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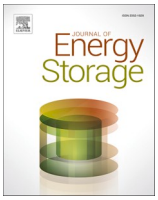

Review Article

Porous media and foam application in battery thermal management systems: A comprehensive review focused on its impact, numerical modeling, and experimental preparation.

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ABSTRACT

The optimization of performance, safety, and longevity in electric and hybrid electric vehicles (EV/HEV) necessitates the implementation of efficient battery thermal management systems. In order to accomplish this objective, it is necessary to implement practical Battery Thermal Management Systems (BTMS) to regulate fluctuations in temperature and maintain a desired temperature range and distribution. Porous media and foams have been identified as viable approaches to tackle the aforementioned issues in thermal management systems effectively. The primary objective of this review paper is to provide an analysis of the developments, trends, and limitations pertaining to the utilization of porous medium and foam in BTMS. The underlying mechanisms and benefits associated with the utilization of porous media have been investigated with a particular focus on their influence on improving and optimizing heat transfer within BTMS. The paper analyzes a variety of porous media and foam structures, materials, manufacturing methods, and numerical modeling. Among the different properties of the porous media, porosity was found to have the most impact on BTMS performance and lower porosity leads to better heat transfer and lower maximum temperature (T_{max}) and maximum temperature difference (ΔT_{max}). Also, the permeability of the foam needs to be optimized to keep a balance between the reduction of T_{max} and any possible increase of ΔT_{max}. Porous media commonly employed in BTMS consist of carbon and metal-based foams, with copper foam being particularly significant owing to its superior thermal conductivity. Considering the dynamic nature of heat generation in lithium-ion batteries, Darcy-Brinkman-Forchheimer (DBF) and Local thermal non-equilibrium (LTNE) were found to be accurate for numerical simulations of porous media in BTMS. Furthermore, it has been underscored that further experimental and numerical investigations, as well as optimization analyses, are crucial for optimizing the thermal management systems of electric and hybrid electric vehicle batteries and maximizing the potential of porous media and foam. This paper concludes by proposing potential future research paths to highlight unexplored areas of research.

1. Introduction

The growing carbon production rate, mainly due to fossil fuel consumption, causes many concerns and environmental problems. This is exacerbated by the incomplete burning of diesel or petrol in internal combustion engines, which results in air pollution with a significant impact on health [1]. Furthermore, the transportation sector is found to be responsible for 28 % of the UK and 29 % of the US carbon footprint in 2017 and 2019, respectively [2,3]. To address these issues, laws and regulations have been passed by authorities and governments such as the UK Department of Transport and the European Union's Horizon [2,4]. The UK Department of Transport plans to introduce nearly zero-emission vehicles by 2030, including 50–70 % of cars and 40 % of vans [2]. Electric vehicles (EVs) and hybrid electric vehicles (HEVs) have recently gained much attention in academia and the industry as a potential solution to the highlighted environmental problems [4]. Electric vehicles, as an environmentally friendly and green means of transport, are based on batteries to supply the required power; therefore, they can potentially reduce a considerable amount of environmental pollution and emissions caused by transportation [5].

Numerous issues arise when relying on battery power, such as covering short ranges, long charging periods, and low power-to-weight ratio. In addition to the mentioned limitations, it is crucial to maintain the battery within the appropriate temperature range due to the sensitivity of its performance to operating temperature. Higher or lower

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Nomenclature

ARC	Accelerated-rate calorimetry
BTMS	Battery thermal management system
Bi	Biot number
CPCM	Composite PCM
CAD	Computer-aided design
C—C	Constant current
C—V	Constant voltage
DBF	Darcy-Brinkman-Forchheimer model
ρ	Density
DOD	Depth of discharge
EV	Electric vehicle
EG	Expanded graphite
EGM	Expanded graphite matrix
HBTMS	Hybrid battery thermal management system
HEV	Hybrid electric vehicles
IHC	Isothermal heat conduction calorimetry
Li-ion	Lithium-ion
LIBs	Lithium-ion batteries
LTE	Local thermal equilibrium
LTNE	Local thermal non-equilibrium
T_{max}	Maximum temperature
ΔT_{max}	Maximum temperature difference
MF	Metal foam
NiCd	Nickel-Cadmium
NiMH	Nickel-Cadmium Hydride
PCM	Phase change materials
PCT	Phase change temperature
PP model	Porous electrode model with polynomial approximation
P2D model	Pseudo-two-dimensional model
RC	Radiation calorimetry
r.e.v.	Representative elementary volume
SEBM	Selective electron beam melting
SLM	Selective laser melting
SLS	Selective laser sintering
SP model	Single particle model
C_p	Specific heat capacity
SOC	State of charge
K	Thermal conductivity
TCR	Thermal contact resistance

temperatures can lead to various issues, including reduced battery life, thermal runaway, capacity decline, and self-discharge. As a result, thermal management and cooling of the batteries, especially high-energy batteries, is found to be inevitable and a significant obstacle in the practical consumption of batteries [6–8].

In light of the significance of the battery thermal management systems (BTMS), as shown in Fig. 1, a considerable increase in the number of publications of review papers exploring diverse thermal management approaches on BTMS was observed. These approaches include air cooling [9–12], liquid cooling [6,13–15], PCM cooling [16–23], heat pipe cooling [24–26], and hybrid cooling [9,21,27]. Rashidi et al. [28] conducted a literature review on the use of porous media for thermal management of Li-ion batteries. However, there is a gap in the literature investigating the practical applications and effects of porous media and foams in battery thermal management systems, specifically in the context of BTMS and hybrid battery thermal management systems (HBTMS). To address this disparity, the objective of this study is to conduct an in-depth review involving various experimental and numerical methods regarding the utilization of porous media and foams, such as metal and carbon-based foams, for enhancing heat transfer in BTMS and HBTMS. The review focuses on the properties and structure of porous materials and foams employed in these systems. The study entails a comprehensive review of experimental and numerical techniques, for simulating heat generation and the application of certain porous metal foams, including copper, aluminum, nickel, and graphite foams, in BTMS. The paper explores the potentialities and challenges of employing these particular types of porous media and foams as passive cooling or heating systems. The findings of this study have broader implications beyond the immediate context of BTMS and HBTMS, providing substantial advantages for optimizing EV and HEV. By improving the comprehension of the application of porous media and foams in battery thermal management, a means for enhancing the effectiveness, capability, and durability of EV and HEV batteries is presented. The comprehensive analysis of these thermal management systems based on porous media and foam can provide valuable insights for future advancements of BTMS and HBTMS, aiding in the ongoing efforts to

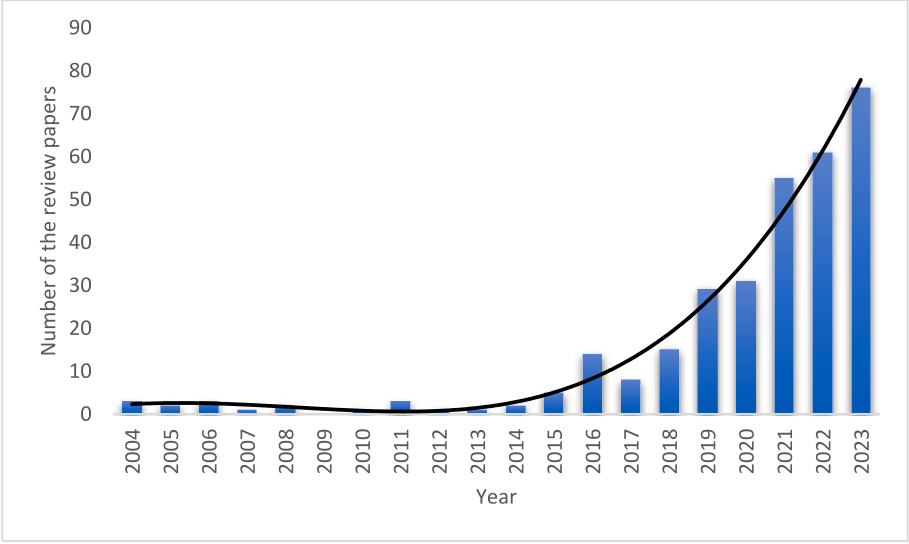


Fig. 1. Number of review papers on battery thermal management systems.

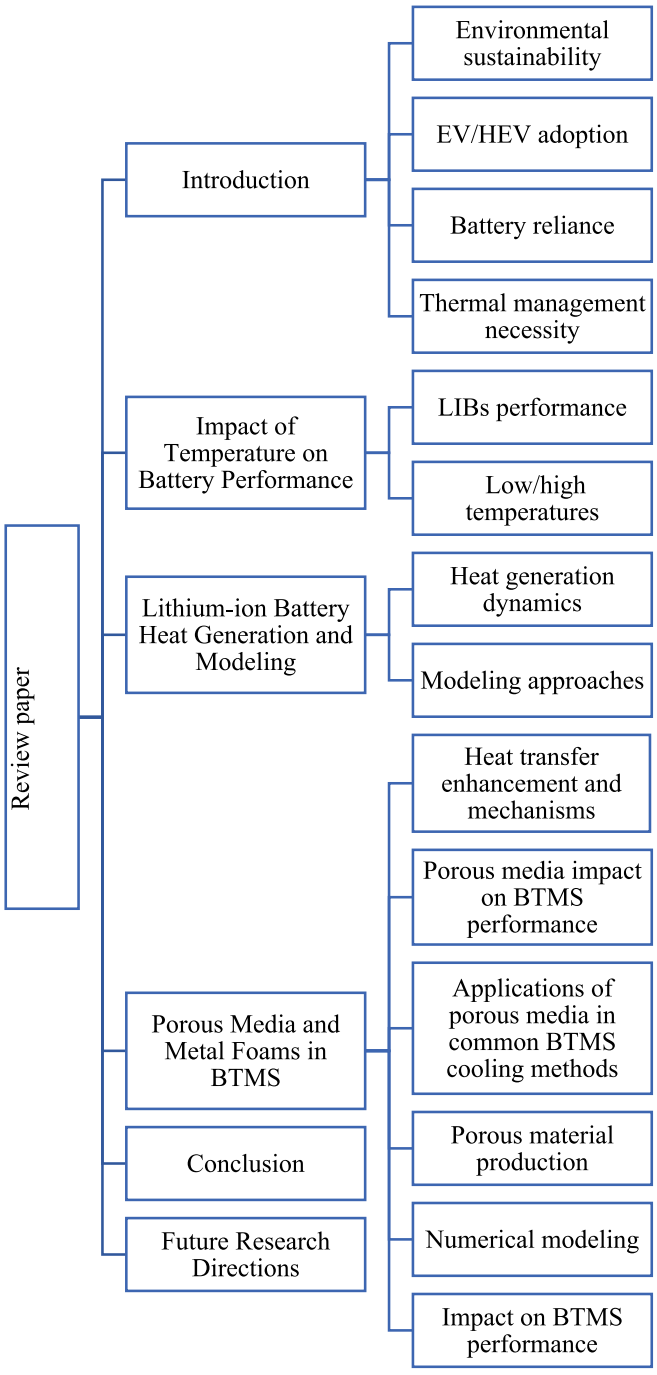


Fig. 2. Overview of the review paper's structure.

enhance their overall performance and sustainability.

Fig. 2 depicts an overview of the review paper's structure, including the major parts and key subjects discussed.

2. Impact of temperature on battery performance

Different types of batteries could be utilized as energy sources in EVs or HEVs, including Lead-Acid, Lithium-ion (Li-Ion), Rechargeable Alkaline, Nickel-Cadmium (NiCd), and Nickel-Cadmium Hydride (NiMH). Comparing the various batteries in terms of specific power and energy, the promising capability of Lithium-Ion batteries (LIBs) is evident for providing higher specific energy and power density [29]. Moreover, vital properties of LIBs, such as no memory effect and lower self-discharge, make LIBs an efficient and reliable energy source for

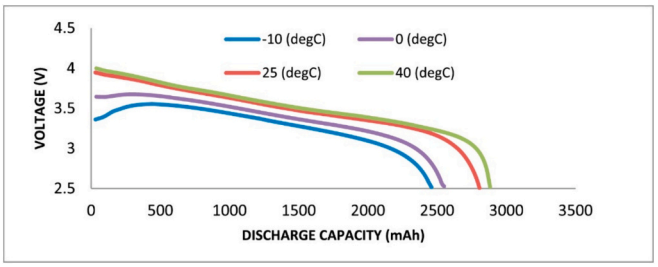


Fig. 3. Thermal dependence of discharge characteristics for 18,650 cells [12].

practical usage in EVs or HEVs. In addition, the Li-ion battery is comprised of eco-friendly elements with no gassing issues and a high level of safety [30].

At low temperatures, battery performance is significantly diminished, limiting their use in cold locations and at high altitudes. Charge acceptance, energy and power capacity, round-trip efficiency, and lifespan of the batteries are affected in low temperatures [31,32]. Moreover, the power and energy of the LIB also decline in low temperatures. It is reported that at −40 °C, compared to 20 °C, LIB could only provide 1.25 % and 5 % of its power and energy density, respectively [31]. Also, at low temperatures, notably below 0 °C, the LIBs age quicker. For instance, a 11.5 Ah Li-ion cell could lose 25 % of its capacity after only 40 cycles at −10 °C [33]. Due to the increased viscosity of the electrolyte when the temperature is too low, the lithium-ion diffusion rate in the electrolyte falls significantly, resulting in a considerable rise in the internal resistance. The amount of lithium-ions participating in the reaction diminishes, directly affecting the storage and release of electricity. Thus reducing the battery's power and capacity [34]. In addition, lithium dendrites may penetrate the film during low-temperature charging, resulting in an internal short circuit, which affects its optimal protection [35]. Lastly, there may be large temperature differences between different regions of the battery pack. The non-uniform temperature distribution within the battery pack can result in local deterioration.

LIBs can also experience performance issues at high temperatures. Firstly, Lithium burns easily and is chemically highly reactive. Considering a battery pack with various cells connected in series or parallel, overheating of even a single cell can easily impact the other cells. This could result in combustion, explosion, or the release of toxic gases such as CO, C_2H_4, H_2S, and HF [36]. Additionally, due to the complex internal power circuit construction of LIB packs, short circuits may occur at high temperatures [37,38]. The capacity and lifespan of LIBs are also diminished by high temperatures [39,40]. According to a study, 800 cycles at 45 °C result in a 36 % capacity loss for Sony 18,650 batteries, and 490 cycles at 55 °C cause a loss of >70 % capacity [41]. A serious safety risk for LIBs at high temperatures is thermal runaway. It is divided into three phases, initial thermal runaway regime, cell venting and runway, and explosive decomposition reaction [42,43].

In addition to low and high-temperature performance, a consistent temperature distribution is essential for the efficient operation of batteries. Due to differences in geometric characterization and thermal physical properties of the material within the battery cell, temperature gradient is expected when heat is generated in all components and transferred in all directions [44]. The temperature is found to be higher in the vicinity of the electrode [45]. Such an uneven temperature distribution would result in non-uniform electrode reaction rates [46], which will subsequently degrade cell performance and cycle life [47]. Literature indicate that a 5 °C rise in temperature difference may result in a capacity loss of 1.5–2 % [48] and a degradation of approximately 10 % of its power capability [49]. Also, the impact of various operating temperatures on lithium-ion battery discharge capacity is depicted in Fig. 3.

According to the literature, the optimal operating temperature range

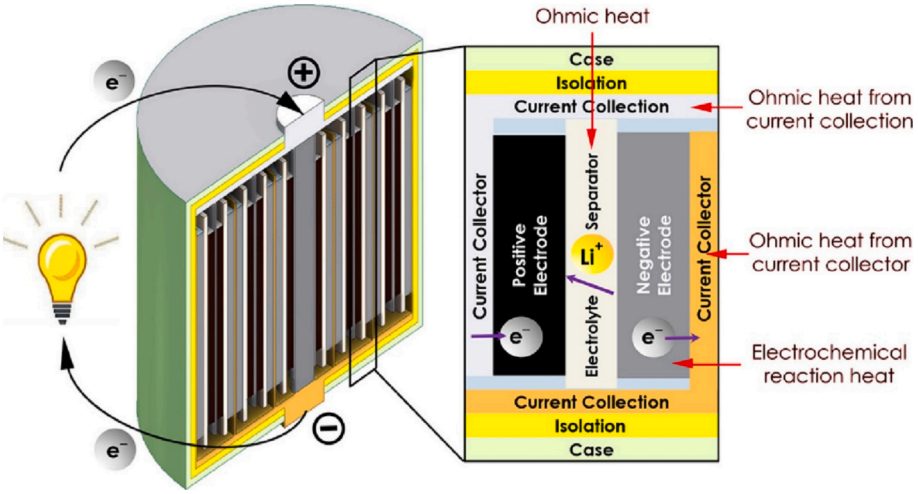


Fig. 4. Schematic of different heat generation forms in LIB [66].

of the battery is 15 °C to 35 °C [50] or 20 °C to 40 °C [51–53], 20 °C to 50 °C [54,55]. Also, the maximum temperature difference (ΔT_{max}) among modules should be <5 °C to maintain a uniform temperature distribution [6,52,53]. Concurrently, the highest safety limit under normal working conditions is regarded as 60 °C [54]. Therefore, a sufficient cooling approach must be considered to avoid the mentioned problems and satisfy the required operating temperature range.

3. Lithium-ion battery heat generation and modeling

To construct an effective BTMS, it is necessary to consider the quantity of different forms of generated heat in LIBs (Fig. 4). Even though heat generation during the discharging phase is greater than the charging process, thermal failure of LIBs is more likely to occur during the charging phase. This is due to the rapid increase in temperature and non-uniform heat generation [56]. According to the different modeling methodologies, battery modeling comprises the electrochemical and electrical equivalent circuit models [57]. The electrochemical model offers detailed insight into a cell's electrochemical reactions and actions through a set of partial differential equations. In general, the electrochemical model can include the single particle model (SP model), the porous electrode model with polynomial approximation (PP model), or the pseudo-two-dimensional model (P2D model) in ascending order of complexity. Although the electrochemical model is accurate, it is complicated and requires highly expensive computational resources to solve the nonlinear differential equations. This makes it inapplicable to the intended application of assessing power and dynamic systems. The electrical equivalent circuit model is another viable method that ignores the complicated electrochemistry of the cell and places basic electronic components, including capacitors and resistors, in a circuit [6]. By incorporating more electronic components, such as Thevenin-based models, Impedance-based models, Runtime-based models, Combined electrical circuit-based models, and Generic-based models, the electrical equivalent circuit model's precision and fidelity can be improved [57]. Numerous review articles have been published on the thermal modeling of batteries [57–65]. Summary of common battery thermal models is demonstrated in Table 1.

Numerous studies also employ a model based on the energy equation balance represented in eq. 1, which incorporates heat stored by the cell (the left side of the equation) as well as heat generated and dissipated. As depicted in Fig. 5, the total heat generation consists of reversible and irreversible terms [67]. The first model for heat generation within a battery was established by Bernardi et al. [68], which included heat generation due to electrical power, the enthalpy of reaction, the heat produced through mixing, and material phase change. The popular simplified form in the literature, which disregards the mixing and phase change effects, is represented in eq. 2, where U and V stand for the open-circuit voltage and operating voltage, respectively. $I(U-V)$ and $IT\left(\frac{\partial U}{\partial T}\right)$ represent the heat generated due to Joule heating and entropy change, respectively.

$$mC_p\frac{dT}{dt} = Q_{gen} - Q_{dis} \tag{1}$$

$$Q_{gen} = I(U-V) - IT\left(\frac{\partial U}{\partial T}\right) \tag{2}$$

An experimental study by Jindal et al. [69] compared the accuracy of the heat generation estimated by the Bernardi model in continuous and pulse discharge of the Li-ion battery. The obtained results indicated an acceptable estimation by the Bernardi model for continuous discharge. However, the values predicted by this model for pulse discharge were found to be higher compared to direct experimental measurements.

Battery thermal performance can be simulated using a thermal model with 1-D, 2-D, or 3-D geometries, which can be thermally connected or dissociated with electrochemical/electrical forms [70]. A lumped-parameter model (1-D) can be established on the assumption that the battery temperature is spatially homogeneous during the heat transfer process. This approximation method's practicality depends on the Biot number (*Bi*), which is the ratio of the battery's internal heat transfer resistance to its surface heat exchange resistance. *Bi* must be <0.1 for the lumped-parameter model to be deemed acceptable [6,71]. It is a common assumption in various numerical studies in literature to consider constant heat generation. In other words, the mentioned assumption ignores heat generation due to entropy change in eq. 2. However, it should be considered carefully to achieve accurate numerical results. Various experimental investigations [72–78] have reported the non-uniform heat generation and temperature distribution of the LIBs. An experimental investigation by Rizk et al. [72] reveals the fact that the share of Joule and entropy heating are different for various C rates. They reported that entropic heat cannot be ignored since it accounts for around 50 % of the total heat produced at a 2/3C current rate. In contrast, at 1C, the contribution of reversible heat is approximately 39 % and considered less significant. Thus, the greater the current, the less substantial the reversible heat.

In contrast to different studies that ignore the second term of eq. 2 (reversible part of the Bernardi model) or assume constant heat generation, various investigations have been carried out to develop models based on the temperature, state of charge (SOC), and depth of discharge (DOD), to model LIB in a more realistic way [55,79–82]. In addition,

Table 1
Summary of various Lithium-ion battery thermal models.

Thermal analysis models	Key modeling parameters	Model contributions and insights
Single Particle Model (SP Model) [98]	Open circuit potential, electrochemical reaction rate constants, diffusion coefficient	- Predicts temperature distribution and highlights thermal gradients. - Guides improved heat dissipation design. - Contributes to safer battery design through thermal runaway simulation. - Evaluates cooling strategies for thermal management integration.
Porous Electrode Model [61]	Electrochemical kinetics, material thermal properties, electrode structure (porosity, tortuosity), heat generation sources (Joule heating, reaction enthalpy)	- Explores porous electrode impacts on performance. - Enhances electrochemical process understanding. - Aids in optimizing electrode structure for better heat management.
Pseudo-Two-Dimensional Model (P2D Model) [99]	Electrochemical reactions, diffusion processes, current distribution	- Incorporates spatial dimensions in simulations. - Offers a comprehensive battery behavior framework. - Useful for detailed battery performance analysis and optimization.
3D Pseudo-Electrochemical-Thermal Model [100]	Mass charge, electrochemical kinetics	- Evaluate current collecting tabs' effects on heat generation. - Offers insights into temperature distribution variations. - Supports comprehensive thermal analysis and battery design improvement.
Electrical Equivalent Circuit Model [101]	Capacitance, resistance, SOC, DOD	- Translates complex electrochemical processes into simpler electrical components. - Facilitates system-level simulations. - Enhances SOC and DOD estimation accuracy.
Mesoscale Electro-Thermal Model [102]	Current, terminal voltage, open-circuit voltage, entropy coefficient	- Focuses on electro-thermal interaction assessment. - Identifies heat generation distribution inside the battery. - Supports thermal management system design.
1D Thermal Mathematical Model [60]	Heat generation parameters, discharge rates, cell capacity and geometry, thermal properties	- Simplifies temperature profile analysis inside the cell. - Focuses on quantifying heat generation aspects. - Assists in basic thermal management strategies.
Finite Element Thermal Model [103]	Physical structure, electrochemical reactions	- Leverages structural insights for temperature distribution exploration. - Facilitates detailed structural and electrochemical interaction analysis. - Enhances design for improved thermal performance.
Kalman Filter Based Electrochemical Model [104]	Butler-Volmer current, microscopic solid material electrolyte concentration, current density	- Integrates electrochemical principles for accurate SOC estimation. - Offers a methodological approach to understanding internal battery reactions. - Useful for dynamic systems analysis and predictive modeling.
Thermal-Electrochemical Coupled Model [105]	Current density, temperature	- Analyzes the dynamic interplay between current and temperature distribution. - Combines thermal and electrochemical dynamics for a holistic understanding. - Aids in the development of advanced thermal management solutions.
3D Thermal Model [106]	Location-dependent convection and radiation	- Investigates the role of spatial thermal influences on temperature distribution. - Offers insights into asymmetric temperature distribution challenges. - Enhances thermal management strategies for uniform heat dissipation.
Bernardi Model [68]	Electrical power, enthalpy of reaction, heat through mixing, material phase change	- Baseline for heat generation understanding. - Simplifies electrochemical interactions. - Highlights the importance of material phase changes in heat generation.

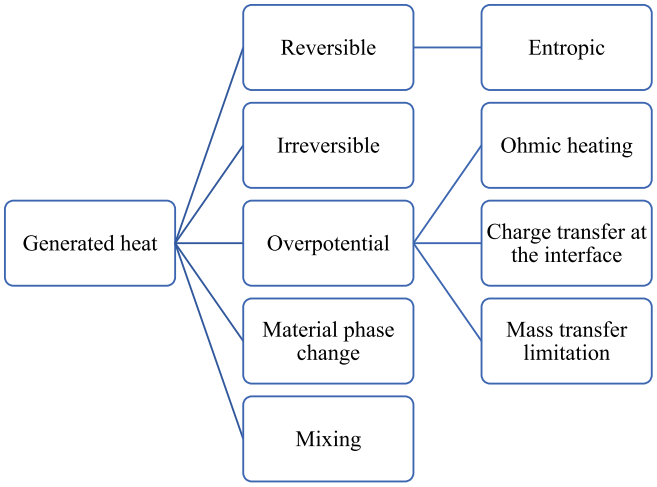


Fig. 5. Heat generation in LIBs [67].

some investigations [83–85] highlighted that the axial and radial thermal conductivity of the cylindrical lithium battery are not the same due to material composition differences in various directions.

According to the investigation by Karimi et al. [79], eq. 2 for a 18,650 Li-ion battery can be redefined as follows:

$$q_{gen} = Ri^2 - T_b \Delta S \frac{i}{nF} \tag{3}$$

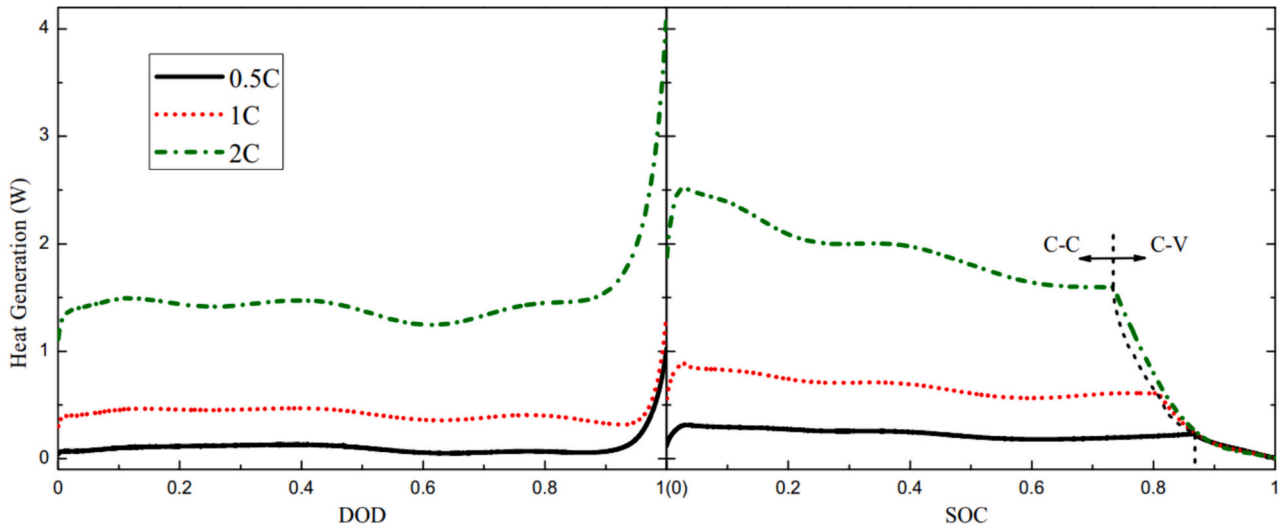


Fig. 6. Single battery heat generation during discharge-charge cycles at 25° C [82].

where *i* and n are the discharge current per unit volume and the number of electrons in reactions, respectively. F, $\Delta S\left(\frac{J}{mol.K}\right)$, T_b, and R are the Faraday constant, the entropy change, the temperature of the battery unit, and the resistance of the battery, respectively. Empirical relations for resistance of the battery based on temperature and SOC are as follows [79]:

$$\begin{aligned} R &= 2.258\times10^{-6}SOC^{-0.3952}\ T=20^{\circ}C\\ R &= 1.875\times10^{-6}SOC^{-0.2787}\ T=30^{\circ}C\\ R &= 1.659\times10^{-6}SOC^{-0.1692}\ T=40^{\circ}C \end{aligned} \tag{4}$$

The entropy change term based on SOC is as follows [79]:

$$\begin{aligned} \Delta S &= 99.88\times SOC-76.67 & 0\le SOC\le 0.77\\ \Delta S &= 30 & 0.77\le SOC\le 0.87\\ \Delta S &= -20 & 0.87\le SOC\le 1 \end{aligned} \tag{5}$$

Wang et al. [83] also developed an experimental correlation for predicting a 18,650 Li-ion battery's internal resistance as follows:

$$R_i = 0.0852+0.00623sin\frac{\pi(SOC-0.23727)}{0.18} \tag{6}$$

Cao et al. [86] also expressed the Bernardi equation for a 18,650 Li-ion battery as follows:

$$Q_{gen} = \frac{I(U-E)}{V}-I\frac{T\Delta S}{V} \tag{7}$$

where V and T are the volume and temperature of each battery. ΔS is determined as a correlation by Onda [87] based on DOD as follows:

$$\Delta S = \left(110.8\times DOD^3-229.1\times DOD^2+64.3\times DOD-11.4\right)F \tag{8}$$

E for charge and discharge of a 18,650 Li-ion battery is defined as follows based on an experimental investigation by Ling et al. [55]:

$$E_{discharge} = -5.50\times DOD^4+8.65\times DOD^3-3.69\times DOD^2+0.45\times DOD+4.12 \tag{9}$$

$$E_{charge} = -28.67\times DOD^6+73.93\times DOD^5-73.96\times DOD^4+35.05\times DOD^3-6.95\times DOD^2-0.5\times DOD+4.23 \tag{10}$$

Different experimental investigations have been carried out to measure the resistance and entropy coefficient of the 18,650 Li-ion battery [88–90].

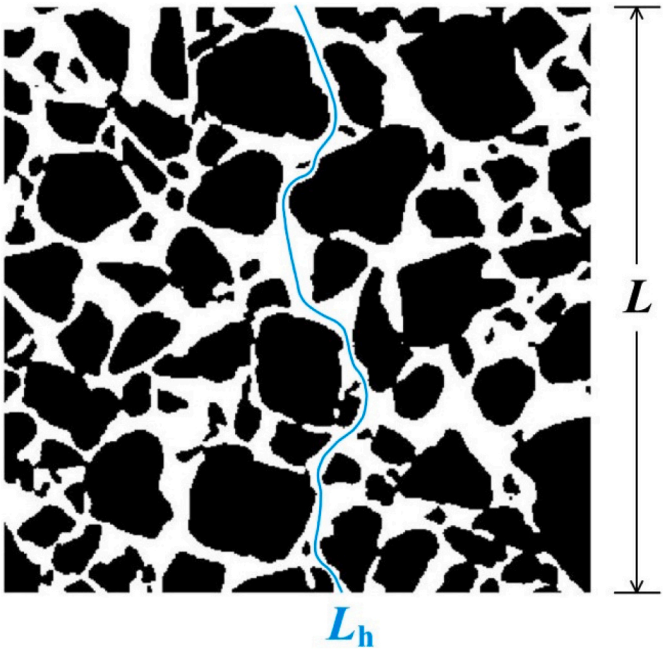


Fig. 7. Definition of the tortuosity in porous media [110].

As shown in Fig. 6 and according to the mentioned models, the heat generation rate is found to be varied during the discharge (left side of Fig. 6) and charge (right side of Fig. 6). Also, charging process involves constant current (C—C) and constant voltage (C—V) stages. Considerable experimental investigations have been done to measure the heat generation rate based on methods such as accelerated-rate calorimetry (ARC) [91–94], radiation calorimetry (RC) [87], intermittent current and V—I characteristics methods [95], and isothermal heat conduction calorimetry (IHC) [96,97].

4. Porous media and metal foams in BTMS

A porous medium is a solid matrix with a large number of randomly linked cavities or pores. They are dispersed in a random manner, devoid of any obvious pattern. Several characteristics distinguish the qualities of porous materials, including their porosity, permeability, effective thermal conductivity, and tortuosity [107,108]. Porosity is defined as

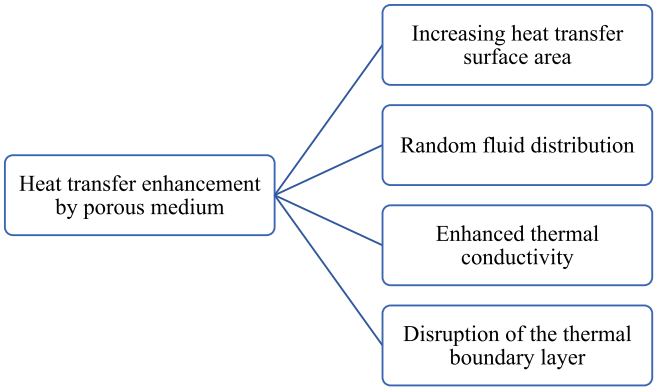


Fig. 8. Heat transfer enhancement afforded by porous media.

the fraction of porous matrix cavities to the entire volume of porous media, which includes pores and solid matrix. Some of the mentioned cavities could be disconnected from others, while others are linked. Since the disconnected cavities have a minor impact on the performance of the porous media, another parameter, effective porosity, is defined as the ratio of the interconnected voids to the total volume of porous media. A porous medium's permeability is dictated by the number and type of pathways inside its structure that allow fluids to move through it. More permeable porous media will enable fluids to sink into more deeply embedded layers within the porous medium. Porosity, the geometry and the size of voids, and the connectivity of voids are all structural characteristics that affect permeability. The porosity of the porous medium and the thermal conductivity of both the solid and fluid phases are key determinants of the thermal conductivity of porous media, which is mainly considered as effective thermal conductivity. As shown in Fig. 7, the tortuosity parameter is defined as the ratio of the pathway of the fluid molecules in porous media to that of in a non-porous medium [109].

4.1. Heat transfer mechanisms and improvement offered by porous media

As shown in Fig. 8, the enhancement of heat transfer processes through porous media occurs through a complex interaction between the structural properties of the medium and their underlying dynamic thermal characteristics. The key aspect of this phenomena is the ability of the porous structure to significantly increase the surface area for heat exchange. The presence of ligaments within the porous media, which creates an extra heat transfer surface in an identical volume compared to the absence of a porous medium, causes the fluid to move through with greater heat exchange. This allows for a more effective thermal interaction between the fluid and the solid matrix [111]. Furthermore, the concept of thermal dispersion conductivity [112,113] plays a crucial role by adding an additional conductive pathway to the porous material's base thermal conductivity through the process of thermal dispersion. This enhances the combined thermal conductivity, therefore improving the overall efficiency of the heat transfer process. Moreover, the porous medium's tortuous pores result in random fluid distribution, which also enhances heat transfer [107].

Porous media offer superior thermal conductivity compared to fluids due to the presence of a solid phase in their structure. The improvement in performance is mainly due to the enhanced thermal pathways enabled by the solid structure integrated into the porous structure. The solid ligaments within the porous medium, frequently consisting of materials with high thermal conductivity, have a significant impact on enhancing the overall heat transfer process. Thermal energy is conducted more effectively compared to the fluid phase. This process of conduction, in addition to the convective heat transfer facilitated by fluid flow through the pores, results in a combined effect that significantly enhances the rate of heat transfer [111,114]. Also, the existence of ligaments disrupts the formation of the thermal boundary layer, which always diminishes the fluid flow mixing. The mixing of the fluid flow could be increased by porous media, which results in a higher heat transfer rate [107,115].

The presence of porous media can have a substantial impact on the heat transfer processes in both BTMS and HBTMS, hence enhancing the effective thermal management of batteries. The presence of interconnected gaps or cavities in the porous structure facilitates several heat transfer mechanisms within the system.

Different heat transfer mechanisms could be anticipated in PCM-based BTMS with porous media. Prior to the commencement of the melting process in the phase change material (PCM), conduction acts as the prevailing mechanism for heat transfer. However, once the process of melting commences, a combination of heat transfer by conduction and natural convection becomes dominant [116]. The insufficient heat transfer during high charge or discharge rates is a major obstacle caused by the limited thermal conductivity of pure PCMs [117]. This constraint leads to an uneven distribution of temperature and problems such as as heat accumulation [21]. An effective approach to improve the thermal conductivity of various types of phase change materials (PCMs) is by incorporating porous media or foams to create composite PCMs (CPCMs) [118]. Incorporating porous media greatly enhances the thermal conductivity of the phase change material (PCM). Furthermore, the metal foam's porous structure allows for the absorption of the molten liquid phase change material through capillary force. This absorption process helps maintain the stable shape and structure of the PCM [119]. The inclusion of porous media in the melted PCM region can augment the buoyant force by elevating thermal conductivity, hence significantly influencing the circulation of liquid PCM by natural convection. The foam with a reduced pore density has wider pores to promote natural convection, thereby boosting the heat transfer rate at the interface between the mushy and liquid areas and accelerating the liquid motion in the mushy zone [116]. Therefore, CPCM is anticipated to exhibit greater natural convection than PCM. Furthermore, pore-scale convective heat transfer in CPCM can be accomplished [120], which increases the local heat transfer rate, especially in the vicinity of the battery. Nevertheless, some studies [121–123] have documented that porous media might hinder natural convection by impeding the flow of liquid PCM.

The limitations of convection heat transfer by air cooling in BTMS, which include low thermal conductivity, specific heat capacity, and heat transfer coefficient, can be mitigated to a certain extent by integrating porous foams. To enhance the thermal performance of the battery pack, porous material could be introduced fully or partially to the BTMS's heat sinks or airflow channels [124]. Additionally, the inclusion of porous medium [125] could lead to improved air distribution. The porous medium provides a larger effective heat transfer surface with higher thermal conductivity compared to air. Additionally, it enhances turbulent flow and mixing near the battery cells. The presence of porous media disrupts the thermal boundary layer, hence increasing the overall rate of heat transfer [126]. Similarly, for the convention in liquid cooling-based BTMS, the insertion of a porous layer or obstacles could affect the reformation of the thermal boundary layer. The presence of porous media in the cooling channels can introduce additional crossflow mixing effects that may disrupt the establishment of the thermal boundary layer. The aforementioned occurrence has the potential to mitigate the undesirable temperature rise of the coolant along the channel. Hence enhancing heat transfer and improving cooling efficiency [111,127]. In addition, the desired temperature can be reached with reduced flow rates when porous material is used in cooling channels. However, it is important to take into account the increased pressure drop due to the porous media [127,128].

4.2. Impact of porous media type and properties on BTMS performance

Regarding the impact of the porous media and foam properties on the heat transfer, opposing ideas exist on how higher porosity impacts the heat transfer rate [129,130]. Limiting the literature on investigations

Table 2
Thermophysical properties of porous materials.

Material	ρ (kg/m^3)	C_p (J/kg.°K)	K (W/m.°K)	Ref.
Aluminum foam	2719	871	202.4	[153]
Copper foam	8978	386	398	[154]
Aluminum oxide foam	3891	765	35	[155]
Nickel foam	8907	442	82	[156]
Graphite foam	2130	700	1700	[157]
Silicon Carbide	3210	700	430	[158]
CF-20 (Carbon foam)	250	750	3.1	[159]
KL1–250 (Carbon foam)	240	884	40	[159]

that have been carried out on BTMS, one can conclude that higher porosity leads to lower heat transfer, thus higher maximum temperature (T_{max}) and maximum temperature difference (ΔT_{max}) within the battery pack [131–133]. The mentioned fact above may be due to the decrease of the solid matrix with higher thermal conductivity in porous media, resulting in reduced effective thermal conductivity and decreased heat transfer [107]. Many researchers, such as [134–136], also highlighted the importance of looking for optimum porosity. Porous media with higher permeability tends to provide better heat transfer due to better fluid flow and more contact with the cooling fluid. Considering the impact of the applied porous media and foams in BTMS, studies proved the positive impact of high permeability on decreasing the T_{max}. However, some investigations mentioned higher ΔT_{max} for high values of permeability [132,133,137]. Generally, the rate of heat transfer improves as the tortuosity parameter increases [138] since there is additional time for heat transfer between the fluid and solid matrix [107].

Porous media is used mainly as metal and carbon-based foams in battery thermal management systems. Common porous media utilized in BTMS are listed in Table 2. The distribution of various foams employed by researchers to enhance the heat transfer is demonstrated in Fig. 9. As shown, almost one-third of the investigations are carried out using copper foam. Copper foam plays a crucial role in the development of BTMS. Studies conducted by Tian and Zhao [139,140] have shown that copper foams, with their distinctive porous structure and excellent thermal conductivity, have a substantial effect on improving heat transfer rates in phase change materials (PCMs). The improvements, which can be as high as 20 times when compared to pure PCM, demonstrate the significant impact that copper foams can have on enhancing thermal performance. Additional conducted investigations emphasize the subtle impact of copper foam characteristics, particularly porosity and pore density, on the effectiveness of heat transfer [141–143]. Aluminum foam is also known for its low weight and exceptional heat transfer ability. The distinctive porous configuration of aluminum foam offers a substantial surface area for excellent heat transfer, guaranteeing cooling throughout the process of both charging and discharging. Studies conducted by Zhang et al. [67] and Hong and Herling [71] have shown that aluminum foam has a beneficial effect on lowering melting times in BTMS with PCM and enhancing the overall heat transfer efficiency of BTMS [144,145]. Although aluminum foam has limits in high-temperature applications, it continues to be an important component in BTMS. It provides a dependable and efficient option for addressing thermal issues in advanced battery systems [146]. Nickel foam, despite its relatively low thermal conductivity (89 W/m-K), plays a pivotal role in enhancing heat transfer rate due to its significantly higher melting point (1455 °C) which makes it suitable for high-temperature applications [147]. The graphite foam's high melting temperature, exceeding 400 °C [148], makes it well-suited for BTMS applications, particularly in PCM-based systems. This allows for improved heat transfer rates while also accommodating the high melting point. The natural permeability of graphite foams enhances their surface area, hence greatly enhancing heat transfer. Nevertheless, with PCM-based BTMS, this enhancement comes with trade-offs, such as reduced latent heat, melting, and solidification rates of the PCM [149,150]. Among the carbon-based foams, extended graphite has gained greater attention, especially in BTMS with PCM, since the thermal conductivity of the PCM-based BTMS could be enhanced without increasing the density [147]. The mentioned fact is due to the expanded graphite's very high porosity [151].

Moreover, a particular type of metal foam coated with carbon-based material has also been considered in BTMS. Hussain et al. [152] experimentally investigated the graphene-coated nickel foam thermophysical properties and performance in BTMS saturated with paraffin. They reported considerable enhancement of thermal conductivity and cooling performance of the BTMS.

Specific results of the impact of porous media type and properties on BTMS performance are summarized in Fig. 10.

4.2.1. Recent application of porous media and foams in different types of common cooling methods in BTMS

Considering the application of porous media and foams with different methods of cooling, it should be mentioned that more investigations have been done in PCM-based BTMS compared to other methods, since the porous media could resolve the low thermal conductivity issue of PCMs [16].

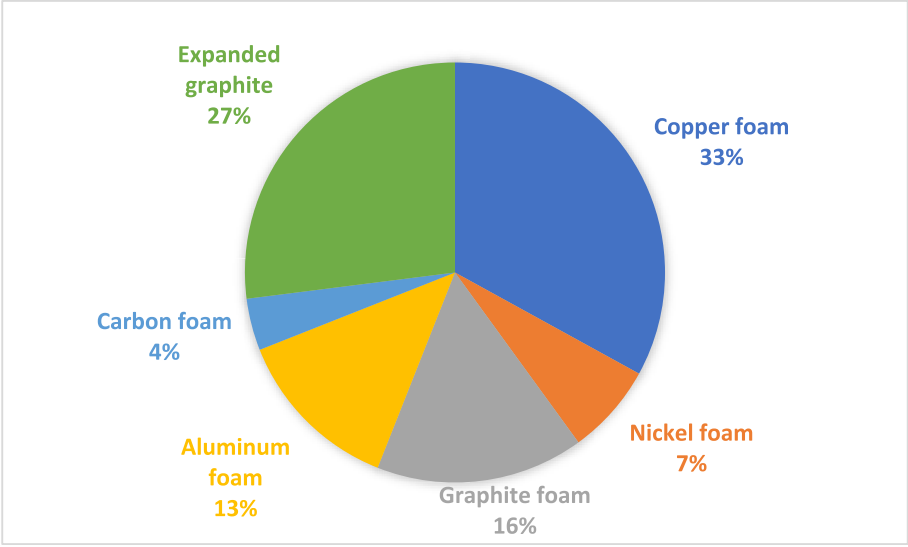


Fig. 9. Distribution of application of different foams in the literature for heat transfer enhancement [147].

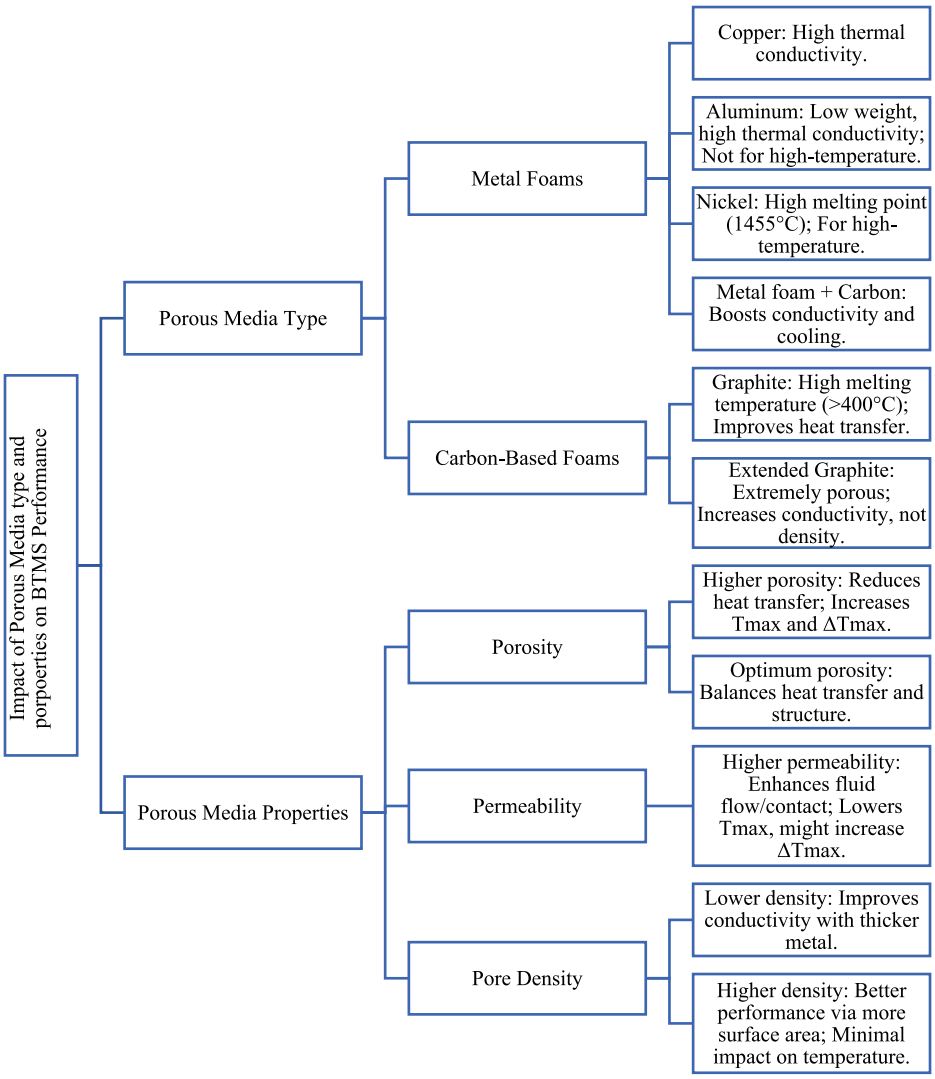


Fig. 10. Impact of porous media type and properties on BTMS performance.

In terms of air cooling, Bashiri et al. [85] numerically investigated a novel BTMS based on air cooling for 18,650 Li-ion batteries. The batteries are covered with different types of porous media, including aluminum foam, copper foam, silicon carbide, aluminum oxide, and graphite. Their finding indicated a significant decrease in the highest temperature of the battery pack following the implementation of porous media. Graphite exhibited remarkable performance, resulting in a decrease of 4 °C in T_{max}. The results highlighted the balance between reduced maximum temperature and increased pressure loss in the battery pack. Wang et al. [160] conducted a numerical analysis on a prismatic Li-ion battery cell cooling using aluminum foam. The study emphasized the influence of porosity on battery temperature, demonstrating that a decrease in porosity leads to a lower average temperature. Nevertheless, the temperature gradient intensified in lower porosity values. Wang et al. [161] performed numerical simulations to study a BTMS that consists of $LiFePO_4$ pouch cells and aluminum foam. The results indicate that changing the porosity of the aluminum foam has an impact on the average surface temperature of the battery, showing a drop as the porosity decreases. Nevertheless, this decrease was accompanied by a simultaneous increase in the maximum temperature difference.

Recent studies emphasize the potential uses of porous media in liquid cooling BTMS, demonstrating improved heat transfer and energy efficiency in several battery types. In the numerical study conducted by Rabiei et al. [162] a BTMS based on water, aluminum, and a wavy microchannel is developed for prismatic $LiFePO_4$ batteries. Implementation of this design led to a significant decrease in the amount of energy required for pumping, ranging from 50 % to 73 %. Incorporating a thin layer of metal foam resulted in a 50 % reduction in pumping power required to achieve the same temperature range compared to a channel without a porous insert. Their findings highlight the possibility of improving the efficiency of pumping power and temperature regulation in liquid-cooled battery systems by using innovative porous media configurations. Ki et al. [127] experimentally and numerically investigated the application of water and aluminum foam in BTMS with pouch-type lithium-ion batteries. Their novel design effectively demonstrated the distribution of coolant and improved thermal spreading effects. By implementing porous media, the highest temperature is reported to be 43.3 °C, with a maximum temperature difference of <2 °C, while consuming only 3 L/min of water. The study highlighted that the inclusion of a porous metal layer not only augmented the surface area for heat exchange, but also reduced the barrier to thermal dispersion. By adjusting the geometric parameters of the channel and the physical properties of the porous aluminum layer, the thermohydraulic performance is further improved. This resulted in a reduction in vortex formation within the liquid flow path. Xu et al. [163] employed water and expanded graphite in an experimental liquid cooling module with square lithium iron phosphate batteries. The obtained results

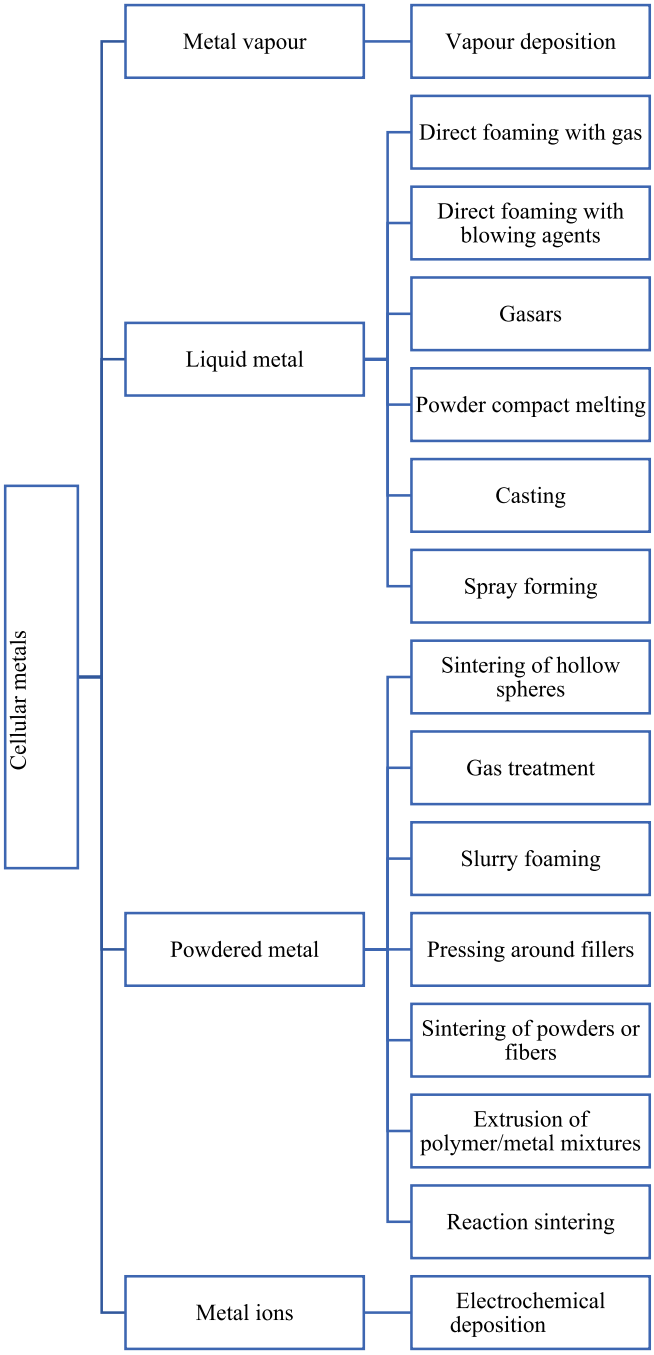


Fig. 11. Various methods to manufacture metal foams [169].

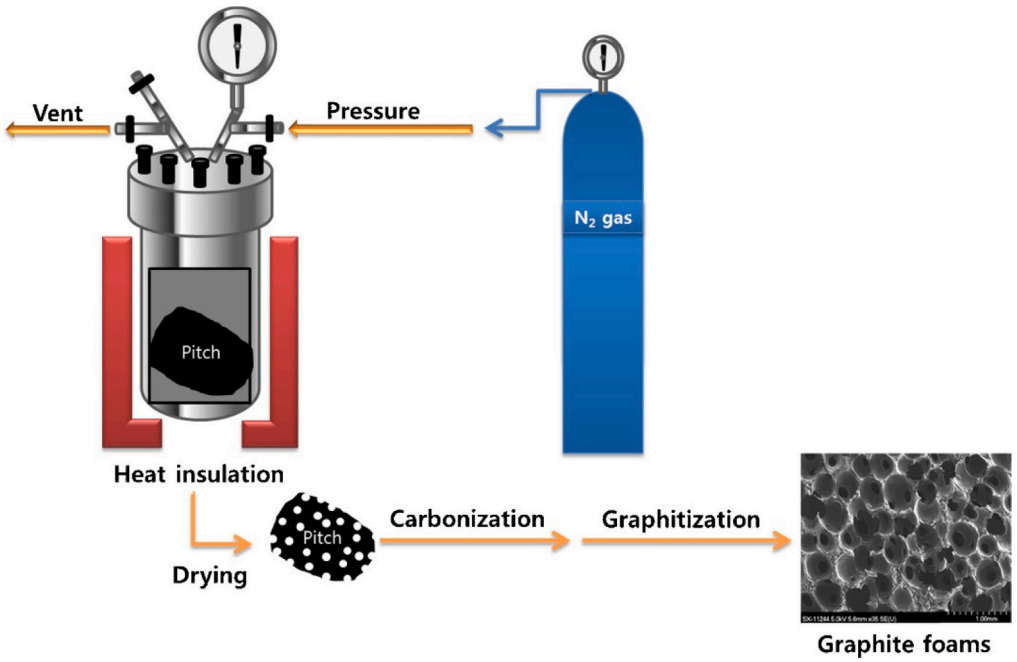
demonstrated that at a water flow rate of 0.8 m/s, the BTMS is able to keep the T_{max} below 42.7 °C and maintain ΔT_{max} under 2.7 °C at a discharge rate of 4C. The incorporation of expanded graphite (EG) and copper foam into silica gel (SG) effectively facilitated the generated heat to copper tubes, demonstrating the capability of porous materials, specifically expanded graphite, in attaining efficient heat dissipation.

Recent investigations have revealed the potential uses of porous materials in HBTMS, which involve a variety of batteries and coolants. The focus has been on numerical and experimental approaches to comprehend the complex interaction between porous materials, coolants, and the performance of HBTMS. Khaboshan et al. [164] numerically studied 18,650 Li-ion batteries HBTMS, involving four copper fin, n eicosane (PCM), and copper foam. The proposed HBTMS could decrease battery surface temperature by 3 K. The affixed fins acted as a network of heat sources, facilitating effective heat distribution throughout the system's core. Zhao et al. [165] studied an HBTMS with 18,650 Li-ion batteries considering water, paraffin, and copper foam, employing both experimental and numerical analyses. The obtained results indicated that increased Reynolds numbers (*Re*) resulted in variations in temperature throughout the battery pack. Nonetheless, as *Re* escalated to 112, T_{max} decreased by 6 K, but at the expense of an increase in pump power. Liu et al. [166] investigated a battery pack of 18,650 Li-ion batteries considering an HBTMS based on water, PCM, and copper foam. Their numerical analysis demonstrated that the hybrid system substantially decreased temperatures compared to natural convection. The research underscored the significance of flow velocity in determining temperature stability, thereby emphasizing the possibility of effective heat dissipation. Kiani et al. [167,168] experimentally investigated the application of nanofluids and paraffin in conjunction with copper foam as an HBTMS. Their findings demonstrated that the combination of paraffin's high latent heat and copper foam's enhanced thermal conductivity resulted in a decreased rate of temperature increase. Moreover, the inclusion of a magnetic field significantly augmented the effectiveness of the HBTMS.

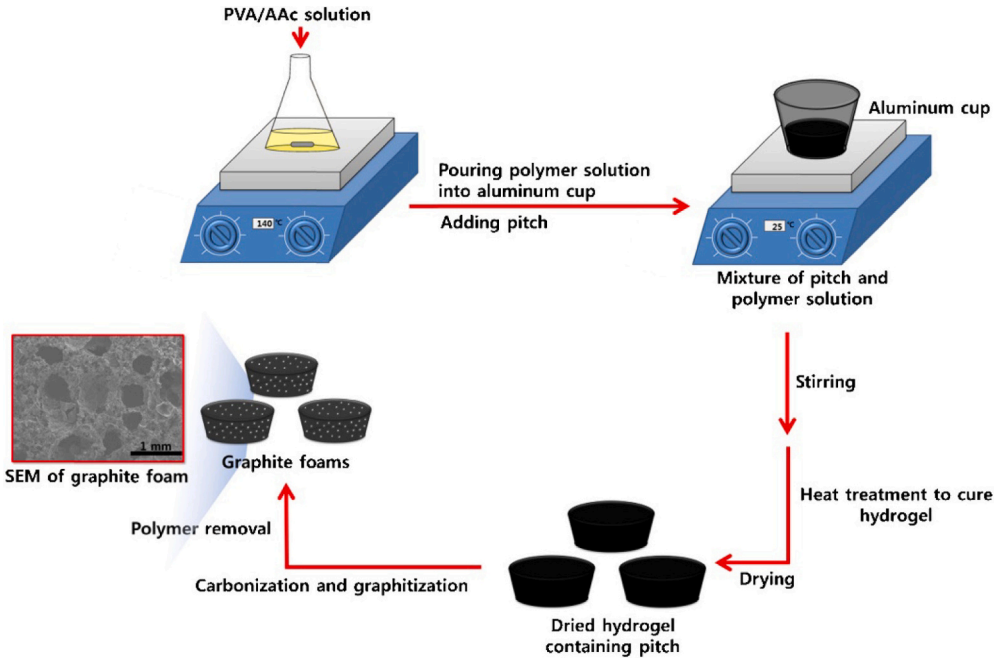
4.3. Porous material production and preparation

As shown in Fig. 11, various methods have been reported in the literature to produce metal foams that could impact their physical properties. According to [169], methods for producing porous metal foams are often categorized based on the original condition of the metal: liquid, solid, metal vapor/gas, or metal ion solution. The initial liquid-state production method includes solid–gas eutectic solidification, powder metallurgy, investment casting, space-holder casting, and osprey process. Each of the mentioned methods produces porous media with different porosities. Solid–gas eutectic solidification is reported to have the widest range of porosity of 5–95 %. Investment casting allows for the creation of intricate structures by pre-shaping polymer foam. Space-holder casting could be used to manage the distribution of pores. Solid-state production involves sintering metal powder/fiber, slurry foaming, pressing around space-holder fillings, and sintering metallic hollow spheres. A large porosity range could be obtained by slurry foaming and pressing around space-holder fillings. The sintering of metallic hollow spheres method is found to produce a more uniform distribution of pores. The vapor state approach involves the vapor deposition method, which is appropriate for producing porous media with a high porosity of 92–95 %. The final category, the ionic state, is associated with the electro-deposition process, which is able to provide porous media with a customized pore morphology [170]. The mentioned methods of production can result in open-cell or closed-cell pores. Closed-cell porous foam could be obtained by the powder metallurgy or sintering of metallic hollow spheres methods. Considering the application in BTMS, open-cell porous foams are preferred. More details about the production methods of metal foams could be found in [171,172].

The manufacturing process of porous carbon foams with high thermal conductivity involves employing a range of methods and approaches to attain desired characteristics that are crucial for their utilization in thermal management systems, energy storage, and other industrial applications. A common approach is integrating other components, such as natural graphite, carbon nanotubes, and carbon nanofibers, into the precursors of carbon foam. This leads to increased physiochemical properties and improved thermal conductivity [173–175]. Ensuring the appropriate inclusion of thermally conductive additives is essential for enhancing both the overall thermal conductivity and mechanical strength [176]. It is crucial to thoroughly evaluate how additives will affect the characteristics of carbon foams since they alter the porous structure of these materials [176]. Templates offer other common approach to produce carbon foams with exceptional thermal conductivity. The utilization of metal foams as templates for the creation



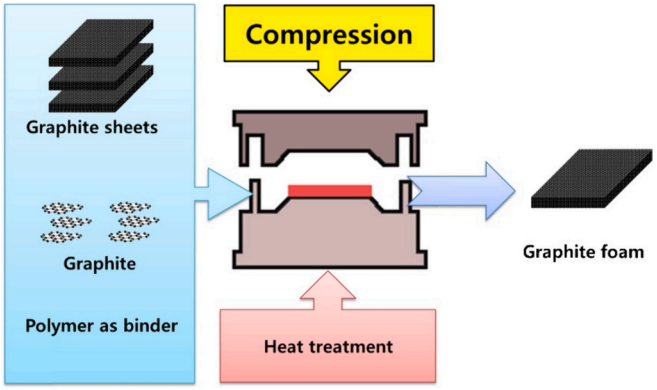
(a)



(b)

Fig. 12. The procedure for producing graphite foams; (a) blowing technique [184], (b) polymer-based template approach [188], and compression of graphite and/or graphite sheets [163].

of graphene foam using chemical vapor deposition is effective in producing the required porosity and thermal conductivity [177]. In addition, the utilization of polymers as templates involves immersing porous polymers in a dispersion of carbon foam precursor. This process allows to produce carbon foams with a high degree of crystallinity after undergoing carbonization and graphitization [178]. The application of these approaches is crucial for improving the thermal conductivity, mechanical strength, and porous structure of carbon foams, thus making them highly adaptable materials for a wide range of applications [176]. Carbon foams are prepared using diverse approaches to regulate cell structure and physical properties. The addition of graphite particles to mesophase pitch, together with subsequent processes of blowing, carbonization, and graphitization, enhances both compressive strength and thermal conductivity [179]. Various blowing agents and methods,



(c)

Fig. 12. (*continued*).

such as supercritical foaming [180] and sacrificial template procedures [181], create carbon foams with different cell sizes and structures. The inclusion of additives such as vapor-grown carbon fibers [182] and multi-walled carbon nanotubes [183] improves both the mechanical and thermal characteristics. Selecting appropriate precursors and establishing effective methods are essential for attaining desirable characteristics in carbon foams.

Graphite foams can be fabricated by techniques such as blowing, employing polymer-based templates, and compressing graphite or graphite sheets [184]. As demonstrated in Fig. 12 (a), the blowing method encompasses the application of heat treatment or heat treatment with blowing additives at various pressures, temperatures, and pitch concentrations, leading to the formation of bubbles of different sizes [185,186]. Polymer-based template technologies provide a cost-effective and direct method for manufacturing graphite foams. As shown in Fig. 12 (b), the procedure involves introducing a polymer template and pitch slurry solution into a pressure vessel, where pressure adjustments regulate the quantities of pitch infused into the polymer foam. The impregnated pitch is dried by heating it to a temperature range of 200–400 °C. This process leads to carbonization and graphitization, resulting in the formation of graphite foam when the sacrificial polymer template is removed. Using polymer templates enables the control of bubble size according to the thickness of the template [187]. The thermal conductivity, bulk density, and compressive strength of the foams were found to be influenced by different concentrations of pitch slurry. Polymer templates, such as PU foams and hydrogels, offer a diverse method for effectively manipulating the size and arrangement of bubbles. It is important to acknowledge that when compared to other methods such as blowing, graphite foams produced via polymer templates may have lower compressive strengths and thermal conductivities. This is because the amount of graphite that can be impregnated into the polymer template is limited [188,189]. According to Fig. 12 (c), the third method involves compressing graphite or exfoliated graphite. During this procedure, graphite and/or graphite sheets, coupled with a polymer binder, are inserted into a mold, and subjected to compression and heat treatment [190]. These foams offer advantages for many applications, due to their uncomplicated production procedure and high conductivity. Although the use of a polymer as a binder may decrease the compressive strength of graphite foams, it has the advantage of superior recovery qualities, enabling repeated compression and release [184]. Moreover, fillers could be used to improve heat conductivity and compressive strength [191]. However, challenges could arise due to their limited dispersibility, alignment, and interfacial adhesion. Surface treatments, such as the incorporation of boric acid and boron oxide, are used to tackle these issues and enhance specific thermal and mechanical properties in graphite foams [192,193]. This technique presents a favorable approach for manufacturing graphite foams that possess highly ordered structures and enhanced thermal conductivity [184].

A broad range of processes and surface treatments significantly expand the possible applications of carbon and graphite foams across multiple industries, including but not limited to thermal management systems, catalyst supports, and filtering technologies [176,184,194].

3D printing technology, which entails layer-by-layer printing of powders such as metal, plastic, or ceramics, can produce porous media, which provides a new method for preparing open-cell foam. Direct and indirect printing are common processes in the additive manufacturing of porous media. Direct printing involves printing fragments directly, whereas indirect printing combines printing patterns with traditional casting to produce foams [195]. The direct printing method is based on computer-aided design (CAD) models of unit cells. It employs techniques such as direct selective laser sintering (SLS), selective electron beam melting (SEBM), and selective laser melting (SLM) [196–198] to create cellular structures in stainless steel, copper, titanium, and their alloys. SLS is an additive manufacturing technique that employs a high-intensity laser to selectively bind layers of powdered polymers or metals. Using a digital design, the laser employs the process of sintering or fusing powder to produce a tangible three-dimensional object during the printing process. SLS is renowned for its versatility in producing complex geometries without the need for support structures. This technique is well-suited for quick prototyping and manufacturing small quantities because of its accuracy and efficient use of materials [199]. SEBM is a cutting-edge method of 3D printing that involves the gradual fusion of metal powder using an electron beam. In SEBM, the focused electron beam selectively melts and solidifies the metal powder bed to create the intended object. This method is appropriate for complex metal components with strong mechanical characteristics. High-density metal parts could be 3D printed by SEBM [200]. SLM is a precise additive manufacturing method extensively employed for fabricating metal components. SLM utilizes a laser to specifically heat and combine layers of metal powder, gradually constructing a three-dimensional object from the bottom to the top. The process takes place within a controlled environment to guarantee accurate temperature control and the preservation of material integrity. The capability of SLM to produce fully dense metal parts with intricate geometries has led to its recognition as a key technology in aerospace, medical, and automotive applications. The method's capacity to be used with a diverse range of metals enhances its versatility and wide-ranging applicability [201].

Due to the metals' high reflectivity and thermal conductivity, the direct printing method is frequently difficult and expensive [195]. Since printing metal foams is an expensive and time-consuming procedure that requires costly machinery, large-scale industrial applications are still in their infancy. As a result, the process is frequently used for niche

applications, such as biomedical implants and aerospace components.

4.4. Porous media numerical modeling

Porous media could be studied from two different points of view, microscopic and macroscopic. Considering the microscopic view, only a few channels within the porous media could be observed, and conventional fluid mechanic equations could be applied [111]. However, from a macroscopic point of view, the application of the same equations seems impossible due to the complex structure of the medium. Therefore, a volume-averaging model was proposed to describe fluid flow within the porous medium to address this issue. To determine the properties of a porous medium using this method, a control volume was employed as a representative of its structure, and the parametric values were derived as the mean over the control volume. These values were then included in the system as characteristics. This volume was referred to as the "representative elementary volume (r.e.v.)" [111].

An initial approach to model fluid flow within the porous medium was proposed by Darcy [202], which included creeping flows with a Reynolds number of <1. Beyond that Reynolds number, a boundary layer emerges in the vicinity of the solid boundary. In other words, the Darcy equation states a linear relationship between pressure loss and velocity. However, it is only applicable at low velocities [114]. Forchheimer [203] developed the Darcy model by adding a square velocity term, considering nonlinear drag [107]. In porous medium with high porosities over 0.95 [204] or high velocities [205], considering the effect of solid boundaries on flow is vital, which is not considered in the Darcy and Forchheimer models. Therefore, the Brinkman model [206] adds another term to the fundamental Darcy law to take into account the no-slip boundaries at solid walls within the porous region [207]. To perform more accurate simulations of porous media, it is recommended by many researchers [107,114,208,209] to use the Darcy-Brinkman-Forchheimer model (DBF), which is claimed to be more consistent with experimentally obtained data. As presented in eq. 11, the Darcy, Brinkman, and Forchheimer terms address viscous, boundary, and inertial effects, respectively, as part of the DBF model [107]. DBF model is also recommended for the numerical simulations of the BTMS based on PCM, liquid, and hybrid cooling [76,85,137,159,165,168].

The mathematical model for DBF is as follows [114]:

$$\nabla P = -\frac{\mu}{K}V + \tilde{\mu}\nabla^2 V - \frac{c_F}{\sqrt{K}}\rho_F |V|V \tag{11}$$

where ∇P are V are pressure drop and velocity of the fluid within the porous media, respectively, and μ, K, $\tilde{\mu}$, c_F, and ρ_F are dynamic viscosity, permeability, effective dynamic viscosity, inertia factor, and fluid density coefficients, respectively.

Various investigations have been carried out to develop correlations for predicting permeability (K) and inertia factor (c_F) based on porous media's properties such as porosity pore density. The most common empirical formula for permeability and inertial factor calculations of foams has been developed by Calmidi and Mahajan as follows [210]:

$$K = 0.00073 d_f^2 (1-\varepsilon)^{-0.224}\left(\frac{d_f}{d_p}\right)^{-1.11} \tag{12}$$

$$c_F = 0.00212(1-\varepsilon)^{-0.132}\left(\frac{d_f}{d_p}\right)^{-1.63} \tag{13}$$

where d_f represents the equivalent diameter of metal foam fibers and d_p demonstrates the equivalent pore size calculated as follows [111]:

$$\frac{d_f}{d_p} = 1.18\sqrt{\frac{1-\varepsilon}{3\pi}}\left(\frac{1}{1-exp^{-\left(\frac{1-\varepsilon}{0.04}\right)}}\right) \tag{14}$$

$$d_p = \frac{0.0254}{PPI} \tag{15}$$

where ε and PPI are the porosity and pore density of the copper metal foam.

To study heat transfer within a porous medium, two methods have been proposed: (1) under local thermal equilibrium (LTE) conditions and (2) under local thermal non-equilibrium (LTNE) conditions. The former assumes that the fluid and solid phases are subject to the same local temperatures, while the latter correlates with different temperatures [114,208]. In other words, the LTE condition implies that the local temperature differential between the fluid and solid phases of the porous system is negligible at any point inside the bulk porous medium, meaning that both phases have the same temperature at any location. Therefore, only a single-phase conductivity model is utilized to compute the temperature distribution within a porous medium, not separate models for each phase. Indeed, this model ignores the convection and radiation mechanisms of heat transfer between the various phases in the porous media. The LTNE model determines the temperature of each phase in a porous media by solving an energy equation for each one [114,211]. Despite the higher computing expenses involved with this approach [209,211–213], previous studies [111,114,212,214–217] have found that this method yields more precise results than the LTE model.

The governing energy equation for porous media in the LTNE model is as follows for solid and fluid phases, respectively [111]:

$$(1-\varepsilon)(\rho C_p)_s \frac{\partial T_s}{\partial t} = K_{s,eff}\nabla^2 T_s - h_{sf}a_{sf}(T_s - T_f) \tag{16}$$

$$\varepsilon(\rho C_p)_f \frac{\partial T_f}{\partial t} + (\rho C_p)_f \varepsilon V \nabla T_f = K_{f,eff}\nabla^2 T_f + h_{sf}a_{sf}(T_s - T_f) \tag{17}$$

where h_{sf} denotes the inter-phase heat transfer coefficient and a_{sf} represents the specific surface area of the porous medium between the fluid and solid phases.

Different experimental [111,218,219] correlations have been developed to predict the h_{sf} and a_{sf}. The most common ones are as follow:

$$h_{sf} = \begin{cases} 0.76 Re_d^{0.4} Pr^{0.37} K_f/d_f, (1 \le Re_d \le 40) \\ 0.52 Re_d^{0.5} Pr^{0.37} K_f/d_f, (40 \le Re_d \le 10^3) \\ 0.76 Re_d^{0.6} Pr^{0.37} K_f/d_f, (10^3 \le Re_d \le 2\times 10^5) \end{cases} \tag{18}$$

$$a_{sf} = 3\pi d_f \left[1 - e^{-((1-\varepsilon)/0.04)}\right] \Big/ (0.59 d_p)^2 \tag{19}$$

The initial and simplified approach for defining effective thermal conductivity (K_{eff}) is as follows [220]:

$$K_{eff} = (1-\varepsilon)K_f + \varepsilon K_s \tag{20}$$

Moreover different studies have been done for accurate determination of K_{eff}. The most common one with application for BTMS is developed by Boomsma and Poulikakos [220] as follows:

$$K_{eff} = \frac{1}{\sqrt{2}(R_a + R_b + R_c + R_d)} \tag{21}$$

where

$$R_a = \frac{4\sigma}{(2e^2 + \pi\sigma(1-\varepsilon))K_s + (4 - 2e^2 - \pi\sigma(1-\varepsilon))K_f} \tag{22}$$

$$R_b = \frac{(e-2\sigma)^2}{(e-2\sigma)e^2 K_s + (2e - 4\sigma - (e-2\sigma)e^2)K_f} \tag{23}$$

Table 3
Conditions for applicability/validity of LTE and LTNE models.

Criteria for model suitability	LTE	LTNE
Reynolds number (*Re*) and Darcy number (*Da*)	LTE is valid for scenarios with low *Re* and *Da*, where convective transport is not dominant, and the flow through the porous media is less turbulent [229].	In cases with higher *Re* and *Da*, where convective transport is significant and the flow may be more turbulent, the LTNE model should be considered, especially if there is a substantial temperature gradient between the solid and fluid phases [224].
Boundary conditions	LTE is prevalent near the wall with isothermal boundary conditions, implying uniform temperature distribution; however, this assumption weakens moving away from the wall towards the channel core [230].	LTNE should be applied when dealing with unsteady heating processes or when the boundary conditions involve significant heat accumulation within the porous material, as LTE assumptions break down under these circumstances [111,221].
Heat transfer coefficient	LTE is suitable when high convective currents or fluids with high heat transfer coefficients are present, indicating effective heat transfer between the fluid and solid phases [218].	When the system has a low heat transfer coefficient, which could indicate a significant temperature difference between phases, LTNE provides a more accurate modeling approach [230].
Thermal conductivity of the fluid	If the fluid has high thermal conductivity, it suggests a quick dissipation of thermal gradients, making LTE a valid assumption [208].	LTNE is necessary when there is a considerable thermal conductivity difference between the solid and liquid phases. This difference can lead to significant temperature gradients that LTE cannot model accurately [224].
Flow velocity	High flow velocities in systems without internal heat sources are well-suited to LTE, as the high rate of flow minimizes the chance for temperature gradients to establish between phases [231].	LTNE provides accurate predictions for metal foam porous media in low flow velocity scenarios, where the solid matrix could significantly influence the overall thermal performance [223]
Pore size	Small pore sizes tend to facilitate thermal equilibrium between phases, making LTE an applicable model [232].	–
Heat transfer coefficient relative to *Re*	If the heat transfer coefficient is directly proportional to the Reynolds number to a power greater than one, it implies effective convective heat transfer that justifies the use of LTE [233].	–
Heterogeneity in porous media	When differences in porosity are minor within heterogeneous porous media, it suggests uniform flow and thermal conditions conducive to LTE [234].	–
System with internal heat generation	–	The LTNE model is more accurate for porous media with an internal heat source due to the inherent non-equilibrium conditions it creates [231].
Porous medium with high porosity	–	High porosity typically indicates a greater potential for temperature differences between phases, making LTNE the more suitable model [230].
Chemical and nuclear reactors, biological systems, and high-speed flows	–	LTNE offers more accurate modeling for systems where rapid thermal responses are necessary, such as in reactors, biological systems, and high-speed flows, where LTE assumptions may not be sufficient [231].
Biot number consideration	–	A minimum criterion for the Biot number exists that helps determine the necessity of using LTNE. If the Biot number is low, it implies that the solid phase's conduction resistance is significant relative to the convective resistance at the fluid-solid interface, thus requiring the LTNE approach [235].
Simulating two-phase flows with rapid phase changes	–	LTNE is essential for modeling two-phase flows that are undergoing rapid phase changes, as it can account for the separate energy balances of each phase, which is critical in such systems [232].
High conductivity porous media	–	For high conductivity porous media, LTE conditions are invalid as they cannot adequately capture the temperature disparities between the phases [236].
Nanofluid flow through porous media	–	The LTNE model is required for modeling nanofluid flow through porous media due to the complex interactions between the nanoparticles, base fluid, and the porous matrix [237].
Chemically active porous media	–	In chemically active porous media where reactions can cause significant local heat generation, the LTNE model is necessary to capture the non-equilibrium effects [234].
No significant difference in thermal resistance	The LTE method is applicable when the local heat transfer thermal resistances of the solid matrix and the fluid are similar, meaning the temperature difference between them is minimal [226].	–

Table 4
Comparison of numerical models for porous media in BTMS.

Model	Application scenario	Advantages	Limitations	Application in BTMS	Key considerations	Accuracy
Darcy	Low velocity flows ($Re < 1$)	Simple and widely applicable for low flow rates	Inaccurate for higher velocity flows	N/A	Best for preliminary or simplified studies	High for low velocity flows; not suitable beyond $Re < 1$
Forchheimer	Moderate velocities where nonlinear drag becomes significant	Better for moderate velocities	Does not account for boundary layer effects	N/A	When flow complexity exceeds Darcy's model applicability	Improved over Darcy for moderate velocities; loses accuracy beyond moderate levels
Brinkman	High porosities or close to solid boundaries	Accounts for boundary conditions near solid structures	Complexity increases with detailed geometries	N/A	Useful in detailed geometrical simulations	Enhanced near solid boundaries; decreases in complex geometries
DBF (Darcy-Brinkman-Forchheimer)	Various BTMS applications, especially complex flow conditions	Comprehensive for varied conditions	High computational cost	Complex BTMS simulations, including PCM, liquid, and hybrid cooling	When accurate simulation of flow and thermal phenomena is critical	Comprehensive across a wide range of conditions; computational cost may limit detailed accuracy
LTE (Local Thermal Equilibrium)	Minimal temperature gradients within phases	Simplifies calculations, easy to implement	May not capture thermal gradients accurately	Simplified thermal analyses in BTMS where detailed gradients are not critical	For systems where phase temperature differences are negligible	Accurate for minimal gradients; decreases with significant gradients
LTNE (Local Thermal Non-Equilibrium)	Significant temperature differences between phases	Detailed thermal behavior analysis	Higher computational requirements	Detailed thermal studies in BTMS, especially with non-uniform heat generation	For accurate thermal management predictions in complex systems	High in scenarios with significant temperature differences between phases; computational detail impacts accuracy

$$R_c = \frac{\sqrt{2} - 2e}{\sqrt{2}\pi\sigma^2 K_s + \left(2 - \sqrt{2}\,\pi\sigma^2\right)K_f} \tag{24}$$

$$R_d = \frac{2e}{e^2 K_s + (4 - e^2)K_f} \tag{25}$$

where e = 0.339 is the experimental constant in the Boomsma and Poulikakos model and σ is defined as follows:

$$\sigma = \sqrt{\frac{\sqrt{2}\left(2 - (5/8)e^3\sqrt{2} - 2\varepsilon\right)}{\pi\left(3 - 4e\sqrt{2} - e\right)}} \tag{26}$$

and

$$K_{f,eff} = K_{eff}\big|_{K_s=0} \tag{27}$$

$$K_{s,eff} = K_{eff}\big|_{K_f=0} \tag{28}$$

Numerous investigations [111,114,211,221–225] have been carried out to analyze the conditions of validity of the mentioned LTE and LTNE methods. On the basis of the thermophysical parameters of the phases and the type of transient process, the temperatures of the phases may not be comparable. In various thermal applications, the temperature difference between the phases is significant. Since heat transfer is inherently unstable, system performance depends on the non-equilibrium level between the phases. The LTE theory's collapse becomes incontestable when the heat within porous material accumulates [111,221]. It is claimed by Vadasz [222] that the LTE model can be employed typically for constant temperature or insulating boundary conditions. However, the majority of heating processes within the applications of thermal engineering are unsteady. Due to the model of heat transfer throughout the porous matrix, the LTNE is therefore anticipated [221]. Lin et al. [223] stated that the LTE model could be utilized with reliability in circumstances of high flow velocity. Li et al. [226] suggested employing the LTE method when there is no substantial difference between the solid matrix and the fluid's local heat transfer thermal resistance. Isfahani et al. [227] recommend LTE when fluid thermal conductivity coefficients fall below 10. Torabi et al. [224] presented particular circumstances under which the LTNE model needs to be applied: (1) Considerable thermal conductivity difference between the solid and liquid phases of the porous media, (2) Conduction as the dominant mechanism of heat transfer or system with low internal Biot number, (3) Internally generating heat within a system. Therefore, it is reasonable to conclude, based on the critical results reported in [107,111,114,211,212,225,228], that great caution should be exercised in future research whenever the LTE or LTNE approach is chosen to be utilized, as their validity may be altered on a case-by-case basis. Detailed conditions for applicability/validity of LTE and LTNE models are presented in Table 3.

Considering the numerical investigation of BTMS using porous foams, it should be mentioned that a great number of studies are based on the LTE method due to the low cost of computation. However, a few publications [127,134] considered the LTNE method, mostly involving BTMS with PCM and porous media. However, comparing these models in investigations involving porous media and foams is essential [127,134].

The capacity of the LTNE model to determine temperature differences between the solid and fluid phases in porous media demonstrates its adaptability and relevance. This is particularly pertinent in the context of heat transfer modeling and cooling in BTMS, as it establishes a fundamental comprehension of the interaction between generated heat and the porous structure, taking into account the transient and non-uniform heat generation in batteries during charging and discharging cycles. Simultaneously, the DBF model illustrates its practicality and performance through offering a robust foundation for simulating fluid flow in porous media. Taking into account the laminar flow in most of the liquid-based BTMS and given the unique features of heat generation in batteries, the DBF model appears to be capable of conducting a comprehensive evaluation of the fluid dynamics occurring within the porous structure. Due to the dynamic nature of battery operation, these models are particularly effective in capturing the interaction between the liquid and solid phases within the porous media.

It can be concluded that to highlight the progress made in BTMS with the inclusion of porous media and foam, it is essential to emphasize the requirement for further experimental and numerical investigations. There are numerous challenges in optimizing porous media and foams, especially when combining with different cooling methods. This is because porous media has a substantial impact on the heat transfer characteristics of the BTMS. The current focus of research is primarily on improving thermal conductivity by means of the utilization of porous media and foams. However, there is a gap when it comes to optimizing heat transfer enhancement, managing the increase in pressure drop, and

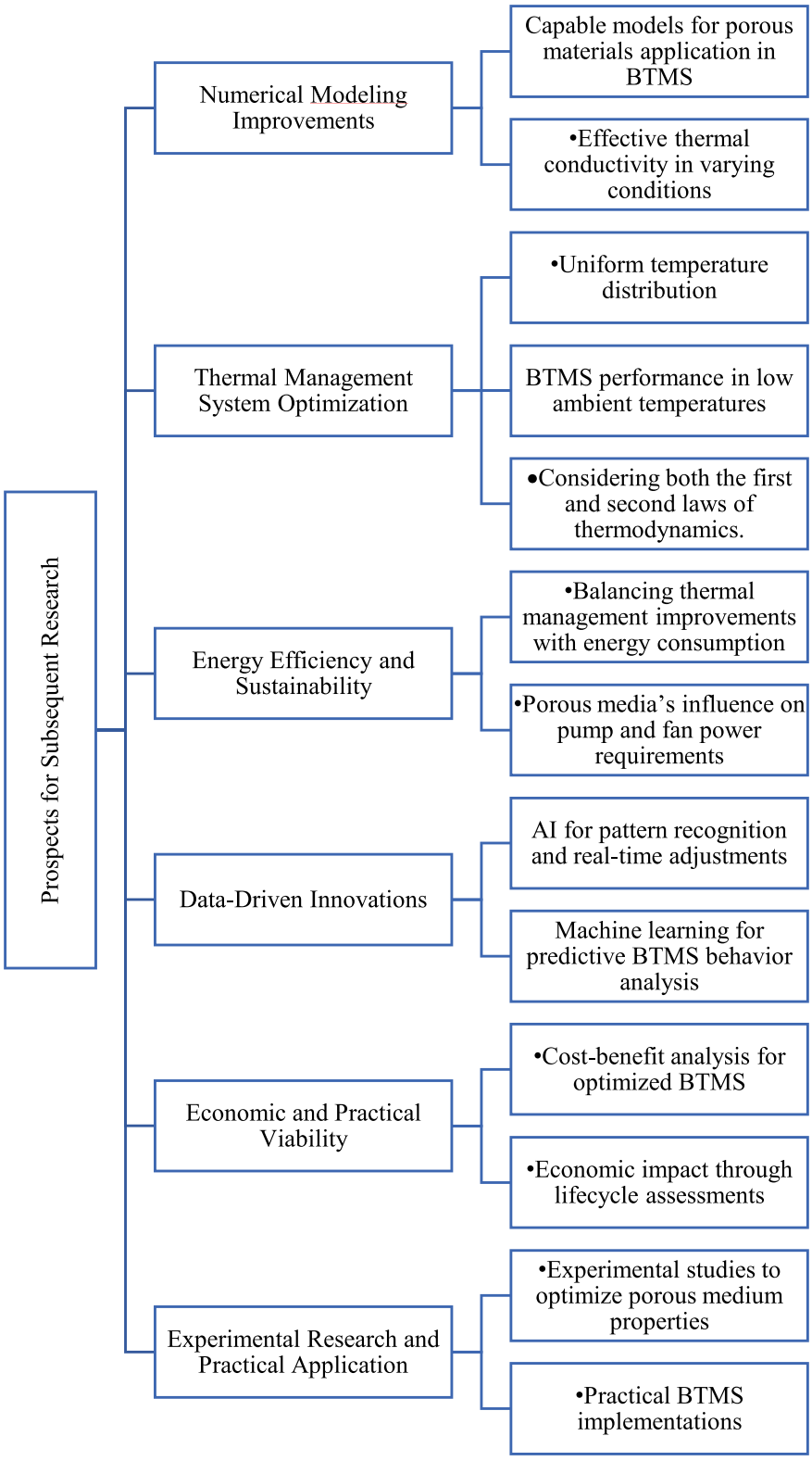


Fig. 13. Recommendations for future research in the application of porous media in BTMS.

minimizing the power requirements of the pump when porous media are integrated. Moreover, the implementation of porous medium in BTMS presents issues associated with thermal contact resistance (TCR), which has a substantial effect on the overall performance of the system. It is crucial to research more for minimizing TCR and effectively attaching porous media and foams to surfaces within the limitations of BTMS design. Conducting comprehensive experimental and numerical investigations on these aspects will undoubtedly lead to a deeper understanding of the effectiveness of BTMS using porous media and foam, paving the way for enhanced thermal management. A comparative summary of the discussed models is illustrated in Table 4.

5. Conclusion

BTMS is crucial for maintaining the effective functionality, performance, and safety of lithium-ion batteries in EVs and HEVs. The increasing demand for environmentally friendly and sustainable transportation options has led to a greater emphasis on developing and optimizing BTMS. This review investigated multiple facets of BTMS, with particular emphasis on the application of porous media and foams as practical means of enhancing heat transfer within these systems. This review also explored the modeling of heat generation in lithium-ion batteries, highlighting the significance of precise models in forecasting thermal behavior. Several modeling approaches, such as the DBF model, were demonstrated to shed light on fluid flow dynamics in porous media. This model is particularly appropriate in the context of employing porous foams in BTMS applications. Porous media and foams have demonstrated the potential to improve heat transfer rates. Hence enhancing the thermal management of batteries. Nonetheless, the efficiency of these systems can be considerably influenced by factors such as the selection of porous materials, porosity, and permeability. Although copper foam has exhibited excellent thermal conductivity, nickel foam has been utilized in situations involving high temperatures. Carbon-based foams, including extended graphite, have garnered considerable interest due to their potential to augment the thermal conductivity of PCM while maintaining a low density. Different strategies were investigated for manufacturing and processing porous media, encompassing liquid-state, solid-state, vapor-state, and ionic-state procedures. The selection of a particular production method can potentially impact the porosity and physical characteristics of porous media. Furthermore, the review emphasized the significance of employing accurate numerical modeling techniques in studying porous media within the context of BTMS. The selection between models based on LTE and LTNE can have a substantial impact on the accuracy of the simulated results. The LTE model is generally recognized for their lower computational cost. However, the LTNE model is regarded as more precise, particularly when there are significant temperature variations between phases of the porous media.

In summary, BTMS plays a crucial role in advancing electric vehicle technology, and the exploration of porous media and metal foams indicate the potential to enhance their efficiency and safety. When designing and improving BTMS involving porous media and foam for different applications, it is crucial to take into account several factors, including but not limited to material selection, porosity, permeability, and modeling methodologies. Additional investigation is required to address the existing knowledge gap and offer a thorough understanding of the thermal management of batteries utilizing porous media.

5.1. Recommendations for future investigations

Future studies pertaining to the utilization of porous media and foams in BTMS could be conducted in the subsequent areas which have been categorized in Fig. 13.

- Graphite is preferable to metallic foams for use in the temperature management system of batteries due to its higher thermal conductivity and lower density. More research is required on the capabilities of graphite for battery temperature regulation.
- Battery temperature control methods that utilize porous materials should be evaluated from a cost-benefit perspective.
- More investigation is required to study the impact of porous media and foams application in BTMS operating in relatively low ambient temperatures.
- More analytical models can be developed to accurately predict the effective thermal conductivity of cooling systems using porous media.
- To achieve a balance between the improvement of thermal management and the BTMS's energy consumption, it is necessary to investigate the effect of porous media on the increase of the pump or fan power.
- The influence of porous media on the entropy generation of proposed BTMSs should be investigated further so that optimizations can be based on both the first and second laws of thermodynamics.
- In order to enhance comprehension and establish a stronger basis for practical implementations, it would be beneficial to conduct additional experimental studies, focusing on the optimization of porous medium and foam properties.
- Data-driven approaches, such as machine learning and artificial intelligence could be considered, to predict thermal runaway propagation of battery modules under uncertain conditions, with a particular focus on the role of porous media.

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Declaration of competing interest

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Data availability

Data will be made available on request.

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