat transfer with simplicity and reasonableness. Moreover, although the prevailing calorimetric technologies have measured the heat generation rate at each electrode of the EDLC and the pseudocapacitor, there is less clarity in the interpretation of the specific heat generation principle at each electrode. For the time being, no further research has been carried out in the literature on the underlying mechanisms behind this phenomenon, which involves both endothermic and exothermic reactions in the LIC charging process. Furthermore, SCs have currently been studied in a relatively limited way with respect to thermal safety, with only phenomena

observed to occur during thermal safety processes. To promote better commercialization of SCs, the detailed runaway mechanism should be analyzed. In short, there is no overall multi-physics field-based model to describe the thermal characteristics and runaway of SCs. The model in this way should account for the thermo-physical properties of all materials for usage and the heat generation rate by all origins, which in turn can promote the design of innovative and productive cooling systems to prevent overheating as well as minimize the related issues associated with aging and performance degradation.

Thermal management systems play an essential role in eliminating the thermal effects of SCs, which enhances temperature homogenization between capacitors, extends capacitor life, and boosts the security of capacitor modules. The air cooling system features attractive industrial applications with lower manufacturing and maintenance costs, along with simplicity in implementation. However, owing to the poor thermal conductivity and specific heat capacity of the operating fluid, the cooling system can restrict applications of capacitor packs for driving over long distances and high power requirements. In addition, relevant optimization algorithms are less commonly used for air cooling systems. Hence, improving the efficiency of air cooling systems without sacrificing available area and power in electric vehicles necessitates additional innovative designs in terms of capacitor pack layouts and airflow paths. Together with advanced algorithms, such as machine learning algorithms and advanced genetic algorithms, this makes computing more convenient when there is not enough computing power and time. Liquid cooling systems have greater compactness and heat conductivity, which enables the temperature of the capacitor to be homogeneously distributed. In addition, the cooling effect progressively deteriorates in the order of the fluid flow, so the improvement of the design of the structure and quantity of flow channels will be an important field of research. The system has less research in the area of capacitor modules at present, and future systems should be expanded from individual units to capacitor modules with consideration of whether the suggested cooling solution can manage the temperature of capacitor modules. PCMs have been found to be quite appealing for absorbing the heat caused by capacitors, but when the test changes from single capacitors to capacitor groups, they are unable to pick up the whole amount of heat. It would be the next research trend to fabricate innovative composite PCMs for high thermal conductivity and latent heat, as well as coupling them with active cooling methods (air cooling or liquid cooling) to form a hybrid thermal management system that assures high cooling performance. The condensers of HPs require immediate cooling to maintain proper function, which is why they are often applied in thermal management systems in conjunction with active cooling approaches, including forced air cooling or liquid cooling, to boost dissipation capabilities.

6. Conclusions

SCs are superior to batteries because of their high power density and particularly high charge/discharge rates, which have received extensive attention. However, their utilization is still influenced by performance and safety concerns. Moreover, SCs have certain requirements for their operating temperature, so the thermal phenomena around SCs need to be understood and regulated. The objective of this review is to provide insights for researchers to establish a connection between past and future. This review paper first describes the principles of energy storage, internal heat generation mechanisms, and research on thermal runaway for several distinct types of SCs. Then, it also reviews the latest research advancements made by a variety of investigators in the development of thermal management systems that employ air-based systems, liquid-based systems, PCM-based cooling systems, and hybrid cooling systems. Several of the concluding observations of this review are outlined below:

1. The working principle of SCs is not the same for various structures. The energy storage mechanism of EDLC is purely a physical process. Pseudocapacitors utilize redox reactions on the surface of the electrode material for the purpose of accumulating

energy. LICs feature both electric double-layer energy storage and a faradaic reaction for energy storage.

- 2. The temperature varies between various kinds of SCs during the charging and discharging process. Therefore, a series of models have been derived to account for temperature changes. For practical situations, the appropriate model is selected to compute the temperature distribution in accordance with accuracy and calculation time. In addition, SCs have been less studied in the area of thermal runaway, concentrating on thermal failure and overcharge/over-discharge and nail-penetration tests.
- 3. Air cooling systems primarily employ airflow to alter capacitors' surface temperature. The air flow rate is changed by additional devices, which influences heat dissipation. However, the forced air cooling system is constrained by the design of air ducts, which makes it impossible to guarantee temperature uniformity in capacitors. Liquid cooling systems require better sealing, where high demands are made on waterproofing, which is typically more complicated to devise than air cooling systems. In general, liquid cooling systems are relatively less researched in the field of SCs.
- 4. PCMs do not require additional energy consumption, thus suppressing the temperature rise of capacitors. Nevertheless, the low thermal conductivity of materials proves to be a problem. By adding an aluminum mesh to the PCM for capacitors and combining it with other thermal management systems, the heat between components is better transferred so as to decrease the temperature of capacitors. Furthermore, with the rather new usage of heat pipes in thermal management systems, there is a need to further investigate the potential of integrating heat pipes with active or passive cooling systems.

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