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Indirect Liquid Cooling for Battery Thermal Management: A Review

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Abstract

The thermal management system of batteries is a critical aspect of battery management for optimizing battery performance and lifespan. Research has rapidly progressed in battery thermal management in the past decade, mainly by adopting indirect liquid cooling methods. This article provides an in-depth overview of the recent developments in the application of indirect liquid cooling for battery thermal management, encompassing fundamental principles, types of fluids, and the strengths and weaknesses of this method. Various heat transfer techniques, such as convective heat transfer and heat generation, are also examined to comprehend effective ways of precisely managing battery temperature. The benefits and challenges of this indirect liquid cooling approach are evaluated, considering crucial criteria like safety. The results of this review demonstrate that the indirect liquid cooling method holds promise as an effective solution to address thermal challenges in batteries, with the potential to enhance overall battery performance and durability.

1. Introduction

Research focused on battery thermal management has experienced a significant surge in the past decade (Fig. 1). As seen in electric vehicles and energy storage systems, the increasing demand for advanced battery technologies has driven battery performance and durability improvements. However, the high speed and efficiency of battery charging and discharging and uncontrolled operating temperatures have led to an elevated risk of thermal degradation and potential failures that impact battery performance and lifespan. Thermal management has become a primary focus in enhancing battery performance and reliability [1]. Effective thermal cooling can reduce the risk of overheating and ensure temperature consistency throughout battery charge and discharge cycles, improving overall battery performance and lifespan [2].

The cooling media for batteries exist in gas, liquid, solid, or combinations of these three phases. Phase transitions in the cooling agent from solid to gas, solid to liquid, and liquid to gas can result in volumetric changes [3]. Liquid cooling methods have long been recognized as efficient approaches to addressing thermal challenges in various applications, including electronics and the automotive industry [4]–[6]. The two most common classifications of liquid cooling methods are direct contact and indirect contact [7]. Direct liquid cooling comes with drawbacks such as the heightened intricacy and cost associated with condensing evaporated vapor, substantial pumping losses in fluids with high viscosity, the expensive nature of the liquid used, challenges related to material compatibility, and an upsurge in the weight of the fluid [8], [9]. Therefore, maintaining and optimizing the indirect liquid cooling method for battery thermal management is a better choice.

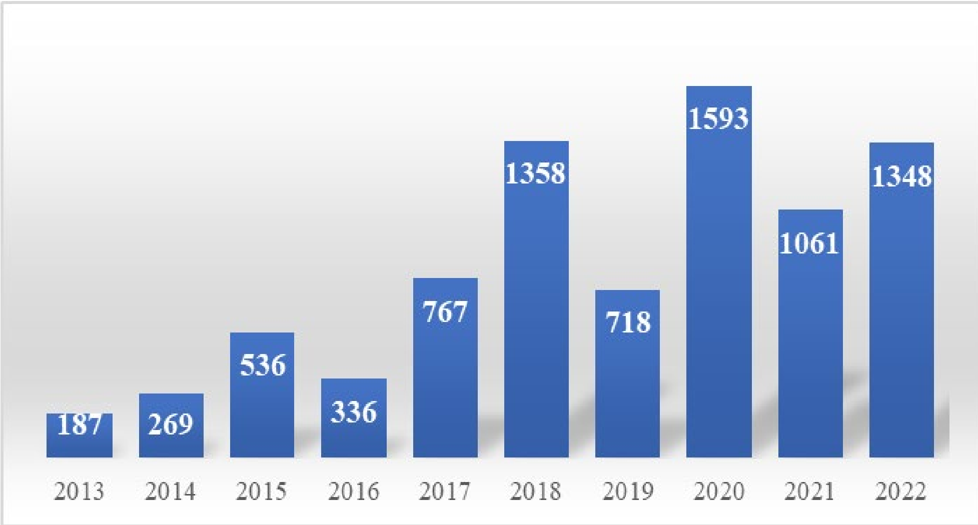


Fig. 1 *Battery thermal management on Scopus search engine within title, abstract, and keywords*

This article aims to provide a comprehensive overview of the application of ILC methods in battery thermal management. The review will delve into the fundamental principles and components of the ILC system, and various types of fluids that can be employed to optimize battery cooling. Different heat transfer techniques will be explored to identify effective means of precisely regulating battery temperature. By analyzing the advantages and limitations of the ILC approach, this article will outline the potential solutions offered by indirect liquid cooling methods in tackling thermal challenges within batteries. A deeper understanding of battery thermal management through indirect liquid cooling methods will contribute valuable insights into delivering safer, more reliable, and more efficient batteries to support future technological advancements.

Nomenclature

A	Surface area	Q_0	Battery initial charge
D_h	Hydraulic diameter	Q_C	Current actual capacity of battery
f	Friction factor	Q_n	Nominal capacity of battery
h	Convection heat transfer coefficient	Q_{cond}	Conduction heat transfer coefficient
I	Working current	Q_{conv}	Convection heat transfer coefficient
j	Colburn factor	Re	Reynold number
j/f	London goodness factor	T	Temperature
k	Conduction heat transfer coefficient	T_b	Temperature of battery cell
L	Flow lenght	T_c	Temperatur of coolant
Nu	Nusselt number	u	Coolant velocity
P	Pressure	u_{in}	Inlet coolant velocity
P_{in}	Inlet pressure	V	voltage of battery cell
P_{out}	Outlet pressure	V_{OC}	voltage of open circuit
Pr	Prantl number	x	Surface thickness
Q	Quantity of electric supplied to the battery	μ	Dynamic viscosity
$\dot{Q}$	Heat generation rate	ρ	Coolant density

2. Performance

The Battery Management System (BMS) consists of software and hardware that functions as a regulator and monitor of battery performance during charging and discharging. The software components of BMS include battery modeling, state estimation, fault detection, and data storage, while the hardware components consist of sensors and monitoring circuits, charge and discharge circuits, safety circuits, and data acquisition [10]. The most crucial and frequently assessed performance of a battery is indicated through the state of charge (SOC) and state of health (SOH), each represented by Eq. 1 and Eq. 2, respectively. SOC represents the battery's state of charge, serving as a guide for monitoring the battery capacity (100%) now. Meanwhile, SOH represents the loss of battery capacity, depicting the reduction in the maximum energy that can be stored within the cell.

$$SOC\% = 100 \times \frac{(Q_0 + Q)}{Q_{max}} \tag{1}$$

where $SOC\%$ is state of charge in percentage, Q_0 is the battery initial charge, Q is the quantity of electric delivered by or supplied to the battery, and Q_{max} is the maximum charge that can be stored in battery.

$$SOH = \frac{Q_C}{Q_n} \tag{2}$$

where SOH is the state of health, Q_C is the current actual capacity of the battery, and Q_n is the nominal capacity of the battery.

2.1 Heat Transfer

The production of heat within a battery cell arises from the resistance of electrochemical reactions and the movement of substances within the cell. The heat generated by the battery during the charging and discharging process is conducted through the surface of the battery. The heat generation rate of the battery in a simplified form can be shown as Eq. 3 [6], [11]–[13].

$$\dot{Q} = I(V - V_{OC}) + I\,T\frac{dV_{OC}}{dT} \tag{3}$$

where I is the working current, V is the voltage of the battery cell, V_{OC} is the voltage of an open circuit, and T is the temperature of the battery cell. The heat will pass through the heat exchanger, considered a thermal resistance, that separates the battery from the liquid coolant. Expanding the surface area and thinning the heat exchanger can be a solution to increase conduction heat transfer. The general equation of conduction heat transfer is shown in Eq. 4.

$$Q_{cond} = -k\,A\,\frac{\Delta T}{\Delta x} \tag{4}$$

where Q_{cond} is the conduction heat transfer, k is the conduction heat transfer coefficient, A is the surface area, ΔT is the difference between the temperature in contact with the battery and the temperature in contact with the cooling fluid, and Δx is surface thickness. Convection heat transfer occurs when heat released from the heat exchanger is cooled by the coolant. The temperature of the coolant in direct contact with the heat exchanger surface tends to approach the temperature of the heat exchanger. As one moves further away from the heat exchanger surface, the fluid temperature decreases. Enhancing convection heat transfer can be achieved by increasing the convective heat transfer coefficient, expanding the surface area, and reducing the temperature of the coolant. The general equation for convection heat transfer is indicated in Eq. 5.

$$Q_{conv} = h\,A\,(T_h - T_c) \tag{5}$$

where Q_{conv} is the convection heat transfer, h is the convection heat transfer coefficient, A is the surface area, T_h is the surface area of heat transfer temperature, and T_c is the coolant temperature. The active method tends to be utilized in ILC with circulated coolant in the system rather than employing passive methods. The flow rate of the coolant can impact the battery temperature and power consumption. A higher coolant flow rate results in a lower battery temperature with increasing power consumption. The non-dimensional number used to represent the flow rate is the Reynolds number, as shown in Eq. 6.

$$Re = \frac{\rho\,u_{in}\,D_h}{\mu} \tag{6}$$

where Re is the Reynold number, ρ is the coolant density, u_{in} is the inlet coolant velocity, D_h is the hydraulic diameter, and μ is the dynamic viscosity. The amount of heat transfer that occurs can be indicated by the Nusselt number which is a non-dimensional number. The Nusselt number is the ratio of convection heat transfer and conduction heat transfer as shown in Eq. 7.

$$Nu = \frac{Q_{conv}}{Q_{cond}} \tag{7}$$

where Nu is the Nusselt number, Q_{conv} is the convection heat transfer, and Q_{conv} is the conduction heat transfer.

2.2 Pressure Loss

The loss of pressure reduction can be caused by structural flow resistance. Structural flow resistance results from the uneven shape of pipes or channels. The development of cooling channel designs leads to the utilization of biological resources, both from plants and animals. Although the complexity of cooling channel structures increases in proportion to their cooling capabilities, the accompanying pressure drop intensifies. Vortex generators, fins, holders, and even batteries can be categorized as structural flow resistance. The general equation used to measure pressure loss is indicated in Eq. 4.

$$\Delta P = P_{in} - P_{out} \tag{7}$$

2.3 London Goodness Factor

The London goodness factor, denoted as *j/f*, is a non-dimensional number used to represent the performance of heat exchangers. The Colburn factor can be calculated using non-dimensional numbers, as indicated in Eq. 8. Flow resistance loss is represented by the Friction factor, which acts as a divisor for the London goodness factor [14], [15]. The Friction factor can be calculated using Eq. 9.

$$j = \frac{Nu}{Re\ Pr^{1/3}} \tag{8}$$

where j is the Colburn factor, Nu is the Nusselt number, Re is the Reynold number, and Pr is the Prantl number.

$$f = \frac{\Delta P}{\frac{1}{2}\rho u} \frac{D_h}{L} \tag{9}$$

where f is the friction factor, P is the pressure, ρ is the coolant density, u is the coolant velocity, D_h is the hydraulic diameter, and L is the flow lenght.

3. Battery Thermal Management System

The battery thermal management system (BTMS) focuses on controlling battery temperature which can increase during charging and discharging. BTMS shown in Fig. 2 is categorized based on energy consumption into active and passive methods [16]. The active method uses additional energy sources such as pumps, blowers, and so on, while the passive method does not use additional energy or heat transfer occurs naturally. Although passive methods are easier to implement and cost-effective, active methods are better in efficiency [17]. Active methods are divided into force air, direct liquid, jacket, and cold plate, whereas passive methods are divided into phase-change-material (PCM) and heat pipes. Heat transfer media are divided into air, liquid, PCM and hybrid. Natural convection and forced convection are both categorized as cooling methods utilizing air as the medium. Natural convection tends to be associated with passive cooling methods, while forced convection is closely related to active cooling methods. Based on the material phase, PCM is divided into solid-liquid, solid-vapor, and liquid-vapor. PCM materials are primarily categorized as organic and inorganic. Eutectic materials comprise a combination of organic and inorganic substances. Paraffin, Fatty acid, Ester, and Alcohol are examples of organic materials operating within the temperature range of 4-150 °C, while Salt, Salt hydrate, Metallic compound, and Metal alloy fall into the category of inorganic materials operating at temperatures ranging from 8-900 °C [18], [19]. Hybrid systems involve a combination of various media, including air-liquid, air-PCM, and liquid-PCM.

4. Indirect Liquid Cooling

Direct contact is often closely associated with immersion cooling, while the indirect contact method is divided into active methods such as jackets and cold plates, as well as passive methods like heat pipes. McLaren has produced the world's first electric car, known as the Speedtail series, which utilizes the immersion cooling method [8]. However, the majority of electric vehicle manufacturers such as Audi [20], Porche [21], and Tesla [22] employ the ILC method. Some studies reveal that one drawback of the ILC method is the limited surface area of contact between the battery and the coolant [23]. Nevertheless, this limitation can be addressed through various optimizations and innovations, both in terms of design and the type of coolant used.

4.1 Heat Exchanger Design

ILC has thermal resistance caused by the separation, called heat exchanger, between the battery and the coolant. However, the presence of a heat exchanger can make the battery safer from short circuits or other failures. The researchers developed various heat exchanger designs as shown in Table 1. ILC with a flat cold plate design tends to be employed in pouch and prism batteries, while coolers with a wavy cold plate and jacket design are inclined to be used in cylindrical batteries.

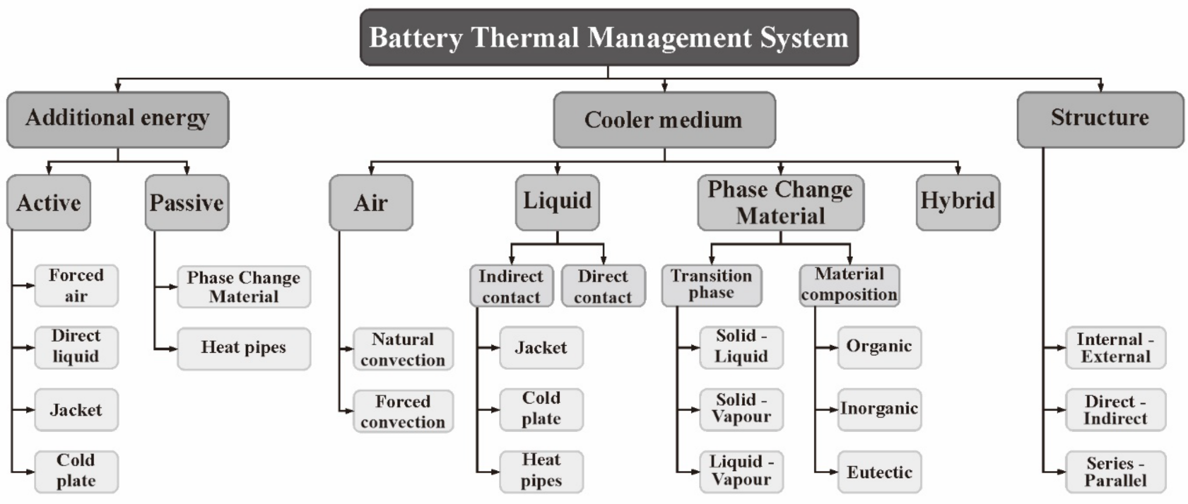
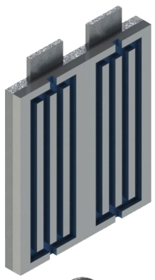
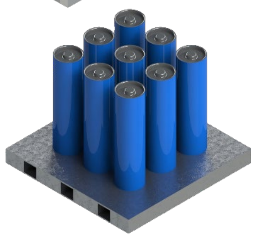
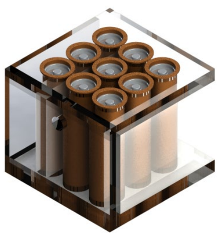


Fig. 2 *General classification of Battery Thermal Management System*

Table 1 *Design of the heat exchanger*

Illustration	Heat Exchanger	Design	Reference
	Flat Cold Plate	Straight Channel	[24], [25]
		Multiple Flow Channel	[26], [27]
		Topology Optimization	[28], [29]
		Animal Shape	[30], [31]
		Plant Shape	[32]–[35]
		Serpentine/ S Channel	[36]–[38]
		Tesla valve	[39], [40]
		Hexagonal Channel	[41]
		Microchannel Heatsink	[42]
		Stamped Zig-zag Turn	[43]
		Additional Fin	[44]–[47]
		Minichannel	[48]–[51]
		Ultra-thin Minichannel	[52]
		Zigzag Minichannel	[53]
	Wavy Cold Plate Channel	Mini Channel	[54]–[56]
		Serpentine Channel	[57]–[59]
		Additional Fin	[60]
	Jacket Holder	Basic	[61], [62]
		Combine with Baffle	[63]

The battery cells are kept from coming into direct contact with the coolant. Therefore, a heat exchanger is needed that functions as a separator between the coolant and the battery cells so that it can minimize corrosion and similar problems [64]. However, the gap between the heat exchanger and the pack must be ensured to be perfectly sealed to avoid leaks [65]. The materials used as heat exchangers tend to be made of metal with high thermal conductivity as shown in Table 2.

Table 2 *Thermal physical properties of heat exchanger [66]*

Property	Copper	Aluminum
Melting Point [K]	1358	933
Density [kg/m^3]	8933	2702
Specific heat capacity [J/[kg.K]]	385	903
Thermal conductivity [W/m.K]	401	237

4.2 Coolant

ILC, in addition to thermal resistance, has the main task of transferring heat from the battery so that the battery temperature is within the optimum temperature range. The advantage of liquid used as cooling media is that they have better thermal conductivity than the thermal conductivity of air [67]. Even though liquid has high thermal conductivity, it has a high viscosity, thereby increasing the pump's power consumption, which is quite large for the same mass flow rate. Still, the liquid is more efficient than air as it can keep the temperature lower than air for the same power consumption [11]. Each cooling fluid has various thermal physical properties with advantages and disadvantages. The most used liquid cooling are water, glycol, oil, nanofluid, and liquid metal, as shown in Table 3.

Table 3 *Thermal physical properties of liquid coolant [67]–[69]*

Property	Pure Water	Ethylene Glycol – Water mixture	Mineral Oil	Hydrofluoroether (NOVEC 7000)	Gallium
Density [kg/m^3]	995.81	1091.66	924.1	1400	6095
Specific heat capacity [kJ/[kg.K]]	4178	3042.02	1900	1300	370
Thermal conductivity [W/[m.K]]	0.6172	0.342	0.13	0.075	29.4
Viscosity [10^{-3} kg/[m.s]]	8.034	11	51.75	4.48	1.89

5. Thermal Runaway

Energy storage refers to the process of capturing and storing energy for later use. It involves changing energy from one form to another and storing it in a medium that can be used to generate electricity or other energy-related tasks. Koohi-Fayegh and Rosen in their journal review divide energy storage based on type, application, and category and compare where one of the energy storage technologies based on type is electrochemical energy storage and batteries [70].

Improving the safety of electric lithium-ion batteries is a concern in the development of the vehicle industry. To improve the safety and performance of lithium-ion batteries, many international organizations and committees have established and promulgated authoritative test standards and specifications that require safety testing and evaluation of batteries in extreme environments or abuse conditions, such as overcharging, high temperatures, short circuits, and impact [71]. Based on the characteristics of the test items, safety tests are generally divided into mechanical, environmental, and electrical tests as shown in Fig. 3.

The rise in discharging or charging rate leads to an escalation in the maximum temperature of the battery module. Furthermore, when subjected to the same current, the temperature of the battery is notably higher during the discharge process compared to the charging process [72]. An increase in temperature which results in thermal runaway which can be detected >30 hours in advance [73]. Temperatures that are too high or too low will damage the separator and affect its electrochemical and thermal characteristics. Thermal runaway on the battery is something that must be avoided to maintain driver safety when using an electric vehicle. One way to maintain safety when using a battery is to maintain the temperature of the battery when operating at an optimal temperature, 20℃ to 45℃, because the separator that separates the cathode and anode is in normal condition [74].

Three types of battery abuse that can cause thermal runaway are mechanical abuse, electrical abuse, and thermal abuse. Mechanical abuse includes collision and penetration (puncture). Collisions can cause the battery to deform, which in turn causes the battery separator to tear, resulting in an internal short circuit. Deformation resulting from penetration (puncture) can also cause leakage of electrolyte, which is flammable, thus causing a fire [75].

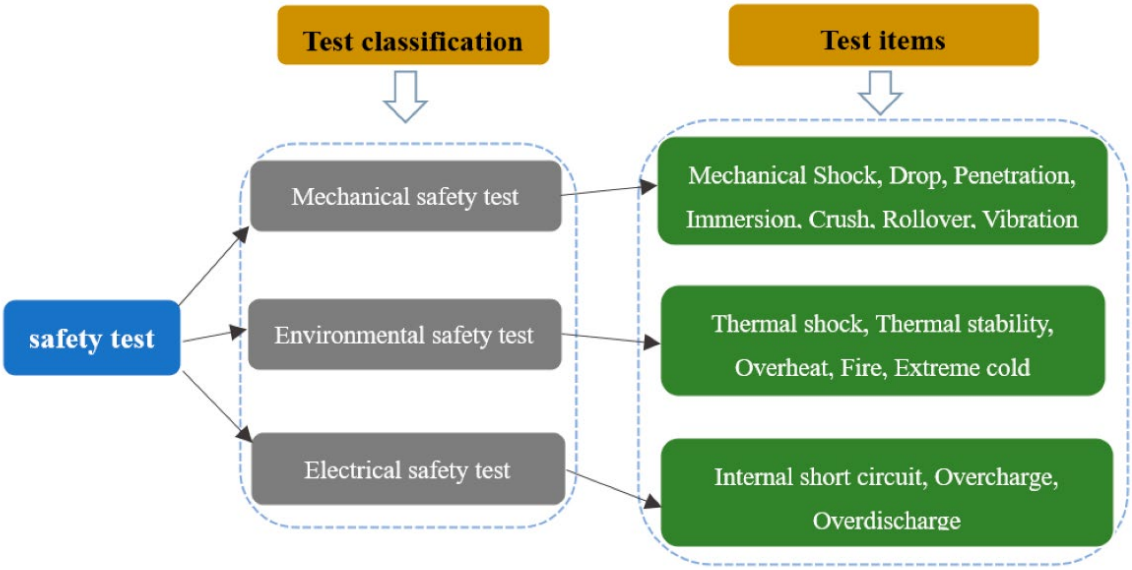


Fig. 3 *Safety test classification [71]*

6. Conclusion

ILC, using a variety of cooling fluids with various characteristics, can reduce temperatures quite significantly. The efficiency of liquid is better than air in reducing battery temperature with the same power consumption. Implementation of the ILC method is easy, cost effective, and able to improve safety in the presence of obstacles. Variations in heat exchanger design can improve performance, such as converting a straight mini duct to a Topology optimization design. Apart from that, the shapes of animals and plants have become quite widely developed designs. Safety testing is a standard that must be met in addition to keeping the battery temperature in the optimal range. Future research is expected to be able to present variations alternative cooling fluids aimed at optimizing BTMS performance.

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Conflict of Interest

The authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception****: Indri Yaningsih, Muhammad Nizam;* ***data and illustration****: Ahmadi Syarif Hidayatullah Dardiri, Dominicus Danardono Dwi Prija Tjahjana;* ***draft manuscript****: Ahmadi Syarif Hidayatullah Dardiri, Indri Yaningsih;* ***review and supervision****: Dominicus Danardono Dwi Prija Tjahjana; Muhammad Nizam.*

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