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Electric Vehicle Battery Optimization With Paper Batteries

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Abstract

The rapidly developing study area of electric vehicles has taken a step further, especially with the new improvements in the battery systems of electric vehicles. Even though studies about this subject are still being conducted, a fully applicable solution has not yet been found. To tackle this problem, a supplementary battery pack formed by paper batteries will be implemented to assist the commonly used Li-Ion Battery(LIB) packs. In addition to this, suggestions to alter the battery cooling mechanism were explained as well. Consequently, with the use of paper batteries and the other solutions, the negative effects of ambient temperature, internal heating, and insufficient battery usage were diminished while increasing the range and efficiency of electric vehicles, and decreasing the carbon footprint.

Keywords
Paper Battery; Electric Vehicles; Li-Ion Battery; Battery Cooling; Efficiency

Nomenclature

k_{ins}	Thermal conductivity coefficient of the insulator (W/mK)
r_{shell}	Radius of the shell of the battery cell (in meters)
T_{coil}	Temperature of the coil of the cell (in K)
T_{cold}	Temperature of coolant inside the pipes (in K)

$\boldsymbol{\rho_{coil}}$	Density of the coil of the cell (in kg/m3)
$\boldsymbol{c_{coil}}$	Specific heat of the coil of the cell (J/kgK)
$\boldsymbol{h_{ins}}$	Thickness of the insulator (in m)
$\boldsymbol{t_0}$	Time needed for a cell to passively reach the optimal temperature
$\boldsymbol{T_{max}}$	Maximum temperature a cell can reach before the active cooling system is initiated
$\boldsymbol{T_a}$	Outer temperature of the cell
$\boldsymbol{l}$	Length of the material

Abbreviations

LIB(s):	Lithium-ion Batterie(s)
EV(s):	Electric Vehicle(s)
BEV(s):	Battery Electric Vehicle(s)

Review of Literature

For the last few decades, battery technology used in EVs has been improving constantly as new researches are being conducted. It is thought that electric vehicles will be the new norm in the future so it is important that they are designed to run as efficiently as possible. One of the core subjects to improve energy efficiency is the battery cooling system and the battery itself

The problem of altering the cooling system has been tackled by numerous studies. Some of the researches on this problem include implementation of a solid-state thermal management system(Chakib Alaoui et al, 2013 [1]), phase-change materials (J. Jaguemont et al, 2015 [2]), investigation of heat pipe's effectiveness(Q. Wang, 2014[3]) and use of nano-fluids in the cooling modules (S. Wiriyasart, 2020 [4]). In his team's research about the implementation of solid-state thermal management systems, Chakib Alaoui et al (2013), showed that a solid-state BTMS could boost the efficiency of their test model, at the expense of increase in both size and weight. J. Jaguemont et al (2015), showed that materials that exchange a large amount of heat during state changes and it might become a staple of the Industry once it leaves the experimental stage. Q. Wang et al (2014), indicated that heat pipes were a viable alternative for cooling of the battery pack via their experiments. Last but not least, S. Wiriyasart et al(2020), displays that nano-fluid in cooling modules can also be a feasible way to optimize the battery thermal management system in the cooling module of an EV. This paper contributes by proposing a more lightweight solution for maximizing the cooling efficiency without making a significant difference in the size of the battery pack with the help of paper batteries.

In summary, the work presented in this paper builds on previous research to explore new ways to increase the efficiency of the BTMS by showing a new way to handle paper batteries. While earlier studies experimented with thermal management systems by altering it, we focused on adding another power source while simultaneously boosting the efficiency of the cooling system.

Introduction

Electric vehicles (EVs) have earned more and more value since pollution and carbon emissions today prompt us to relinquish fossil fuel-based vehicles. The global electric car stock has been increasing with record numbers every year. In 2015, 0.72 million battery electric vehicles (BEVs) were on the road, whereas, in 2019, the number went up to 4.79 million EVs with a rapid and continuous increase.[1] However, this transition to EVs also brings its challenges which have become crucial topics of research for engineers and researchers all around the world. This evolving research is tasked with finding new ways to improve the efficiency of electric vehicles, and many companies are in a race to find the new best solution. In fact, in 2020, 73.5 million pounds was granted to fund electric vehicle research in the UK which is estimated to safeguard around 14.000 jobs.[2] As EVs keep on advancing, batteries continue to go through modifications as well; however, a feasible method to prevent efficiency loss in LIBs, which are one of the core

[1] "Global EV Outlook 2020 – Analysis - IEA." https://www.iea.org/reports/global-ev-outlook-2020. Accessed 2 Dec. 2020.

[2] "£73.5 million to boost green economic recovery in ... - Gov.uk." 23 Jun. 2020, https://www.gov.uk/government/news/735-million-to-boost-green-economic-recovery-in-automotive-sector. Accessed 2 Dec. 2020.

elements of today's EV industry, has not yet been fully developed. As electric vehicle research and developments advance, four major problems for long range EVs arise efficiency loss during acceleration and internal temperature increase, battery cooling system insufficiencies, effects of ambient temperature on battery efficiency, and CO_2 emissions during battery production. When the vehicle starts and begins to accelerate, due to its static inertia during the takeoff, a power input above the expected value is required. This event engenders a loss in the overall efficiency of the vehicle and thus reduces vehicle performance. Furthermore, due to the higher number of stops that would be made during long-distance travels, the necessary excess power increases, decreasing the overall efficiency. Another problem is that, although LIBs can work in a temperature range of -20°C to 60°C,[3] fluctuations from their optimum working temperature, 21°C, [4] causes inefficiency and consequently an unfavorable vehicle performance.
Especially in long-range travels, this problem becomes more significant since the battery is required to expand power rapidly for a large amount of time. Secondly, specifically in long-range drives, the internal heating of EV battery cells becomes a crucial problem. Therefore, the battery cooling system turns into one of the most important components for the production of long-range and efficient EVs. The indirect liquid cooling of EV batteries creates an uneven cooling process throughout the battery pack, decreasing the efficiency of the LIBs. Thirdly, especially in long-range drives the ambient temperature, as it varies frequently and in a large range of values, has a non-negligible effect on battery efficiency and cell life. As mentioned, ambient temperature affects the cell life and battery efficiency significantly[5], making it a noteworthy problem in the design of electric vehicles. Finally, in today's world, CO_2 emissions are one of the most significant world problems and it requires an immediate solution. To create a better future for the world, CO_2 emissions must be critically decreased. However, even though the EV industry is set to shape the future, the CO_2 emissions during both battery and electricity production is an important and improvable factor which must be taken into consideration.

[3] "Temperature effect and thermal impact in lithium-ion batteries ...." https://www.sciencedirect.com/science/article/pii/S1002007118307536. Accessed 2 Dec. 2020.

[4] "In freezing temperatures electric vehicles can let you down." 12 Feb. 2019, https://www.sustainability-times.com/green-consumerism/in-freezing-temperatures-electric-vehicles-can-let-you-down/. Accessed 2 Dec. 2020.

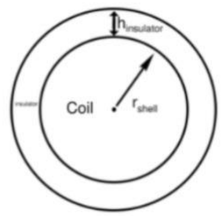
[5] "A novel metabolomic approach used for the comparison of ...." https://cyberleninka.org/article/n/589971. Accessed 2 Dec. 2020.

The aim of this research is to be able to contribute to the improvement of EVs which will most probably be an indispensable part of the automotive industry and our future lives. Thus, this paper's main goal is to develop a feasible solution to increase the range and efficiency of electric vehicles for long-distance travel via the usage of paper batteries as a supplementary source, and improvements in the design of the battery cooling system. Throughout the paper, the mentioned modifications will be hypothetically applied to Tesla Model-3 Long-Range (LR) since it is more energy efficient compared to most of the other EVs, and contains more publicly available information. Overall, these main suggestions will be used to try and overcome the major problems of efficiency loss due to acceleration or internal heating of batteries, the undesirable effects of ambient temperature on battery efficiency, the insufficient battery cooling system of the current EVs, and the overall carbon footprint of the EV.

Utilisation of Paper Batteries

The first and most crucial factor that has a negative effect on the range of commercial EVs is the general properties of the LIBs. These batteries, even though they are efficient while at a constant speed, require to expend loads of additional energy in certain situations. The main causes of this phenomenon are the vehicle accelerating, moving uphill or the batteries falling out of optimum working temperature. Considering that these situations are faced quite frequently in long-range travels, a critical loss in the overall efficiency of EVs occurs. This creates a need for a supplementary power source especially to work efficiently during the aforementioned conditions. However, the already proposed methods come with downsides such as extra weight and increased charge-time, which negate the upsides. In consideration of these requirements, paper batteries become a more rational choice due to their lightweight and flexible design and supercapacitor like properties. Since paper batteries have a much more minimal energy capacity, they were used as supplementary batteries to Li-Ion batteries. The implementation of paper batteries plays a critical role for the overheating problem. Paper batteries are incredibly resistant to temperature changes compared to LIBs. As a result, these batteries will require no extra cooling at times when the LIB overheats; in order to reduce energy consumption and help the LIB pack cool faster, the paper batteries can take over during the car ride in order to avoid any more heating of the main battery. With the paper batteries attached, we calculated the time needed for the paper batteries to work and consequently the amount of paper batteries needed as follows, Assumptions:

1) Flowing water surrounding the battery is assumed to be at constant T_{cold} temperature.



2) We can approximate the system as shown on the left.
Since heat conductivity of coil is high, it could be assumed that T inside coil is constant with r (not time)

Analytical Solutions:

$$=> k 2\pi (r+dr) l \frac{\partial T}{\partial r}\Big|_{r+dr} - k 2\pi r l \frac{\partial T}{\partial r}\Big|_{r}$$

$$= 2\pi r dr l \rho m . \frac{dT}{dt}$$

$$k 2\pi (r+dr) l [\frac{\partial T}{\partial r}\Big|_{r} + \frac{\partial^2 T}{\partial r^2} dr] - k 2\pi r l \frac{\partial T}{\partial r}\Big|_{r}$$

$$= 2\pi r dr l \rho m . \frac{dT}{dt}$$

$$=> k 2\pi r l \frac{\partial^2 T}{\partial r^2}\Big|_{r} dr - k 2\pi l \frac{\partial T}{\partial r}\Big|_{r} dr$$

$$= 2\pi dr l \rho c . \frac{dT}{dt} => k_{ins} . 2\pi l \frac{d(r . \frac{\partial T}{\partial r})}{\partial r} = 2\pi r l \rho c_{ins} . \frac{dT}{dt}$$

To be able to find a numeric solution, we need to do approximation. Since $h_{insulator}$ is narrow compared to r_{shell};

$$k_{ins} . 2\pi (r_{shell} + \frac{h_{ins}}{2}) . \frac{T_{coil} - T_{cold}}{h} = 2\pi r_{shell} . l . \rho_{coil} . c_{coil} . \frac{dT_{coil}}{dt}$$

$$\Rightarrow \frac{1}{2} . k_{ins} . (r_{shell} + \frac{h_{ins}}{2}) . \frac{T_{coil} - T_{cold}}{h_{ins}} = r_{shell} . \rho_{coil} . c_{coil} . \frac{dT_{coil}}{dt}$$

$$\int \frac{-k_{ins}(r_{shell} + \frac{h_{ins}}{2})}{2 . h_{ins} . r_{shell} . \rho_{cell} . c_{coil}} dt = \int d ln(T_{coil} - T_{cold})$$

$$- \frac{k_{ins}(r_{shell} + \frac{h_{ins}}{2})}{2 . h_{ins} . r_{shell} . \rho_{coil} . c_{coil}} t = ln(\frac{T_{goal} - T_{cold}}{T_{max} - T_{cold}})$$

$$\Rightarrow t_0 = \frac{h_{ins} . r_{shell} . \rho_{coil} . c_{coil}}{2 . k_{ins} . (r_{shell} + \frac{h_{ins}}{2})} . ln[\frac{T_{max} - T_{cold}}{T_{goal} - T_{cold}}]$$

Figure 1: Derivation of the "Li-Ion battery cell cooling time formula".

With estimated [10] values of T_{max}, T_{cold}, T_{goal}, h_{ins} based on previous Tesla products and the generally used values, and used the most accurate value for c_{coil}; the calculations resulted in ~111101 paper batteries, additional 222.202 kg weight. This procedure will be controlled automatically by the EV's battery management system (BMS), and similar to the overheating problem, it will begin to use the secondary battery unit when more than the usual power is required throughout the travel, restricting the efficiency loss. This simple process would prevent the LIBs from wasting unnecessary amounts of energy, and consequently, reduce the overall deficiency due to the internal heating of the battery packs.

In addition to the improvements in battery efficiency, paper batteries also play an essential role in the prevention of the extensions in charging time, which is a critical disadvantage of using supplementary battery packs. Since these designs are planned according to long-distance travel, keeping the charging periods short is a crucial factor. As improvements above are taken into account, how the supplementary paper batteries are charged arises as another issue, which brings the topic to another reason why paper batteries are applicable. Due to the fact that paper batteries can be charged faster than LIBs at a rate of 1/3600[6], paper batteries are assumed to be partially charged utilising the regenerative braking technology in Tesla Model 3, shortening the charging time at stops more effectively.

As explained in the introduction, ambient temperature has a significant effect on reducing LIBs' performance, life, and power.[7] This significant impact not only affects the battery but is also important for engineering other battery pack managements, and thus making this concept rather an essential one. As Newton's Law of Cooling suggests;

$$\frac{dT}{dt} = -k(T - T_a) + T_{in}$$

[6] "(pdf) paper battery - ResearchGate." 12 Mar. 2019, https://www.researchgate.net/publication/331672586_PAPER_BATTERY. Accessed 2 Dec. 2020.

[7] "Temperature effect thermal impact in lithium-ion batteries ...." https://www.sciencedirect.com/science/article/pii/S1002007118307536. Accessed 2 Dec. 2020.

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Changing the T_a, representing the temperature of the surroundings, would engender a faster or a slower cooling for the batteries, meaning that there would be an unbalanced need for the cooling mechanism, which would cause inefficiencies. To eliminate the mentioned negative effects and optimize the frequently used mechanism, another approach to the problem is suggested in this research: paper batteries are used to cover the primary battery packs. The paper batteries can act as a separating field between the LIBs and the ambiance due to their insulating properties. Paper batteries can also work in a relatively large range of approximately 498.15 K (from 199.82 K to 366.5 K). This process would help minimize the effects of ambient temperature on the battery cells, which is a crucial factor that affects the heating process of the batteries, especially in long-range transportations. Since paper batteries are thin and flexible flat sheets, they can easily fit inside condensed places, reducing the weight and size of the additional system that would be caused by extra packaging units if worked with a different type of battery. Thus, the packs of paper batteries will be placed on top of the LIB packs, and act as an insulating layer. However, this method can raise another problem which can turn into a disadvantage: while minimizing the effects of ambient temperature, the paper batteries can also prevent the internal heat of the batteries from getting out of the battery packs since they are covered up. This negative outcome can easily be solved with the use of a simple mechanical system which will be automatically controlled by the EV's BMS. The packaging units of paper batteries would be placed on thin rails, and at the same time will be connected to pistons, which actually would not require high values of excess power from the batteries since the paper battery packs are lightweight. Temperature sensors will be placed inside the LIBs, and according to the obtained data, the BMS would move the paper batteries, allowing the main power source to cool down more effectively.

Internal Temperature Problem - Active Cooling

Another segment of the cooling efficiency problem includes the ineffective design of the active cooling mechanism of LIBs in a Tesla Model 3 battery pack, horizontally placed cooling pipes are used, which swerve along the way, covering a larger area of the surface of LIBs. However, this system leads to insufficient cooling as the coolant inside the pipes heats up rapidly as a result of heat transfer between the LIBs and the coolant, and this causes an uneven temperature distribution as shown in Figure 2. This variance is analyzed to be approximately 2°C [9], meaning that the battery cells at the end of the pack would come in contact with a coolant of higher temperature, taking more time to cool down. Thus, a solution that inserts additional cooling pipes with the purpose of creating an even cooling process was generated.

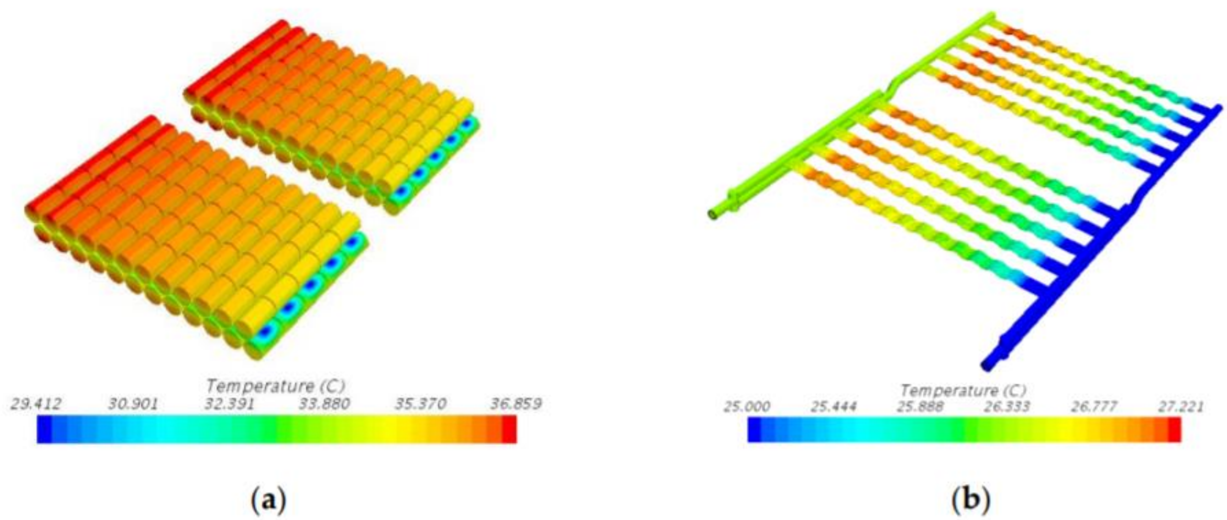

Figure 2: The temperature field at the worst working condition with an effective current 25 A and d = 0.973, Q = 5 L/min, and N = 6: (a) batteries; (b) coolant. [9]

The original Tesla Model 3 cooling design contains curved cooling pipe formations. The initial pipe divides into seven segments for a battery pack and is placed in between the LIBs. A solution answering the aforementioned problem would be implementing an additional cooling system for the outer end of the battery pack, without getting affected by the heat of the initial batteries. In the created design, supplementary cooling pipes start above the initial batteries, and slowly shift in between the final battery cells due to their unique shape, as can be seen in Figure 3. By doing so, the system would be directly cooling the outer end of the battery pack. All of the built cooling pipes would be connected to the same source and outage, becoming a completely connected and stable structure. This solution would prevent the LIBs inside EVs from cooling unevenly and thus inefficiently, by lowering the variance of temperature values.

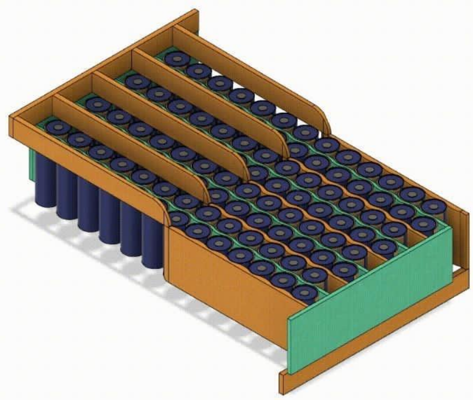

Figure 3: The 3D design model of the suggested battery cooling mechanism

CO_2 Emissions

Paper batteries are designed to work efficiently without occupying a significant amount of space. Thus, implementing paper batteries as a secondary power source would have minimal impact on the EV's size and weight. Therefore, the carbon footprint of the car would not go through notable changes. In addition, the production of paper batteries causes approximately zero carbon emissions[8] due to its production methods, which is another crucial reason behind the selection of paper batteries as the supplementary battery kind. The paper batteries that will be attached to the LIBs will be able to hold 4999.516 Wh of energy, which is equivalent to 289 LIBs' storage. By using paper batteries as a secondary battery instead of LIB, 26.298 kilograms of CO_2 would be prevented from being released into the atmosphere. Another approach to the minimization of CO_2 emissions based on the suggested modifications would be directly related to the measure of how efficient the EV is. As a more efficient EV requires less energy to travel an estimated long-range distance, the required electricity amount decreases as well. Considering that electricity production causes a great fraction of the CO_2 emissions and air pollution, even a slight decrease in the required amount would be crucial. Even though the effects on a single-vehicle might not be quite significant, with the continuously increasing number of EVs all around the world, this alternation would result in a positive outcome on the CO_2 emission problem, especially when the solution is applied to more electric vehicles.

[8] "The Technology Of Making Batteries Out Of Paper - News ...." 2 Jul. 2014, https://www.upsbatterycenter.com/blog/technology-making-batteries-paper/. Accessed 2 Dec. 2020.

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Conclusion

Over the course of this paper, several approaches were analyzed in order to increase the range and efficiency of electric vehicles while minimizing the undesirable effects of internal heating, ambient temperature, unequal cooling mechanisms, and efficiency loss in different driving conditions. Due to the lack of information about Tesla's products as a result of the company's privacy policies, the calculations were computed using approximate values. Considering that there was not a chance to get experimental results due to the lack of resources, even though the data would justify the same concept, the theoretical solutions might not be completely accurate. Nevertheless, with the conducted research and mathematical solutions, profitable and practical methods, which can affect the future of the EV industry, were found. It was calculated that a single 2170 battery cell was cooled down in approximately 12.24 minutes, and the LIB packs were cooled down in nearly 0.522 hours, and therefore 222 kg of paper battery (111,100.3638 paper batteries) would be required for the desired solution. Regardless of the various reasons behind choosing paper batteries as a supplementary power source, the overall additional weight can cause disadvantages if no precautions are taken. Also, considering this paper's alternative battery cooling structure design, the main goal of increasing the range and efficiency would be accomplished; however, by compromising a certain part of the maximum luggage weight or passenger capacity, the additional weight of the secondary power source can be neglected as well. Consequently, using paper batteries as a secondary power source, creating an insulating layer to diminish the negative effects of ambient temperature, and altering the design of the battery cooling pipes will decrease the number of stops that would be required in long-range travels, and increase the overall efficiency of EVs. Finally, this increase in efficiency and the utilisation of paper batteries will indirectly result in less CO_2 emissions due to lower energy consumption and the manufacturing process.

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