SURVEY OF AIR BATTERY THERMAL MANAGEMENT ON THE AUTONOMOUS MOBILE ROBOTS

by

Sevgi AYDIN[a*]***, Kadri Suleyman YIGIT***[a]***, and Ismail Hakki SAVCI***[b]

[a] Mechanical Engineering, Faculty of Engineering, Kocaeli University, Kocaeli, Turkey
[b] Product Development Department of FORD OTOSAN Company, FORD OTOSAN,
Istanbul, Turkey

Review paper
https://doi.org/10.2298/TSCI220805022A

With the development of computer technologies and battery systems, mobile robot systems have gained an important place in our lives. The Li-ion batteries, which attract attention for portable applications due to their high power output, light weight, and no memory effect, must operate in a limited temperature range in order to operate safely and for a long application life. This case makes it necessary to use battery thermal control systems that will provide temperature control for Li-ion battery applications. Within the scope of our study, Li-ion battery thermal management systems were investigated in detail. A detailed literature review was carried out on air thermal management systems, with their application and systemic convenience. Due to restricted packaging space for battery in mobile robots, cooling will be more challenging in the future. The air thermal management system, which has limited thermal management capability due to the low thermal properties of the air, is a thermal management method that will be sufficient especially for low scale applications.

Key words*: Li-ion battery, battery cooling, air temperature control, control air battery thermal management system, air cooling*

Introduction

Autonomous mobile robots that reduce manpower in the industry and increase system efficiency have attracted significant attention from the production industry, with the development of computer and software technologies and the Industry 4.0 industrial revolution [1, 2]. Autonomous mobile robots have become tools used in many operations of the production industry today, including production-lines and storage processes [3-5]. Each component of robot systems consist of many mechanical and electrical systems has an ideal operating temperature [6]. Thermal management for each of these components is very important for both itself and for their interactions with each other [7].

The temperature control of Li-ion battery power generation systems, which is widely preferred in mobile robot systems, is of vital importance for battery systems to operate safely and efficiently in the required cycle life [8]. The electrochemical reaction during the battery charge-discharge process creates reaction heat and joules heat due to ohmic resistances during ion transfer, and this state causes the battery temperature to increase exponentially during operation if cooling is not performed during battery operation [9]. It is recommended that battery

---

[*] Corresponding author, e-mail: sevgi.57.aydin@gmail.com

systems operate in the 15-35 °C operating temperature range, with the maximum temperature difference not exceeding 5 °C. In case the battery operated outside these temperature ranges, irreversible damage may occur to the battery. For this reason, various active or passive thermal management systems are used to to keep battery temperature under control.

Battery heat generation processes are difficult to understand, due to the difficulty of knowing how the electric current is distributed in the battery and variation of battery electrochemical reaction rate with time and temperature [10]. In order to carry out the cooling system design and optimization studies in a rational way, a good understanding of the battery heat generation processes is required. For this reason, many studies have been carried out on the electrochemical modelling of battery heat generation processes depending on the battery charge discharge rate and battery operating temperature [9-11]. Wu [9] studied temperature distribution and heat transfer models for simulate the temperature distribution. Kwon and Park [12] carried out numerical simulations to measure the amount for battery degradation and thermal runaway of battery operating wide temperature range. Tang *et al.* [13] noted that the heat generation on the battery surface is uneven, that the temperature is not homogeneously distributed on the battery surface and a higher amount of heat build-up in areas close to the cell current collection ports. It is not possible to achieve battery temperature distribution homogeneity and this case creates an important constraint for thermal management. It was concluded that the battery heat generation and heat generation inhomogeneity increased as the discharge rate increased, and the ambient temperature had little effect on the average heat generation rate.

Mobile robot systems consist battery power generation systems and with it associated of many electronic components and devices. Battery thermal control is not only for the safe and efficient operation of the battery, it is also necessary for the safety and efficient operation of affected by battery temperature systems and devices working in connection with the battery [4-7].

Air and liquid thermal management systems are predominantly preferred methods for battery temperature control. The air thermal management system, which is the subject of this study, a simple, low weight, leak free air thermal management system that uses air-flow to remove battery heat is the oldest preferred thermal management method for controlling battery temperature. It is not suitable to be used alone in extreme conditions and high power batteries, because of the low heat transfer ability of the air and low thermal management ability.

In our study, a detailed literature summary about air thermal management system, one of the basic battery thermal management systems, was prepared. It was observed that the studies focused on design optimization and design proposal. Due to it would be quite expensive and complex for studies to proceed only through experimental studies, it was seen that the studies were mainly carried out as numerical analysis and experimental verification.

Battery thermal management systems

Operation of battery systems outside the lower and upper operating temperature limits seriously battery capacity and service life deterioration, and even in consequence of thermal leaks such as combustion and explosion, it creates irreversible safety problems [14-18]. Thermal management systems are required to heat or cool the battery depending on the operating and ambient conditions of the battery system for the battery to meet the required performance and service life [17, 19].

Air thermal management system

It is a thermal management method of controlling the temperature of the battery by natural air convection or forced air convection by the fan [19]. Although natural-convection usually does not provide adequate thermal control, it may be adequate for thermal management at low discharge rates. Zhang *et al.* [20] studied the thermal control by natural air convection of a battery pack consisting of nine cells placed in various lay-outs. From straight row, square and circular placed lay-out battery packs, the straight row were obtained lower battery temperature in natural air convection, and then with square and cylindrical lay-out, respectively. Then, the effect of the distance between the batteries on the thermal properties of the battery pack was examined, it was seen that increasing the distance between the battery cells decreased the maximum temperature and the maximum temperature. However, it should not be forgotten that improves the thermal properties with increasing the distance between the batteries, but it is not a desirable situation, as increasing the distance between the battery cells will increase the battery pack volume. Yu *et al.* [21] observed the necessity of using a forced air battery thermal management system for battery pack safety at higher discharge rates, although the system thermal properties can be kept within the desired range at discharge rates as low as 0.5C in natural air cooling for the battery scheme in which they work.

Considering the studies with natural air convection and their results, it can be concluded that the forced air cooled air thermal management system provides a more reliable thermal control than the natural air convection thermal management system. In air thermal management system studies, researchers mainly focused on forced air convection air thermal management and focused on flow system modelling and flow system optimization [19, 22]. In flow system modelling and optimization studies various focal points were focused on. These, the cell arrangement in the battery pack, the cooling air inlet and outlet positions are design initiatives that will change the flow characteristics.

In so far as the flow path and characteristics of the batteries change depending on the arrangement of the cells in the battery pack, depending on the cell lay-outs, the thermal management capability of the battery pack varies. In the study of Fan *et al.* [23] examined the effects on thermal management efficiency of 32 cylindrical battery cells are arranged in a staggered and cross layouds of cells aligned in the battery pack, see fig. 1. The battery pack with the aligned cell arrangement was found to provide the best thermal performance. Following the aligned cell lay-out the most efficient cell arrays are staggered, diagonal, respectively. Aligned battery pack arrangement for thermal management required up to by 2% lower fan power consumption than cross arrangement. The most important factor for thermal management is the number of cells in the module, beyond cell arrangement and flow rate.

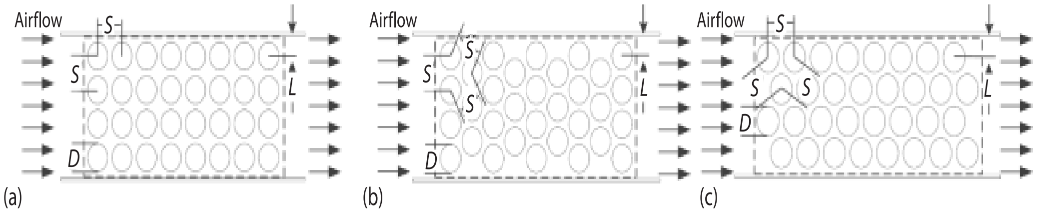

Figure 1. Staggered and cross cell layouds [23]; (a) aligned arrangement, (b) staggered arrangement, and (c) cross arrangement

Since the cooling air-flowing in the battery pack absorbs the heat of the battery cells, the ability of the air to absorb heat decreases, battery temperatures increase in the direction of cooling air-flowing, higher temperatures occur in the battery pack output cells. To prevent this situation, by making design modifications to the air inlet section in order to improve the cooling efficiency and temperature homogeneity of the battery pack, Shahid and Agelin-Chaab [24] designed a system, where the cell temperatures are higher that will provide fresh air supply to the outlet cells. With this design initiative, which provides fresh air supply to the outlet cells, 18.3% lower maximum temperature and 54.6% lower temperature difference were achieved. Na *et al.* [25] designed a battery pack that provides reverse air-flow between layers, in which the air-flow area is bisected by a polyamine plate for lower the temperature of the battery output cells and to increase the temperature uniformity of the battery pack. Due to the thermal interactions of the reverse air-flow layers, lower maximum temperature and higher temperature uniformity were achieved compared to the single-layer system. Similar to Na *et al.* [25] and Xu *et al.* [26] used a design that divides the air-flow field into layers. Unlike the other study, the flow direction was the same in the air-flow layers. At 2 m/s inlet air velocity, 3C discharge velocity, the single-layer design provided 5.15% less max temperature and 16.01% less maximum temperature difference than the unlayered design.

In battery packs cooled by one-way air-flow, another method used for to prevent of increase the output cells to higher temperatures and the decrease in the temperature homogeneity of the battery pack, has been the design of a system that allows the air-flow to flow back and forth in a certain period with valves that open and close at certain intervals. Mahamud and Park [27] designed and suggested a system that will provide forward-backward air-flow in a certain period, the schematic representation of which is given in fig. 2. It was stated that the shorter the forward-backward air-flow time, the lower the temperature difference and the maximum temperature. The maximum temperature difference and the maximum temperature decreased by 10 °C and 1.5 °C, respectively, compared to unidirectional air-flow with a back-and-forth air-flow period of 120 seconds. Wang and Ma [28] examined the strategies of unidirectional cooling, reciprocating cooling with constant period reciprocating air-flow, and active-controlled reciprocating cooling in their study. With reciprocating air cooling, the battery pack temperature uniformity was significantly improved. With the active control, the cooling power consumption for required cooling has been significantly reduced.

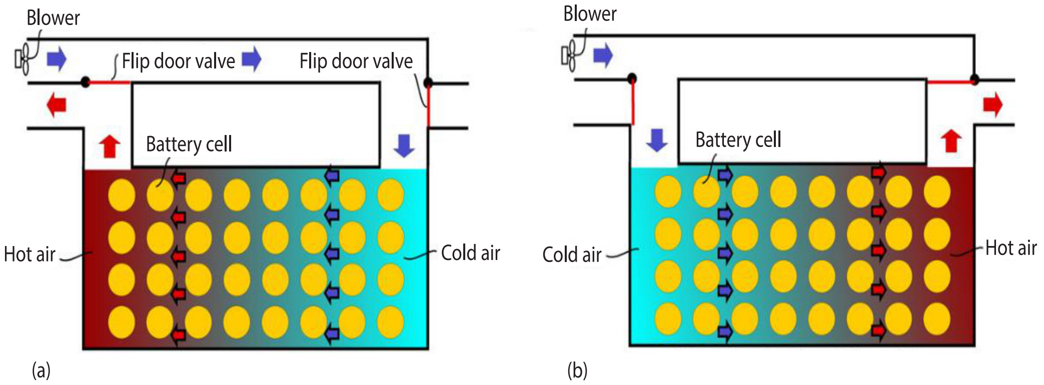

Figure 2. Reciprocating air cooling that provides forward-backward air-flow [27]; (a) flow direction from right to left and (b) flow direction from left to right

Lu *et al.* [29], who did not use the conventional battery module lay-out, created a battery module by being fixed on plates with ventilation holes in six rows of 252 cells, and the way of providing battery temperature control with axial air-flow was followed. In the analyzes carried out, investigated the effects on thermal management of duct size and number of ducts to allow cooling air to flow between battery packs. It was stated that increasing the channel size would not be an effective way to increase the thermal management efficiency, and increasing the number of channels was more effective. In another study using a battery module with a similar battery module lay-out as Yang *et al.* [30] studied the cooling of battery cells by axial air-flow, evaluating the effects of inter-cell radial spacing and cooling air-flow rate. Increasing the radial spacing of the battery pack slightly increases the battery pack average temperature while improving temperature uniformity. In addition, increasing the radial spacing of the cells from 2-10 mm reduced the cooling system parasitic power losses by 95.5%. Increasing the cooling system air-flow rate reduces the battery pack's maximum temperature and minimum temperature, while also improving the temperature uniformity within the battery pack, as it reduces the maximum temperature more than the minimum. Yang *et al.* [31] propose placing radiators with bionic surface structure to the battery surfaces to increase the heat transfer area to improve the thermal management of the battery pack consisting of cylindrical cells cooled by axial air-flow. It has been reported that the increase in bionic surface thickness and height effectively reduces the maximum temperature and maximum temperature difference, and the bionic surface shape affects the maximum temperature and maximum temperature difference at a negligible level.

Cooling air inlet and outlet location has been another research topic due to it affects the air-flow path and characteristics, thermal characteristic and thermal management efficiency of the battery module [32-35]. Li *et al.* [34] compared thermal kontrol effect of the fan positions. In terms of thermal performance, the fan on the back of the battery is more advantageous than on the side of the battery was reported. The reason for this is that in the design where the fan is positioned on the side surface of the battery, the heat transfer efficiency and thermal homogeneity are low, since the cooling air continues to heat up inside the battery pack. It has been reported that increasing the fan position and number to increase the effective heat transfer area will increase the thermal management capability. Battery holders have been ignored in studies examining the effects of fan position on thermal management.

Controlling the battery temperature with cooling air-flowing in the tangential direction has been one investigation subject in air thermal management systems. The tangential air-flow is sent to the battery pack cells placed at regular intervals, the cooling air is distributed tangentially to the intercellular channels and leaves the battery pack at varying positions depending on the tangential blower type. Depending on whether the air-flow directions are different or in the same direction, tangential air blower thermal management systems are called *u*-type and *z*-type tangential air blowers, respectively.

In the study of Li *et al.* [35] optimized the mass-flow rate and intercellular flow channel size for the *U*-type tangential air-cooled thermal management system. When the inter-cell flow channels of the battery pack are too wide, almost all of the flow will flow from the front flow channels of the battery pack, and the cooling air-flow will not flow to the back flow channels, this case causes a higher maximum temperature in the back cells and a higher temperature difference in the battery pack. Xie *et al.* [36] evaluated the cooling air inlet-outlet nozzle angles and made optimizations in *U*-type tangential air blower thermal management. It was determined that the optimum inlet and outlet nozzle angle was 2.5°, and the maximum temperature and temperature difference were reduced by 12.82% and 29.72%, respectively. Gocmen and Cetkin [37] used the elevated battery position improve the thermal management performance of the thermal management system in the *Z*-type tangential blower system operating at fast and ultra-fast discharge rates. With the elevated battery positions, the cooling air showed uniform flow resistance and velocity. Thanks to this design, the maximum temperature between cells has been reduced from 12-0.3 K. A fin was added to the thermal management design to increase the uniformity of intercellular temperature, electrical resistance, and aging rate above 6C discharge rates.

Table 1. Air thermal management system studies in the literature

	References	Battery type and capacity	The way of work	Battery load	T_{max} [°C]	ΔT [°C]	T_{env} [°C]	Working output
1	[20]	2,5 Ah 9 18650 cylindrical cells	Experimental	1-3C	55.4	3.2	35	The best thermal management performance is the line, square and cylindrical type lay-out, respectively, inside the battery lay-out
2	[38]	20 Ah, pocket type $LiFePO_4$ cell	Numerical (ANSYS), experimental	1-5C	52.2	6.7	23	In 3C, 4C and 5C discharge rates, the battery pack maximum temperature exceeded 40°C safety upper limit
3	[21]	22 pcs 2.7 Ah Panasonic NCR18650PF	Experimental	0.5-1C	30.5	2	25	It has been observed that forced air cooling is necessary for the battery to operate in safe thermal conditions at discharge rates above 0.5C discharge rate. Increasing the air supply flow rate in forced air cooling gradually reduces the maximum temperature
4	[39]	1,5 Ah Sanyo 18650 lithium-ion cell	Numerical (ANSYS), experimental	3C	33,50	–	25	Forced air cooling was required for long-term safe and stable operation. For forced air cooling, the cell arrangement with axial symmetry is very advantageous for cooling capability and thermal homogeneity
6	[22]	6 Ah capacity cell	Experimental					It was observed that as the distance between the cells increased, the air-flow rate inside the battery decreased, decreasing flow rate increased the battery temperatures
7	[40]		Numerical (COMSOL), exp.	2C	33,5	1,5	25	The aligned battery lay-out is a better choice for thermal management performance
8	[23]	3,6 Ah, 32 18650 cells	Experimental	2C			20	The battery pack with the aligned battery arrangement was found to provide the best thermal performance
9	[41]	16 serial lithium-ion cells	ANSYS, experimental	2C, 3C	31.25	1.01	25	It was determined that the 4x4 aligned cell arrangement was the most effective in terms of cooling performance
10	[42]	18650 lithium-ion cell	Numerical					As the cell numbers in the module increases, the cooling efficiency of the module decreases, while the temperature uniformity increases. In case the row of cells in the module exceeds eight, battery lay-out has no effect on thermal management performance
11	[43]	3,6 Ah battery	Numerical		28	0.11	22	With high discharge rates, the battery temperature and the maximum temperature difference between the cells increase significantly.

→

Table 1. Continuation

	References	Battery type and capacity	The way of work	Battery load	T_{max} [°C]	ΔT [°C]	T_{env} [°C]	Working output
12	[24]	2.5 Ah, 32 Samsung INR18650-25R	Numerical (ANSYS)			5	23	With the design changes made to the cooling air inlet plenum, 18.3% lower maximum temperature, 54.6% lower temperature difference were obtained
13	[44]	Battery pack consisting of 32 18650	Numerical (ANSYS), experimental		30-31.7	5.69-7.45	23	The design in which vortex generator and jet inlets are added to the inlet plenum, reduced the maximum temperature difference and maximum temperature by 21.5% and 5%, respectively
14	[45]	32 pcs 2.5 Ah 18650 lithium-ion cells	Numerical (ANSYS), experimental		34.40			When the input plenum was placed onp of the battery pack, the maximum temperature was reduced by 9%, the temperature uniformity was improved by about 39%
15	[25]	300 W 20 pcs cylindrical cell	ANSYS, experimental	3C	37,8	0.9		With the layered reverse air-flow system, lower maximum temperature and higher temperature uniformity were achieved compared to the single-layer system
16	[26]	2.5 Ah, 20 pcs cells	Numerical (ANSYS), experimental	3C	40	5	25	At 2 m/s inlet air velocity, 3C discharge rate, the single layer design provided 5.15% less max temperature and 16.01% less max temperature difference than the design without layer.
17	[27]	3.6 Ah cylindrical cell	Numerical (ANSYS)			4	35	The back-forth air-flow significantly improved the temperature uniformity inside the battery pack
18	[28]	20 Ah 18 $LiFePO_4$ cell	Experimental					Piston cooling with the back-forth air-flow significantly improved battery pack temperature uniformity compared to unidirectional air-flow cooling
19	[46]	8 26650 cylindrical cells	Experimental		<40	1	20	The battery module temperature difference has decreased significantly (from 4.1-1 °C) with active-controlled back and forth air-flow thermal management system design
20	[47]	37 Ah, pocket type cell	Experimental		20	6	25	Forth air-flow is more effective in terms of thermal management in the system where the battery is cooled by back-forth air-flow of the battery
21	[48]	9 pcs 3,35 Ah Panasonic NCR18650B	Experimental					In order to ensure the safe operation of the battery in harsh operating conditions, direct evaporative cooling system, which reduces the air temperature, is integrated into the air inlets of the back and forth air-flow system

→

Table 1. Continuation

	References	Battery type and capacity	The way of work	Battery load	T_{max} [°C]	ΔT [°C]	T_{env} [°C]	Working output
23	[49]	2.2 Ah 18650 lithium-ion cells	Numerical (ANSYS 14.5)					The effects of air inlet and outlet locations and cooling channel length on thermal management performance were analyzed
24	[30]	32 pcs 26650 $LiFePO_4$ cell	Numerical (ANSYS 14.5)		<40	<4	25	Increasing the radial spacing between cells improved the battery pack average temperature and temperature uniformity
25	[50]	10 Ah 38120 cylindrical cell	Numerical	1-5C			25-35	Active cooling is required for safe operation of the battery at high discharge rates and ambient temperatures
26	[51]	2 Ah, 18.650 cylindrical lithium-ion cell	Numerical (FLUENT), experimental	3-5C	<37	<5,5	25	Increasing the air hole number and hole diameter increase thermal management performance at the expense of very little power consumption. Increasing the inlet air pressure lowers battery module temperatures at the expense of power consumption
27	[31]	2.6 Ah capacity cylindrical 18650 cells	Numerical (FLUENT 18.2)	3C	<34	<5.32		It has been reported that the increase in bionic surface fin thickness and height effectively reduces the maximum temperature and maximum temperature difference, the bionic surface shape affects thermal manegement at a negligible level
28	[32]	15,6 Ah 60 pcs 18650 cells	Numerical, experimental	0, 5C 1C	<40		25	Having the air inlets and outlets on different sides of the module side surfaces provides better performance
29		12 LiC battery module	Numerical, experimental		30	<1		The lowest maximum temperature and the best temperature uniformity were achieved by designing the air inlet and outlet on opposite module side surfaces
30	[52]	25 pcs 18650 lithium-ion cells	Numerical (ANSYS)	3C	37	4.6	25	As the ventilation hole number is increased, the cooling capability increases depending on the changing air-flow rate, flow path and temperature
31	[53]	$LiFePO_4$ prismatic cell		1C	<35			The tangential air blower design with the same direction air inlet and outlet provided better thermal management performance
32	[35]	36 pcs cells	Numerical (ANSYS 17.0)			6.4		The large flow channels between the battery pack cells cause higher max temperature and temperature difference
33	[54]	2.2 Ah $LiFePO_4$ battery	Numerical	3-6C	51	3.1		The homogeneous distribution of the cooling air inside the battery pack can be improved by the inlet and outlet plenum angle optimizing, the maximum temperature and temperature difference can be reduced

→

Table 1. Continuation

	References	Battery type and capacity	The way of work	Battery load	T_{max} [°C]	ΔT [°C]	T_{env} [°C]	Working output
34	[55]	100Ah	Numerical (ANSYS)	1C, 1.5C	37.58	2.3	25	As the battery pack air-flow channel size and air intake angle increase, the battery temperature decreases
35	[56]		Numerical (ANSYS)			1.6		Cooling channel geometry, channel number and cooling plate material affect the thermal management capability
36	[57]	16 Ah battery consisting	ANSYS, experimental		39.2	2.6		As the cooling air-flow rate is increased, the heat transfer capability of the system increases, but the pressure losses increase
37	[58]	2.2 Ah 2 × 36 $LiPePO_4$ cells	Numerical	4C, 5C	<42.6	<2.9	27	Increased the flow channel size around the high temperature cells and reducing the maximum temperature difference by more than 29%.
38	[59]	2 × 12 $LiPePO_4$ battery	Numerical (FLUENT)	5C		<5	27	With the distance optimization between the cells, the maximum temperature difference was reduced by more than 60%
39	[36]	10 pcs prismatic	Numerical, experimental		<36.5		25	Thermal manegement capacity increase, with the optimization of the cooling air inlet and outlet nozzle angle and the distance between cells within the battery pack.
40	[60]	8 pcs 15 Ah prismatic pocket type cells	Numerical (ANSYS 12.0)					It was found that the maximum temperature and temperature difference of the battery module decreases as the channel size increases
41	[61]		Numerical			4.1		With regionally different cell distance, battery pack volume, maximu temperature and maximum temperature difference have been reduced
42	[62]		Numerical (ANSYS)		47.46	0.33		The research results showed that the addition of a flow deflector to the air diffuser nozzle and flow channels effectively improves thermal management performance
43	[63]		Numerical (ANSYS 17.0)		~37	~11	25	The thermal performance of the straight flow distributor was better than the arc and parabolic flow distributor
44	[64]	1.1 Ah 4 × 6 18650 lithium ion cells	Numerical	1-5C				By adding a 60° angle flow distributor and giving a 5 mm rounding diameter to the edges of battery packet profile to *Z*-type tangential air blow air thermal management system, the maximum temperature is reducing 36.66%

→

Table 1. Continuation

	References	Battery type and capacity	The way of work	Battery load	T_{max} [°C]	ΔT [°C]	T_{env} [°C]	Working output
45	[65]	1400Wh 72 pcs cells	Numerical (STAR CCM+)		52.8			The conical manifold design and opening a vent at the battery pack significantly increased cooling performance, significantly reducing fan power losses
46	[66]	12 × 2 pcs cells	Numerical	5C	<45	<5	27	By opening a vent at a point far from the cooling air outlet location, thermal management efficiency was increased and pumping power losses were reduced
47	[67]	1.6 Ah capacity $LiMn_2O_4$ pocket type cells	Numerical (ANSYS), experimental	3C	26.63		22	The J-type thermal management system provided lower maximum temperature with extra air evacuation region, better temperature uniformity, thus better thermal management capability
48	[68]	50 Ah lithium titanate battery					>10	The use of metal foam heat exchanger was found to be an effective method in terms of thermal management
49	[69]	3 pcs 20 Ah $LiFePO_4$ pocket type cell	Numerical (ANSYS-CFX)		<35	<5	30	The use of heat sink with aluminum foam heat transfer area provided better thermal management performance than non-aluminum foam heat sink
50	[70]	19,5 Ah, 8 $LiFePO_4$ cells	Numerical (ANSYS)	3C	40	5	25	The use of metal foam in the heat absorber increased the cooling efficiency
51	[71]	8S6P 18650 cell	Numerical (ANSYS)	5C	<42	<7		Multiple inlets and outlets of cooling air improved battery thermal control performance
52	[72]	40 cells battery	Numerical (ANSYS)					With the inclusion of porous material in the battery pack, the average temperature of the battery was reduced
53	[73]		Numerical, experimental	5C	<35			This proposed porous cold plate structure was useful in preventing these damages that may occur during heating-cooling of the battery
54	[74]	8 Ah, 8 lithium iron phosphate cells	Numerical (ANSYS), experimental	1- 3C	<40	<5	30	Mass-flow rate of 5 g/s and water loading rate of 3% were sufficient to keep the maximum temperature and temperature difference of the battery module below 40 °C and 5 °C, respectively

→

Table 1. Continuation

	References	Battery type and capacity	The way of work	Battery load	T_{max} [°C]	ΔT [°C]	T_{env} [°C]	Working output
55	[75]	24 pcs 18650, 26650, 42110 lithium-ion cells	Numerical (Fluent 14.0), experimental	5C				Type II and Type III are more advantageous at low inlet air velocities, while Type I is more advantageous at high inlet air velocities; therefore, it is not true that reverse air-flow will necessarily provide more advantageous thermal management
56	[76]		Numerical		<60		5-48	With this thermal management design, the battery pack has been enabled to operate within the safe range up to 48 °C ambient temperature
57	[77]	55 Ah battery module	Numerical		0.6-2C		20	Developing a battery pack design that will shorten the air-flow path and increase the heat dissipation performance improves thermal management performance
58	[78]		Numerical				20	Cylindrical cells provide less compact and more efficient thermal management capability than prismatic cells
59	[79]		Numerical, experimental	1C	33.1		24	Reduced heat build-up in the battery pack mid-cells with jet cooling; air inlet was provided from the bottom between the floor plate and the batteries, and heat removal between the batteries was strengthened
60	[37]		Numerical, experimental	1-10C		0.3	25	With the raised battery position, the flow distribution in the battery pack is increased homogeneously, thus providing higher thermal management capability
61	[80]	12 prismatic battery	Numerical (COMSOL)					It was evaluated that the cooling air, which is used for cooling the battery system that meets the residential energy needs, is used as the heat source of the residential air conditioning system.
62	[81]		Numerical (COMSOL)		<30		25	Cells of the battery pack were placed in a triangular arrangement. As the distance between the cells and the battery pack air outlets increases and the cooling air inlet speed increases, the battery pack temperatures decrease.
63	[82]	15 Ah capacity	Numerical, experimental		41.65	0.5	25	By adding six secondary air vents and a partition the ninth flow channel to the battery thermal management design, the max temperature and temperature difference were reduced by 4.95% and 91.89%, respectively.
64	[83]	3200 mAh, 4 × 6 cells	Numerical (FLUENT)		<35		20, 30	Rectangular fins have been added on the cylindrical batteries so that the battery pack can operate in the optimum temperature range.

Summary information about many more studies is given in tab. 1. Fan *et al.* [60] evaluated the use of unequal channel spacing to improve temperature uniformity, as the cooling channel size increases between the cells at constant cooling air-flow rate, the maximum temperature difference decreases, the maximum temperature increases. It was stated that unequal channel spacing did not have a significant effect on improving temperature uniformity, that it has an lowering effect on maximum temperature. Li *et al.* [61] suggested using regionally different intercellular channel widths.

Zhang *et al.* [62] intercellular duct and cooling air inlet manifold evaluated to addition of flow diverter for to enhance the thermal management capability of the *Z*-type tangential blown air thermal management system. Research results showed that it effectively improves thermal management performance by increasing flow homogeneity of the addition of a flow diverter to the air distributor manifold and flow channels.

The *U*-type and *Z*-type tangential blower air thermal management systems create similar temperature distributions in opposite regions of the battery pack. The use of secondary vent is one of the preferred design initiatives in order to improve the maximum temperature and temperature homogeneity of *U*-type and *Z*-type tangential air discharge thermal management systems. Hong *et al.* [66] evaluated the use of secondary vents to increase cooling efficiency. The diagram of the secondary vent locations evaluated in fig. 3. is given. Among the secondary vents, both the best thermal management efficiency and the lowest pumping power loss were achieved with the outlet – *r*, which is the vent at the furthest point from the cooling air outlet location.

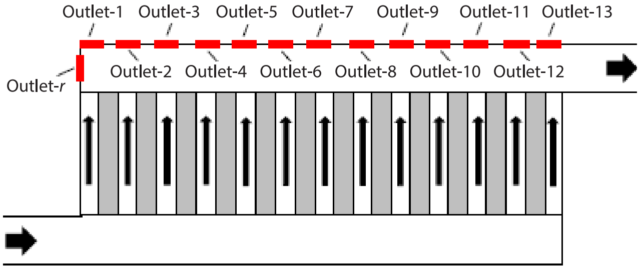

Figure 3. Using of secondary vent [66]

Metal foams have become a preferred material for the development of heat transfer and flow processes in recent years, thanks to their advantageous geometries. Metal foam structure is also a preferred material in battery thermal management system design development studies [68-70] used a thermal air thermal management design with an aluminum foam-based heat exchanger. Giuliano *et al.* [68] used a thermal air thermal management design with an aluminum foam-based heat exchanger. Wang *et al.* [70] studied the effects of metal foam porosity and pore density on thermal management capability for a system using metal foam in the battery pack flow field. Wang *et al.* [70] stated that aluminum foam heat sink is used in thermal management system provides 30% lower average max temperature than without matal foam thermal management system, at the expense of pumping power losses. Removal of metal foam mass in certain areas of the heat sink reduced pumping power requirements by reducing pressure losses, improved temperature homogeneity significantly.

We have mentioned before, that use of air as the cooling fluid has limited thermal management performance due to the low specific heat capacity of the air. Saw *et al.* [74] proposed a highly original and remarkable design for the air thermal management system. It used mist air containing water droplets for battery thermal management. Using dry and mist air was compared experimentally and numerically. As a result of the research was determined that the system using mist cooling air provided better performance with maximum temperature drop and temperature uniformity. The reason for the decrease of the maximum temperature battery and the improvement of the thermal homogeneity battery is the evaporation of water droplets in mist air by absorbing the heat produced in the battery.

Conclusions

Mobile robot systems have taken an important place with the development of battery power generation systems and computer systems in our lives. Temperature control is the biggest handicap of Li-ion battery power generation systems in order to operate safely within the required power, lifetime.

When the battery thermal management studies were examined, it was determined that the studies were mainly carried out on automotive applications, although real systems work with a lot of cells or battery module, almost all of the studies have been worked on a battery module or pack consisting of one or very few cells. Considering these situations, related studies should be interpreted for robot applications.

Thermal management studies were conducted on design proposition, design development and design optimization. The studies were mainly carried out as numerical simulation and experimental verification due to the long and costly experimental work. The results obtained in the studies are as follows.

- Regardless of the thermal management method, the thermal management of cylindrical cells is more efficient than prismatic cells due to their geometry. The uniformity of the thermal capacities of the battery pack cells increases the temperature homogeneity of the battery pack. In case of charge and discharge under the same conditions, thermal management loads are unequal, more heat is produced in the charging state than in the discharge.
- At medium and high charge-discharge loads, the use of without forced convection air convection for thermal management of the battery packet is insufficient in most cases. Thermal management performance is highly dependent on the placement of the cells in the battery pack. The battery pack array, which will reduce the interaction of the cells with each other as much as possible, provides better thermal management performance for air thermal thermal management without forced convection.
- Although forced air convection provides higher thermal management performance than non-forced convection, it is not a method that provides effective thermal management in all conditions. As with the without convection air thermal management system, the arrangement and arrangement of the batteries within the battery pack has an impact on thermal management performance. For forced convection air thermal management, the aligned arrays of cells in axial symmetry in the battery pack provide more effective thermal management performance. Another important consideration for a forced convection air thermal management system is the flow path of the cooling air through the battery pack. The cooling air progresses by losing its cooling efficiency due to the effect of heat gain and friction factor during the flow. For effective thermal management, the cooling air must be distributed homogeneously inside the battery pack and its travel distance must be short.
- In order to obtain a homogeneous temperature distribution in the battery pack, the cooling air must be homogeneously distributed in the battery pack. In the studies for this situation, using conical air inlet and outlet nozzles, adding a flow deflector to the battery pack and adding a secondary ventilation hole were the ways followed.

Acknowledgment

The authors would like to thank FORD OTOSAN and TUBITAK for 118C121 project number 2244 Ph.D. industry scholarship program for their support in making this study.

References

[1] Ghelichi, Z., Kilaru, S., Analytical Models for Collaborative Autonomous Mobile Robot Solutions in Fulfillment Centers, *Applied Mathematical Modelling*, *91* (2021), Mar., pp. 438-457

[2] Wang, C., *et al*., How to Secure Autonomous Mobile Robots an Approach with Fuzzing, Detection and Mitigation, *Journal of Systems Architecture*, *112* (2021), 101838

[3] Fragapane, G., *et al*., Planning and Control of Autonomous Mobile Robots for Intralogistics: Literature Review and Research Agenda, *European Journal of Operational Research*, *294* (2021), 2, pp. 405-426

[4] Karamuk, S. M., Ocaklı, H., A Survey on Traction System Development of Automated Guided Vehicles, *European Journal of Technique (EJT)*, *12* (2022), 1, pp. 1-12

[5] Savci, I. H., *et al*., Improving Navigation Stack of a Ros-Enabled Industrial Autonomous Mobile Robot (AMR) to be Incorporated in a Large-Scale Automotive Production, *International Journal of Advanced Manufacturing Technology*, *12*0 (2022), 1, pp. 3647-3668

[6] Clauer, D., *et al*., Usage of Autonomous Mobile Robots Outdoors – An Axiomatic Design Approach, *Procedia CIRP*, *96* (2021), 1, pp. 242-247

[7] Sevinchan, E., *et al*., A Review on Thermal Management Methods for Robots, *Applied Thermal Engineering*, *140* (2018), July, pp. 799-813

[8] Ma, S., *et al*., Temperature Effect and Thermal Impact in Lithium-Ion Batteries: A Review, *Progress in Natural Science: Materials International*, *28* (2018), 6, pp. 653-666

[9] Wu, M.-S., Natural Science: Materials International Heat Dissipation Design for Lithium-Ion Batteries, *Journal of Power Sources*, *109* (2002), 1, pp. 160-166

[10] Alihosseini, A., *et al*., Experimental Study and Numerical Simulation of a Lithium-Ion Battery Thermal Management System Using a Heat Pipe, *Journal of Energy Storage*, *39* (2021), 102616

[11] Panchal, S., *et al*., Experimental and Theoretical Investigations of Heat Generation Rates for a Water Cooled $LiFePO_4$ Battery, *International Journal of Heat and Mass Transfer*, *101* (2016), Oct., pp. 1093-1102

[12] Kwon, H. Park, H., Numerical Simulation of Prismatic Lithium-Ion Battery Life Cycles under a Wide Range of Temperature, *International Journal of Precision Engineering and Manufacturing – Green Technology*, *6* (2019), Jan., pp. 63-73

[13] Tang,Y., *et al*., Study of the Thermal Properties during the Cyclic Process of Lithium Ion Power Batteries Using the Electrochemical-Thermal Coupling Model, *Applied Thermal Engineering*, *137* (2018), June, pp. 11-22

[14] Tang, A., *et al*., Optimization Design and Numerical Study on Water Cooling Structure for Power Lithium Battery Pack, *Applied Thermal Engineering*, *159* (2019), 113760

[15] Ramadass, P., *et al*., Capacity Fade of Sony 18650 Cells Cycled at Elevated Temperatures – Part I: Cycling Performance, *Journal of Power Sources*, *112* (2002), 2, pp. 606-613

[16] Hu, M., *et al*., Study on Cycle-Life Prediction Model of Lithium-Ion Battery for Electric Vehicles, *International Journal of Electrochemical Science*, *11* (2016) 1, pp. 577-589

[17] Ma, S., *et al*., Temperature Effect and Thermal Impact in Lithium-Ion Batteries: A Review, *Progress in Natural Science: Materials International*, *28* (2018), 6, pp. 653-666

[18] Zhao, X., Thermal Performance Analysis and Optimal Control of Power Lithium Cell Thermal Management System for New Energy Vehicles, *Thermal Science*, *24* (2020), 5B, pp. 3375-3383

[19] Zhang, X., *et al*., A Review On Thermal Management of Lithium-Ion Batteries for Electric Vehicles, *Energy*, *238* (2022), 121652

[20] Zhang, Y., *et al*., *et al*., Effects of the Structure Arrangement and Spacing on the Thermal Characteristics of Li-Ion Battery Pack at Various Discharge Rates, *Applied Thermal Engineering*, *165* (2020), 114610

[21] Yu, X., *et al*., Experimental Study on Transient Thermal Characteristics of Stagger-Arranged Lithium-Ion Battery Pack with Air Cooling Strategy, *International Journal of Heat and Mass Transfer*, *143* (2019), 118576

[22] Choi, Y. S., Kang, D. M., Prediction of Thermal Behaviors of an Air-Cooled Lithium-Ion Battery System for Hybrid Electric Vehicles, *Journal of Power Sources*, *270* (2014), Dec., pp. 273-280

[23] Fan, Y., *et al*., Experimental Study on the Thermal Management Performance of Air Cooling for High Energy Density Cylindrical Lithium-Ion Batteries, *Applied Thermal Engineering*, *155* (2019), June, pp. 96-109

[24] Shahid, S., Agelin-Chaab, M., Experimental and Numerical Studies on Air Cooling and Temperature Uniformity in a Battery Pack, *International Journal of Energy Research*, *42* (2018), 6, pp. 2246-2262

[25] Na, X., *et al*., Reverse Layered Air-Flow for Li-Ion Battery Thermal Management, *Applied Thermal Engineering*, *143* (2018), Oct., pp. 257-262

[26] Xu, Y., *et al*., Numerical Analysis and Surrogate Model Optimization of Air-Cooled Battery Modules Using Double-Layer Heat Spreading Plates, *International Journal of Heat and Mass Transfer*, *176* (2021), 121380
[27] Mahamud, R., Park, C., Reciprocating Air-Flow for Li-Ion Battery Thermal Management to Improve Temperature Uniformity, *Journal of Power Sources*, *196* (2011), 13, pp. 5685-5696
[28] Wang, H., Ma, L.,Thermal Management of a Large Prismatic Battery Pack Based on Reciprocating Flow and Active Control, *International Journal of Heat and Mass Transfer*, *115* (2017), Part A, pp. 296-303
[29] Lu, Z., *et al*., Thermal Management of Densely-Packed EV Battery with Forced Air Cooling Strategies, *Energy Procedia*, *88* (2016), June, pp. 682-688
[30] Yang, T., *et al*., Investigation of the Thermal Performance of Axial-Flow Air Cooling for the Lithium-Ion Battery Pack, *International Journal of Thermal Sciences*, *108* (2016), Oct., pp. 132-144
[31] Yang, W., *et al*.,Thermal Performance of Axial Air Cooling System with Bionic Surface Structure for Cylindrical Lithium-Ion Battery Module, *International Journal of Heat and Mass Transfer*, *161* (2020), 120307
[32] Jiaqiang, E., *et al*., Effects of the Different Air Cooling Strategies on Cooling Performance of a Lithium-Ion Battery Module with Baffle, *Applied Thermal Engineering*, *144* (2018), Nov., pp. 231-241
[33] Soltani, M., *et al*., The 3-D Thermal Model Development and Validation for Lithium-Ion Capacitor Module Including Air-Cooling System, *Applied Thermal Engineering*, *153* (2019), May, pp. 264-274
[34] Li, X., *et al*., Experiment and Simulation for Pouch Battery with Silica Cooling Plates and Copper Mesh Based Air Cooling Thermal Management System, *Applied Thermal Engineering*, *146* (2019), Jan., pp. 866-880
[35] Li, M., *et al*., Modelling and Optimization of an Enhanced Battery Thermal Management System in Electric Vehicles, *Frontiers of Mechanical Engineering*, *14* (2019), June, pp. 65-75
[36] Xie, J., *et al*., Structural Optimization of Lithium-Ion Battery Pack with Forced Air Cooling System, *Applied Thermal Engineering*, *126* (2017), Nov., pp. 583-593
[37] Gocmen, S., Cetkin, E., Emergence of Elevated Battery Positioning in Air Cooled Battery Packs for Temperature Uniformity in Ultra-Fast Dis/Charging Applications, *Journal of Energy Storage*, *45* (2022), 103516
[38] Kalkan, O., *et al*., Experimental and Numerical Investigation of the $LiFePO_4$ Battery Cooling by Natural-Convection, *Journal of Energy Storage*, *40* (2021), 102796
[39] Wang, K., Thermal Investigation of Lithium-Ion Battery Module with Different Cell Arrangement Structures and Forced Air-Cooling Strategies, *Applied Energy*, *134* (2014), Dec., pp. 229-238
[40] Yang, N., *et al*., Assessment of the Forced Air-Cooling Performance for Cylindrical Lithium-Ion Battery Packs: A Comparative Analysis Between Aligned and Staggered Cell Arrangements, *Applied Thermal Engineering, 80* (2015), Apr., pp. 55-65
[41] Zeng, J. E. Y., *et al*., Heat Dissipation Investigation of the Power Lithium-Ion Battery Module Based on Orthogonal Experiment Design and Fuzzy Grey Relation Analysis, *Energy*, *211* (2020), 118596
[42] Singh, L. K., *et al*., A Numerical Study on Thermal Management of a Lithium-Ion Battery Module Via Forced-Convective Air Cooling, *International Journal of Refrigeration*, *131* (2021), Nov., pp. 218-234
[43] Jilte, R. D., Kumar, R., Numerical Investigation on Cooling Performance of Li-Ion Battery Thermal Management System at High Galvanostatic Discharge, *Engineering Science and Technology, an International Journal*, *21* (2018), 5, pp. 957-969
[44] Shahid, S., Agelin-Chaab, M., Analysis of Cooling Effectiveness and Temperature Uniformity in a Battery Pack for Cylindrical Batteries, *Energies*, *10* (2017), 1157
[45] Shahid, S,. Agelin-Chaab, M., Development and Analysis of a Technique to Improve Air-Cooling and Temperature Uniformity in a Battery Pack for Cylindrical Batteries, *Thermal Science and Engineering Progress*, *5* (2018), Mar., pp. 351-363
[46] He, F., Ma, L., Thermal Management of Batteries Employing Active Temperature Control and Reciprocating Cooling Flow, *International Journal of Heat and Mass Transfer*, *83* (2015), Apr., pp. 164-172
[47] Wang, S., *et al*., Improved Thermal Performance of a Large Laminated Lithium-Ion Power Battery By Recip Rocating Air-Flow, *Applied Thermal Engineering*, *152* (2019), Apr., pp. 445-454
[48] Zhao, R., *et al*., Experimental Study of a Direct Evaporative Cooling Approach for Li-Ion Battery Thermal Management, *International Journal of Energy Research*, *44* (2020), 8, pp. 6660-6673
[49] Lu, Z., *et al*., Parametric Study of Forced Air Cooling Strategy for Lithium-Ion Battery Pack with Staggered Arrangement, *Applied Thermal Engineering*, *136* (2018), May, pp. 28-40
[50] Zhang, Z., *et al*., Thermal Modelling and Cooling Analysis of High-Power Lithium Ion Cells, *Journal of Thermal Science*, *20* (2011), Nov., pp. 570-575

[51] Zhou, H., *et al*., Thermal Performance of Cylindrical Lithium-Ion Battery Thermal Management System Based on Air Distribution Pipe, *International Journal of Heat and Mass Transfer*, *131* (2019), Mar., pp. 984-998

[52] Zhang, F., *et al*., Design Optimization of Forced Air-Cooled Lithium-Ion Battery Module Based on Multi-Vents, *Journal of Energy Storage*, *40* (2021), 102781

[53] Peng, X., *et al*., Thermal Performance Investigation of an Air-Cooled Lithium-Ion Battery Pack Considering the Inconsistency of Battery Cells, *Applied Thermal Engineering*, *153* (2019), May, pp. 596-603

[54] Chen, K., *et al*., Design of Parallel Air-Cooled Battery Thermal Management System through Numerical Study, *Energies*, *10* (2017), 10, 1677

[55] Ye, M., *et al*., The Structure Optimization of Lithium-Ion Battery Pack Based on Fluid-Solid Conjugate Thermodynamic Analysis, *Energy Procedia*, *152* (2018), Oct., pp. 643-648

[56] Sun, S., Dixon, R., Development of Cooling Strategy for an Air Cooled Lithium-Ion Battery Pack, *Journal of Power Sources*, *272* (2014), Dec., pp. 404-414

[57] Chen, K., *et al*., Configuration Optimization of Battery Pack in Parallel Air-Cooled Battery Thermal Management System Using an Optimization Strategy, *Applied Thermal Engineering*, *123* (2017), Sept., pp. 177-186

[58] Chen, K., *et al*., Configuration Optimization of Battery Pack in Parallel Air-Cooled Battery Thermal Management System Using an Optimization Strategy, *Applied Thermal Engineering*, *123* (2017), Aug., pp. 177-186

[59] Chen, K., *et al*., Design of the Cell Spacings of Battery Pack in Parallel Air-Cooled Battery Thermal Management System, *International Journal of Heat and Mass Transfer*, *127* (2018), Part A, pp. 393-401

[60] Fan, L., *et al*., A Parametric Study on Thermal Management of an Air-Cooled Lithium-Ion Battery Module For Plugin Hybrid Electric Vehicles, *Journal of Power Sources*, *238* (2013), Sept., pp. 301-312

[61] Li, W., *et al*., A Surrogate Thermal Modelling and Parametric Optimization of Battery Pack with Air Cooling for EVs, *Applied Thermal Engineering*, *147* (2019), Jan., pp. 90-100

[62] Zhang, F., *et al*., Design Optimization of Forced Air-Cooled Lithium-Ion Battery Module Based on Multi-Vents, *Journal of Energy Storage*, *40* (2021), 102781

[63] Wang, N., *et al*., Effect Analysis on Performance Enhancement of a Novel Air Cooling Battery Thermal Management System with Spoilers, *Applied Thermal Engineering*, *192* (2021), 116932

[64] Xi, Y., *et al*., Novel z-Shaped Structure of Lithium-Ion Battery Packs and Optimization for Thermal Management, *Journal of Energy Engineering*, *146* (2020), 04019035

[65] Park, H., A Design of Air-Flow Configuration for Cooling Lithium Ion Battery in Hybrid Electric Vehicles, *Journal of Power Sources*, *239* (2013), Oct., pp. 30-36

[66] Hong, S., *et al*., Design of Flow Configuration for Parallel Air-Cooled Battery Thermal Management System with Secondary Vent, *International Journal of Heat and Mass Transfer*, *116* (2018), Jan., pp. 1204-1212

[67] Liu, Y., Zhang, J., Design a j-Type Air-Based Battery Thermal Management System through Surrogate-Based Optimization, *Applied Energy*, *252* (2019), 113426

[68] Giuliano, M. R., *et al*., Experimental Study of an Air-Cooled Thermal Management System for High Capacity Lithium-Titanate Batteries, *Journal of Power Sources*, *216* (2012), Oct., pp. 345-352

[69] Saw, L. H., *et al*., Computational Fluid Dynamics Simulation on Open Cell Aluminum Foams For Li-Ion Battery Cooling System, *Applied Energy, 204* (2017), Oct., pp. 1489-1499

[70] Wang, Y., *et al*., Thermal Performance Of Lithium-Ion Batteries Applying Forced Air Cooling with an Improved Aluminum Foam Heat Sink Design, *International Journal of Heat and Mass Transfer*, *167* (2021), 120827

[71] Hu, Y., Mao, B., Numerical Analysis and Optimization of Thermal Performance of Lithium Battery Pack Based on Air-Cooling Strategy, *Thermal Science*, *26* (2022), 5B, pp. 4249-4258

[72] Li, Z. Z., *et al*., Optimization for Cooling System of Batteries Having Porous Material Using Design of Experiments, *International Journal of Precision Engineering and Manufacturing*, *16* (2015), Feb., pp. 275-279

[73] Son, Y. W., *et al*., On Thermally Managing Lithium-Ion Battery Cells by Air-Convection Aspirated in Tetrahedral Lattice Porous Cold Plates, *Applied Thermal Engineering*, *189* (2021), 116711

[74] Saw, L. H., *et al*., Novel Thermal Management System Using Mist Cooling for Lithium-Ion Battery Packs, *Applied Energy*, *223* (2018), Aug., pp. 146-158

[75] Zhao, J., *et al*., Thermal Management of Cylindrical Power Battery Module for Extending the Life of New Energy Electric Vehicles, *Applied Thermal Engineering*, *85* (2015), June, pp. 33-43

[76] Fathabadi, H., A Novel Design Including Cooling Media for Lithium-Ion Batteries Pack Used in Hybrid and Electric Vehicles, *Journal of Power Sources*, *245* (2014), Jan., pp. 495-500
[77] Xu, X. M., *et al*., Research on the Heat Dissipation Performance of Battery Pack Based on Forced Air Cooling, *Journal of Power Sources*, *240* (2013), Oct., pp. 33-41
[78] Xun, J., *et al*., Numerical and Analytical Modelling of Lithium Ion Battery Thermal Behaviors with Different Cooling Designs, *Journal of Power Sources*, *233* (2013), July, pp. 47-61
[79] Yu, K., Thermal Analysis and Two-Directional Air-Flow Thermal Management for Lithium-Ion Battery Pack, *Journal of Power Sources*, *270* (2014), Dec., pp. 193-200
[80] Mustafa, M., Effect of Inlet and Outlet Size, Battery Distance, And Air Inlet and Outlet Position on the Cooling of a Lithium-Ion Battery Pack and Utilizing Outlet Air of Cooling System to Heat an Air Handling Unit, *Journal of Energy Storage*, *46* (2022), 103826
[81] Li, F., *et al*., Numerical Simulation of Air Outlet Spacing Change in Thermal Management Lithium-Ion Battery Pack with Triangular Arrangement for Use in Electric Vehicles, *Journal of Energy Storage*, *49* (2022), 104112
[82] Zhang, F., *et al*., Cooling Performance Optimization of Air Cooling Lithium-Ion Battery Thermal Management System Based on Multiple Secondary Outlets and Baffle, *Journal of Energy Storage*, *52* (2022), 104678
[83] Oztop, M., Sahinaslan, A., Control of Temperature Distribution for Li-Ion Battery Modules Via Longitudinal Fins, *Journal of Energy Storage*, *52* (2022), 104760

Paper submitted: August 5, 2022
Paper revised: September 15, 2022
Paper accepted: September 21, 2022

Published by the Vinča Institute of Nuclear Sciences, Belgrade, Serbia.