

Thermal control ways for Li-Ion batteries cooling: A review**Caminhos de controle térmico para baterias de Li-Ion cooling: Uma avaliação**

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ABSTRACT

Thermal management system is a relevant aspect for Li-ion batteries, mainly for electric vehicles. For this reason, several cooling methods have been proposed along the years, considering effect of both thermal conduction and convection. This study reviews the main methods applied for cooling Li-ion batteries: the use of phase change materials PCMs, air-forced and liquid cooling. Cell Arrangements are also presented due to the effect of temperature distribution. Finally, a discussion on the use of flow boiling as a mechanism of heat transfer in Li-ion batteries is presented.

Key words: lithium-ion battery, thermal management, optimization, heat exchanger.

RESUMO

O sistema de gerenciamento térmico é um aspecto relevante para as baterias de íon-lítio, principalmente para veículos elétricos. Por esta razão, vários métodos de resfriamento foram propostos ao longo dos anos, considerando tanto o efeito da condução térmica quanto o da convecção. Este estudo analisa os principais métodos aplicados para o resfriamento de baterias de íon de lítio: o uso de materiais de mudança de fase PCMs, resfriamento forçado a ar e líquido. Os arranjos celulares também são apresentados devido ao efeito da distribuição de temperatura. Finalmente, é apresentada uma discussão sobre o uso da ebulição de fluxo como mecanismo de transferência de calor em baterias de íon de lítio.

Palavras-chave: bateria de íon de lítio, gerenciamento térmico, otimização, trocador de calor.

1 INTRODUCTION

A global demand for vehicles is presenting a rapid growth, especially in developed countries. Nowadays, electric vehicles (EVs), hybrid electric vehicles (HEVs) and plugin hybrid electric vehicles (PHEVs) represent an alternative due to absence of nonrenewable resources such as petroleum or natural gas. In fact, environmental problems concerning pollution and greenhouse effect represent a challenge. The use of Li-ion batteries has become the main choice for energy storage units of EVs, mainly because of high energy, power density and capacity of accepting high charging rate in such batteries. But the performance of Li-ion cells is influenced directly by the temperature. At low temperature, Li-ion batteries present a decreasing performance and a low life expectancy with increasing the temperature [1]-[4]. In critical cases, the overheating of batteries can cause dangerous damages, including fire and/or explosion [5]. For this reason, a thermal management is needed and has become a challenge. Several thermal managements systems have been implemented in Li-ion batteries, including cooling via phase change materials (PCMs) [6], heat pipe cooling [7], forced air cooling [8]-[11], mist cooling and liquid cooling [12]. But such thermal management systems present serious limitations due to the generation of a large amount of thermal energy caused by electrochemical reactions during discharging process, causing overheating of the battery and a non-uniform temperature distribution. Considering these aspects, the use of other thermal management systems would be interesting to guarantee a better temperature control, including, for example, flow boiling to increase the heat transfer coefficient, compact heat exchangers to maximize the contact area – volume ratio of the working fluid, etc.

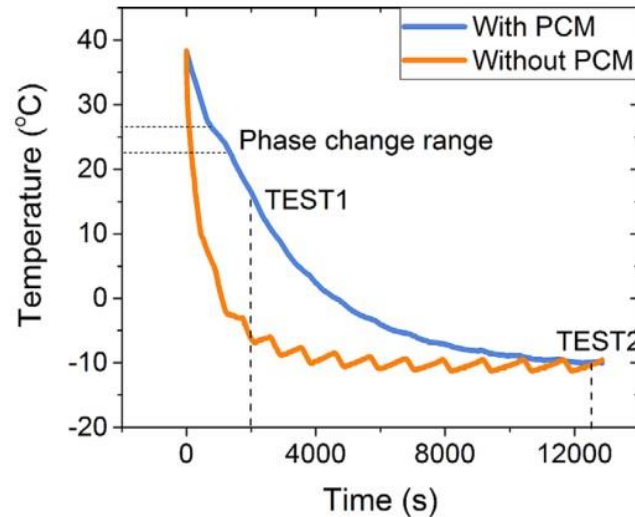
2 MAIN THERMAL MANAGERMENTS

2.1 PHASE CHANGE MATERIALS (PCMS)

The absence of motive components and compact configurations are some advantages related to the use of PCMs. In fact, the heat generated by Li-ion batteries can be absorbed by this type of material the phase change process, avoiding the increase of temperature along the time, helping to extend the working time of the batteries [13]. PCMs are generally classified into organic PCM (OPCM) and inorganic PCM (IPCM). Even considering advantages of IPCMs like lower volume changes and wider phase change temperature, most studies have been focused on investigation of OPCMs due to their negligible super-cooling [14] and low cost [15]. Ling et al. [16] studied the effect of a RT28/fumed silica composite PCM with a phase change temperature of 20 °C on a Li-ion battery operating below 5 °C. Figure 1 presents the results of battery temperature with and without PCM during preliminary cooling tests as a function of time. As it can be seen, in less than

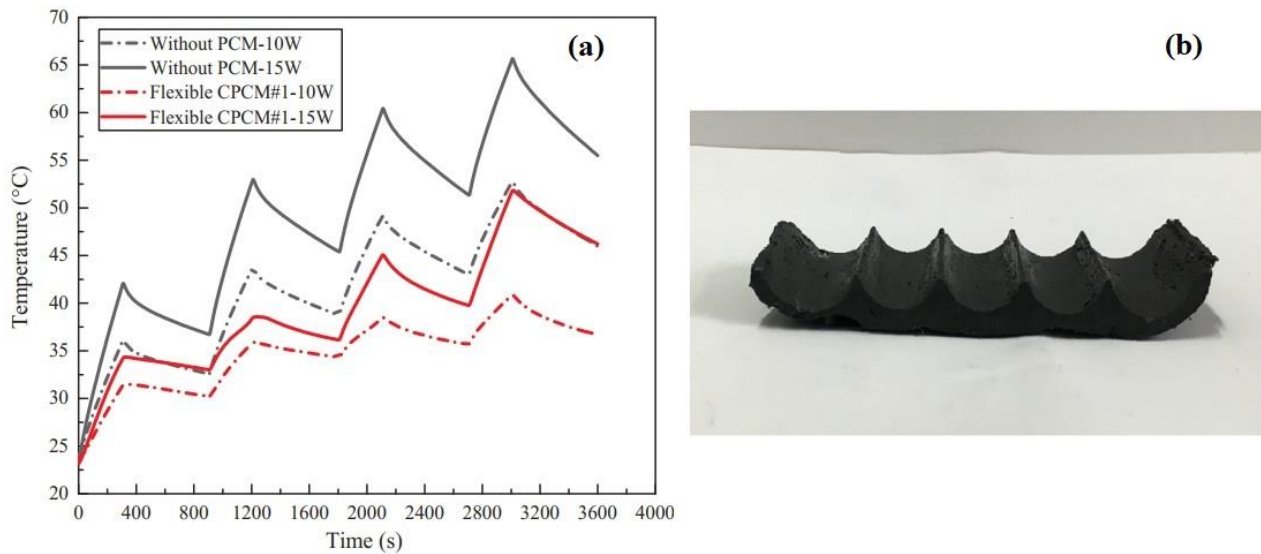
1 hour, the temperature of the battery without PCM drops to ambient temperature. On the other hand, even after being soaked in the cold environment for more than 3 h, the temperature of the cell remains above $-10\text{ }^{\circ}\text{C}$ with PCM.

Figure 1: Cooling curve of battery cell with and without PCM. Adapted from [16].



Investigations on flexible form-stable composite phase change materials CPCM applied in Li-ion battery thermal management are also found in literature [17]-[22]. But generally, PCMs present low thermal conductivity, causing a temperature gradient during the heat transfer. To overcome this feature, many authors have struggled to add thermal conductivity enhancement materials, carbon fibers [23], metal foam [24], expanded graphite [25], [26] and nano graphite sheets [27]-[28]. Figure 2(a) shows an example of the transient behavior of temperature found by [13] during an investigation considering an ambient temperature of $25\text{ }^{\circ}\text{C}$, using two different CPCMs. And according to the authors, the temperature of battery pack dropped by more than $18\text{ }^{\circ}\text{C}$ with the use of CPCM. Figure 2(b) presents an CPCM model used by the authors.

Figure 2: (a) Thermal performance of a flexible CPCM in transient working condition; (b) Photograph of a CPCM investigated. Adapted from [13].



Anyway, considerable temperature gradient found in PCMs represents a challenge to thermal management. For this reason, several authors have implemented nanostructures to decrease both thermal resistance and heat latent of such materials. [29] used a physical mixing method to obtain six different nanosilica (NS)-enhanced CPCMs. Figure 3 presents some images obtained from a scanning electron microscope SEM. According to the authors a new class of CPCMs with considerable anti-volume-change and anti-leakage performances were obtained by adding small amounts of NS. In particular, the CPCM battery module with NS (CPCM-NS5.5) presented better cooling effect due to the reduce gap between the batteries and the module. For this reason, the maximum temperatures of CPCM-NS with 5.5 wt% of NS were found to be between 1.6 and 5.9 °C lower than those of CPCM without NS.

2.2 AIR-FORCED

Some efforts have been expended to the study of forced convection to thermal management in Li-ions batteries. An important investigation was performed by [8] to analyze the influence of convective heat transfer using air as a working fluid. The authors investigated both numerical and experimental cases. According to their results, module temperature decreases with increase of freestream air velocity and with increase the distance between battery cells. [9] also investigated the influence of the convection heat transfer on the thermal performance of Li-ion batteries packs, considering the several mass flow rates of cooling air in 3D numerical simulations. Figure 4(a)-(b) presents profiles of temperatures found in wall batteries and air velocity inside the pack. The authors emphasize that the cell in the center and front end of the pack is hotter than the cell on the side. Such

a behavior is due to lack of air flow to the end of battery pack and concentrating of heat at the center of the battery pack. Moreover, the highest temperature also occurs at the end of the cell body which is located in the slot on the holding plate and block the cooling air reached the cell surfaces. The simulation results confirm that the designed air cooling system is capable to maintain the battery temperature within the desired range. The configuration of cells inside packs also represents a problem to the heat transfer. To study this parameter, a focus on different cell arrangements with forced air cooling was given by [11]. For this, the authors implemented a 3D CFD model was implemented to analyze the impact of different air cooling strategies on module thermal characteristics. Five different cell arrangements battery module were investigated, including 1 x 24, 3 x 8, 5 x 5 cell arrangements, a 19-cell hexagonal arrangement and a 28-cell circular arrangement. Figure 5 presents surface temperature obtained with and without the use of fan on battery module. Results show that 5 x 5 cell arrangement presents the best cooling capability, but the hexagonal structure offers the best space optimization as well as the cooling effectiveness.

Figure 3: SEM images of (a) expanded graphite, (b) CPCM-NS0, (c) NS, (d) CPCM-NS3, (e) CPCM-NS5.5 and (f) CPCM-NS7. Adapted from [29].

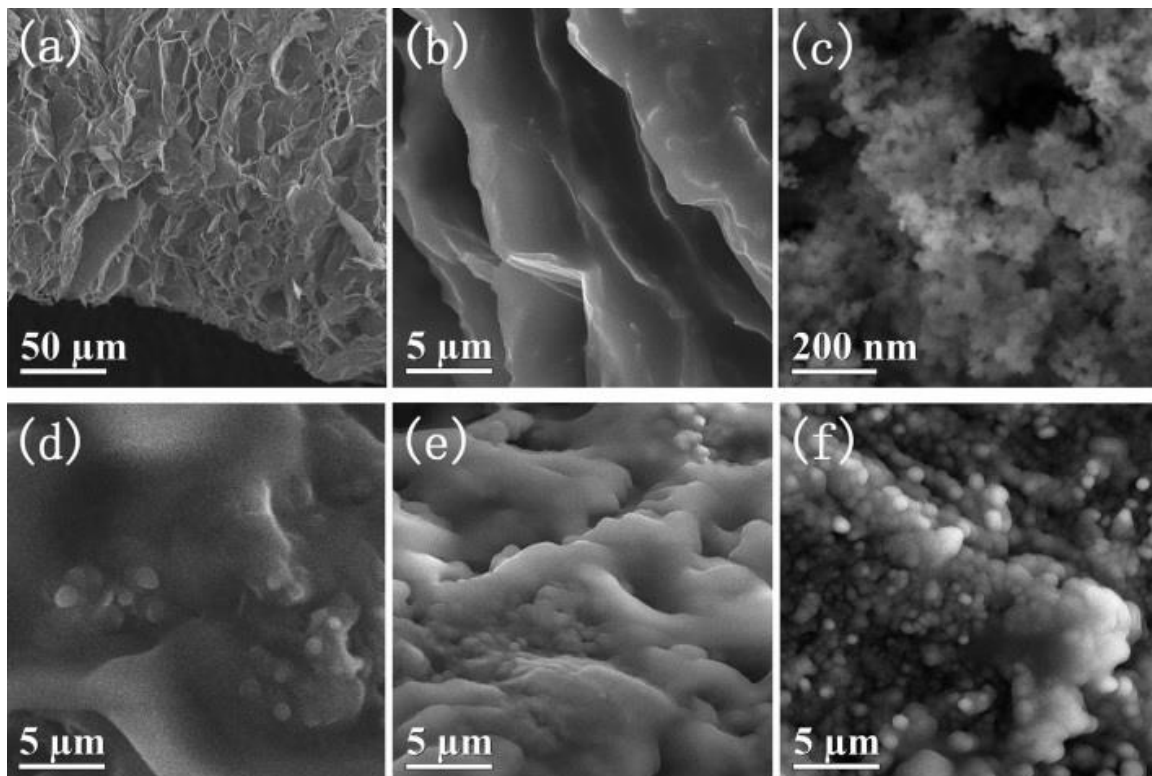


Figure 4: (a) Temperature distribution of the cells in the battery pack, (b) left side view of battery pack with velocity contour of airflow through the intake plenum, compartment and exhaust plenum. Adapted from [9]

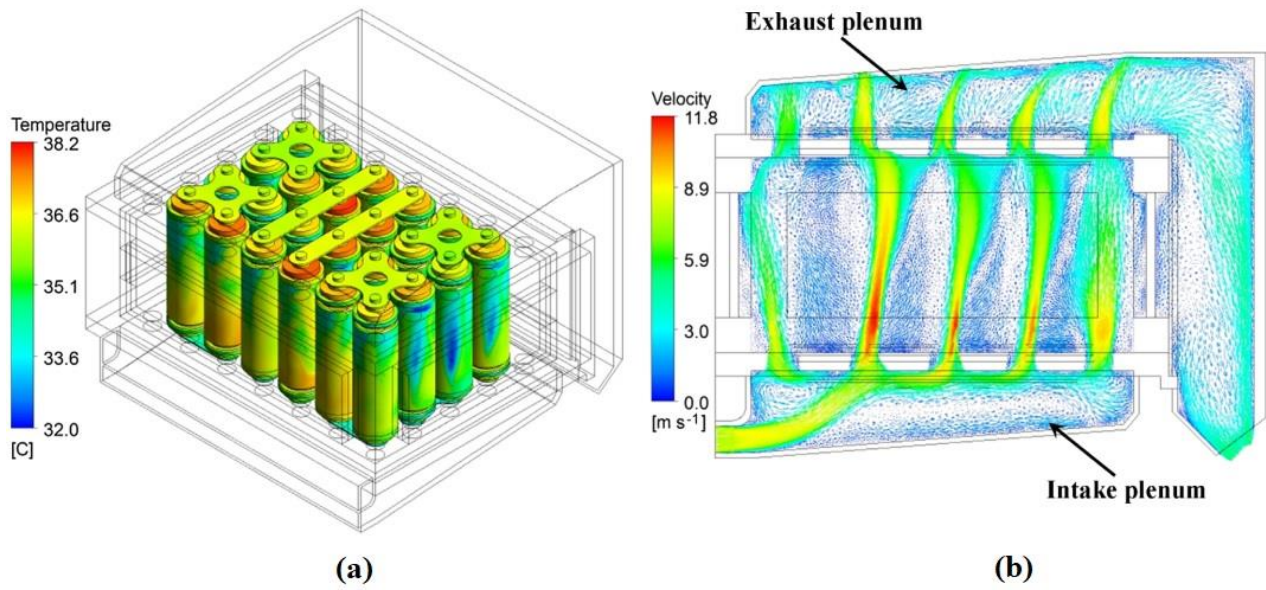
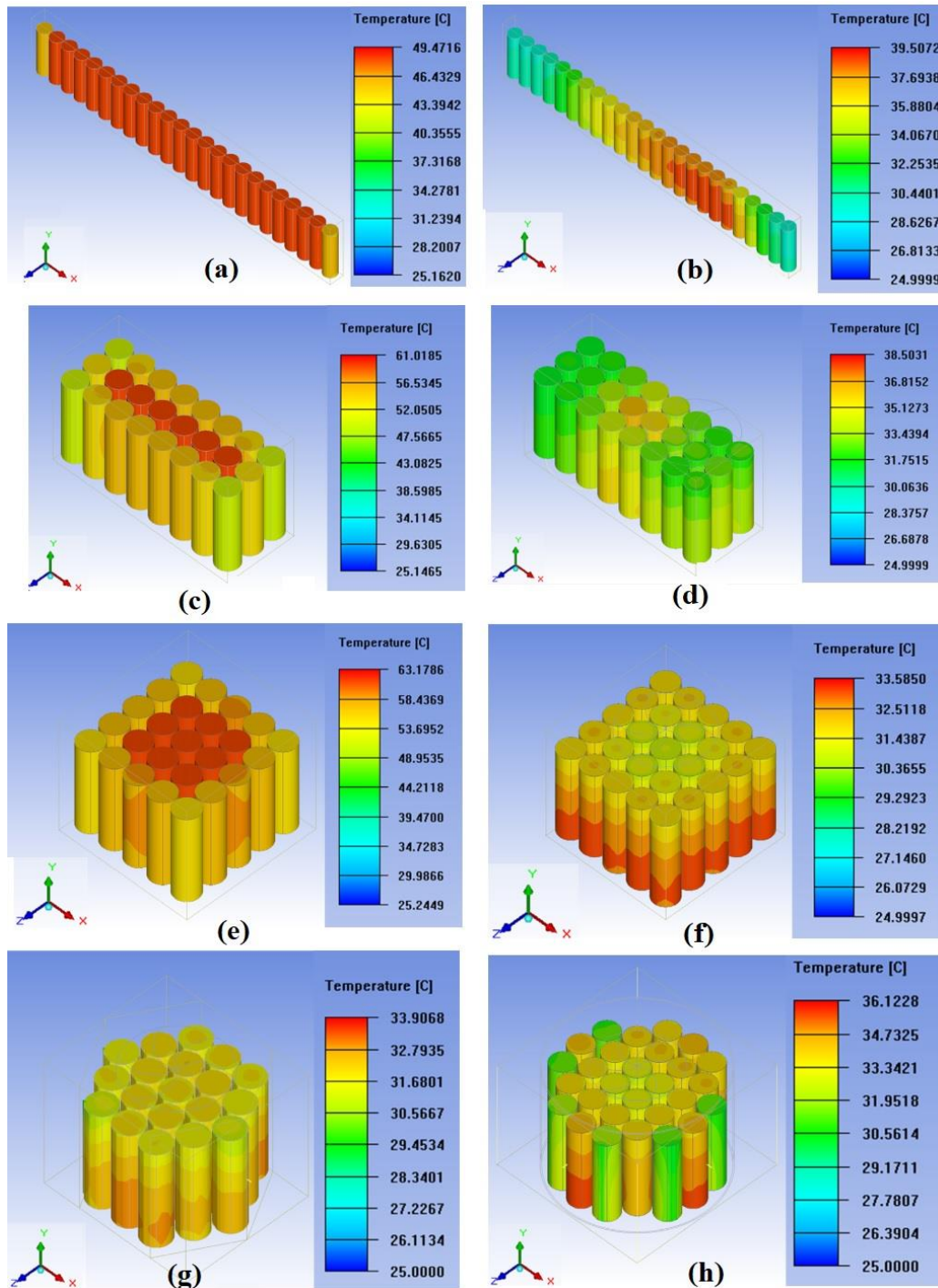


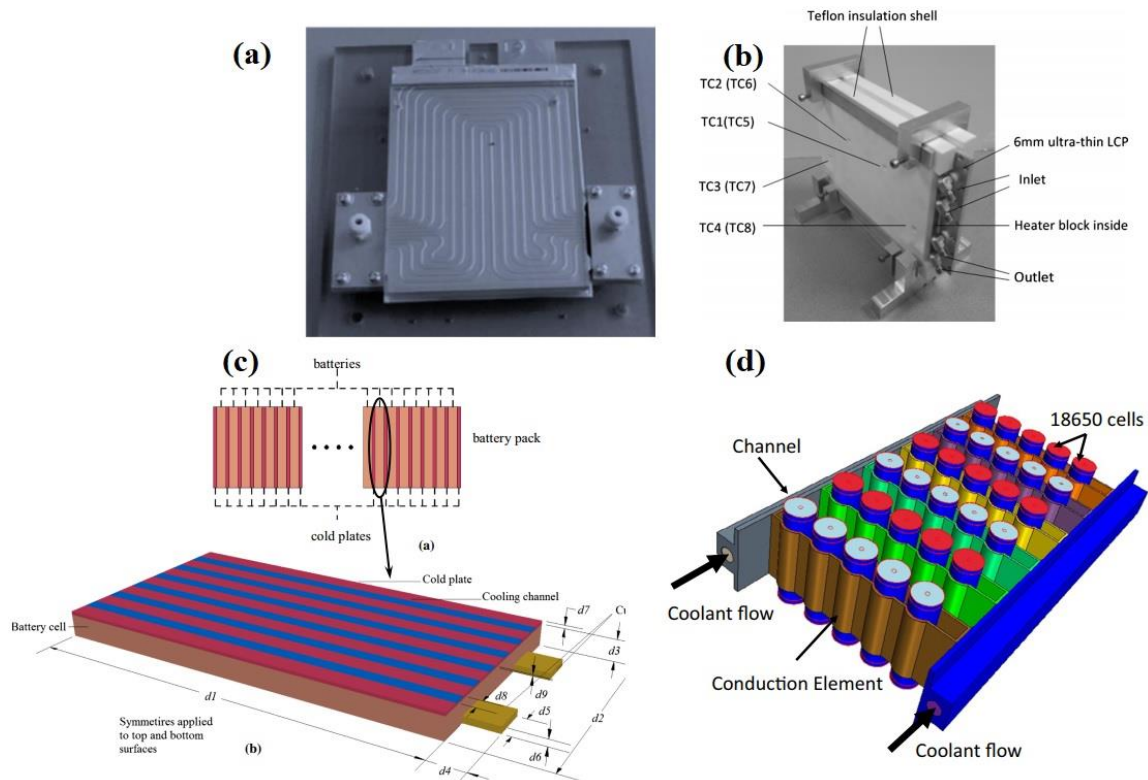
Figure 5: Temperature distribution on cell surface of (a) 1 x 24 cell arrangement module without fan, (b) 1 x 24 cell arrangement module with fan on the top surface of the module, (c) 3 x 8 battery module without airflow, (d) 3 x 8 battery module with fan on the top surface of the module, (e) 5 x 5 battery module without forced air cooling, (f) 5 x 5 battery module with fan on the top surface of the module, (g) hexagonal battery module with fan on the top, (h) cylindrical battery module with fan on the top. Adapted from [11].



2.3 LIQUID COOLING

Generally, liquid cooling is more complex, but this option offers a higher cooling capacity than air cooling system. Liquid cooling of the battery modules usually uses a heat spreader sandwich or a cold plate between the cells or submerging the cell in a dielectric fluid. In most cases, water, oil and ethylene glycol mixture are normally used as a working fluid to transfer heat from the batteries. However, the disadvantages of liquid cooling devices are related to the necessity of larger spaces and the increase of vehicle total weight, higher cost, high pumping power, potential leakage of cooling fluid and poor thermal contact between the cold plate and cell. For this reason, some authors have investigated the use of compact heat exchangers to minimize those problems. A study of a cold plate with nine multiple small channels for a prismatic Li-ion battery was performed by [30] using water as a cooling liquid as shown in Figure 6(a). The authors investigated temperature profile from 1 to 4 °C discharge rates and boundary conditions ranging from 5 to 35 °C. According to results, the temperature distribution was improved and presented an increasing behavior with the increase of discharge rates. A compact heat exchanger was analyzed by [31] focusing in a complex geometry containing oblique fins, Figure 6(b). Besides the temperature, the heat transfer coefficient was also investigated due its direct relationship with heat fluxes and superheat temperature (the difference between wall temperature of the battery and water temperature) along the module with the aid of CFD method. Numerically, it was reported the improvement of heat transfer caused by the oblique fins. And experimental results also indicated the increase of the heat transfer coefficient with the increase of mass flow rate. Several other studies have been found in literature related to the heat transfer with the use of liquid cooling with compact and complex geometries, as presented by [32] and [33], shown in Figures 6(c)-(d).

Figure 6: Heat exchangers studied to thermal management in Li-ions batteries presented by (a) [30], (b) [31], (c) [32], (d) [33].



2.4 FLOW BOILING - A POSSIBILITY?

Although liquid cooling methods can remove large amounts of heat from Li-ions batteries, the risk of superheating is still present due to limitations of thermodynamics properties of working fluids such as thermal conductivity, Prandtl number, specific heat, etc. For this reason, the latent heat associated with the effects of nucleate and convective boiling found in flow boiling phenomena would be an interesting option. During many years, a lot of authors have focused on the study of heat transfer and pressure drop during flow boiling. Considering the existence of limitations in this case such as high reduce pressures [34]-[36], toxicity [37], the use of working fluids with low saturation temperatures can result in more efficient processes of heat transfer. In this case, the use of hydrocarbons would be a good option even the existence of flammability [38]-[41]. Some works have presented high heat transfer coefficient found with hydrocarbons, mainly with R-600a [42], in small heat exchangers, but results related to the use in Li-ion thermal management have not been presented [43]. It is also possible to highlight that the use of multiple sources of energy as a power source for an electric vehicle allows to improve its performance increasing its autonomy and extending the life cycle of the onboard battery [44].

3 CONCLUSION

Researchers from various parts of the world have reported experimental and theoretical results on thermal managements of Li-ion batteries. Based on the results regarding the performance of different technics for cooling such types of batteries, it can be understood that PCMs present thermophysical limitations and the use of CPCM's can be a better alternative although limitations related to high temperature gradients have been still presented. Better results have been found in the cases related to forced convection, mainly in the cases of liquid cooling. The configuration of the cell inside the modules also represents a challenge to optimize the heat transfer of Li-ion batteries. This study also offers a discussion on the use of flow boiling as a heat transfer mechanism for heat exchange.

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