Analytical Study and Comparison of Solid and Liquid Batteries for Electric Vehicles and Thermal Management Simulation

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Abstract— As the world is growing very fast and the major role player is the technical sector, but when it comes to the Automotive world one cannot forget e-mobility and hence we are also contributing our part in it. We are doing an in-depth study on Solid-state batteries and Liquid state batteries and detailed comparison between them. In the end, we are also doing the thermal management of the batteries using a Simulation tool called the Simulink/Simscape Language Model. E-mobility is still in the developing phase and there are a lot of opportunities available and we targeted the Battery part. In this report we are showing with different facts, proves, calculations and experiments that how solid-state batteries (SSB) are better than currently using liquid state batteries (LSB) because experts believe that the future is of solid-state batteries because of its versatility and many advantages over LSB. We did the comparison between the current electronic vehicles using LSB(Lithium-Ion) and the future vehicles using SSB on various aspects according to our experiment, research and the result we got is outstanding and also found to be the worthy step toward the development of SSB. We also did the thermal management of the battery to increase its on-road efficiency and the result is quite satisfying as we took a small load to check the battery performance and we also gave the comparison of thermal management using two different heat transfer coefficient (5 W/m^2 K and 25 W/m^2 K) and we are able to get better cooling efficiency when we increase the value of heat transfer coefficient. Results, proposed ideas, and the research analysis clearly giving a green signal towards the speedy development of Solid-state batteries and how it overcomes the different disadvantages of Liquid state batteries, whereas Thermal Management Model proposes with several changes give us the in-depth view of the temperature rise and also by changing the heat transfer coefficient one can select a better cooling system for batteries, to operate it in an optimized range of temperature.

Keywords— solid battery, liquid battery, electric vehicles, thermal management simulation

I. INTRODUCTION

The main difference between solid and liquid batteries is the use of solid electrolytes instead of liquid electrolytes. Lithium-ion batteries have gone so far in terms of development, but experts think that lithium-ion technology has reached the maximum level of its efficiency. The next step in the future will require a different type of battery, and that's where the solid-state battery comes in.

SSBs (solid-state batteries) are low mass, compact geometry and have a higher power density than liquid batteries based on liquid electrolytes. The main challenge for the prevalent introduction of SSB is to find an appropriate and efficient electrolyte for large batteries and also a cheaper mean of manufacturing.

Electrochemical systems such as batteries using aqueous electrolytes were not suitable for their use in the biomedical devices, electronic devices needing memory backup and other consumer-oriented applications [1]. As early as the turn of this century, it was recognized that certain compounds in the solid-state could function as electrolytes and several studies have been done using these solid electrolytes in the electrochemical cell. In recent years, considerable progress has been made in the development of practical solid-state batteries as energy sources. A solid-state battery will be defined as one in which anode, electrolyte, and cathode are solids. Solid-State Batteries offer some attractive advantages over their liquid counterparts. They are inherently robust, spill-proof and usually non-corrosive. They are compact and well suited to miniaturization and the ability of the component to stay in position can do obviate the need for separators, membranes and/or diaphragms which add to the mass and volume of liquid systems without producing a concomitant increase in energy and power. Thin-film configuration can be used and sometimes these can be formed into unusual shapes that fit them for 191 specialized applications. They can perform adequately over wide temperature ranges which are highly desirable for military and other uses.

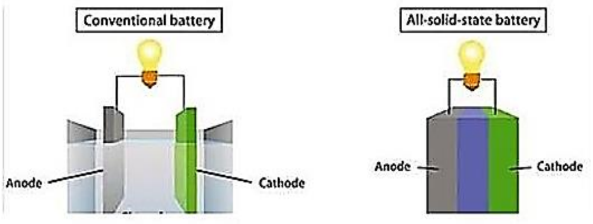


Fig.1 Conventional and SSB

II. SOLID STATE BATTERY COMPANIES

Comparison between two companies on different parameters for a solid-state battery.

Table No. 1

S.No	Parameters	Hitachi Zosen	Stereax
1	Electrolyte	Solid electrolyte sulphide (Li2 -P2)	Solid electrolyte
2	Cathode	Ni series	Lithium Cobaltate
3	Anode	Graphite type	Silicon
4	Size	50 mm × 50 mm	12 mm x 12 mm,
5	Industry	In Automotive sector for more power requirement	In Medical field for small power requirement.
6	Status	Still under research	In use for very small purposes.
7	Expected	Expected launching year would be 2021-22.	Already in the market.
8	Operating temperature	-40 ° C to 130 ° C *	-20°C to 100°C

*These are the approximate values given by different companies because nobody has a concrete idea about the actual temperature.

There are some companies who are major manufacturer of liquid state batteries (Lithium-ion), but currently involved in research & development of Solid-State Batteries (SSB).

1. Samsung-SDI
2. Panasonic
3. Toshiba
4. Tesla
5. LG-Chem
6. A123-System
7. ecobalt-Solutions
8. BYD
9. Johnson-Control

III. COMPOSITION OF SOLID-STATE BATTERIES

3.1 Cathode

The cathode in the solid-state battery is important because it supplies the battery with the necessary ions during charging and vice-versa during discharging. Commonly used cathode materials for lithium-based solid-state batteries are lithium metal oxides, as they exhibit most of the above-mentioned necessary properties. Lithium cobalt oxide (LCO), which has the stoichiometric structure $LiCoO_2$, is a widely used lithium metal-based oxide. LCO has a layer structure suitable for the lithium/delithiation process and has a relatively high specific energy of about 150 mAh g-1, making it a preferred cathode material. Lithium manganese oxide ($LiMn_2O_4$) is another material used in the cathode of solid-state batteries. In addition to these lithium-based oxides, vanadium-based oxides have also been tested as they have similar layer structures that help in the lithium/delithiation process [3].

3.2 Anode

Carbon and carbon-based materials are commonly used anode materials in solid-state batteries. Graphite is also widely used as an anode material in solid-state batteries, which has several advantages, such as a layered structure capable of absorbing lithium ions during the lithing/delitriding process, its ability to withstand a large number of charge and discharge cycles, and its relatively simple fabrication. Graphite can also be easily doped with other materials to improve its capacity. The main problem with graphite is its relatively low capacity. Soft carbon is another material that is used. Anodic systems based on metallic alloys have also been studied, in particular, Sn, Pb, Sb, Al and Zn and their alloy systems [3].

3.3 Electrolyte

Since the performance of a solid-state battery depends on the diffusion of ions within the electrolyte, solid electrolytes must have high ionic conductivity, very low electronic conductivity and a high degree of chemical stability. Crystalline materials such as lithium halides, lithium nitride, oxy salts, and sulphides have proven themselves as solid electrolytes. The most advantageous properties of the solid electrolyte are that there are no corrosive or explosive leaks and the risk of an internal short circuit is lower and therefore safer.

The most commonly used thin-film solid electrolyte is the LiPON electrolyte (lithium phosphorus oxide nitride). It is usually a glass-like electrolyte obtained by RF magnetron sputtering [3].

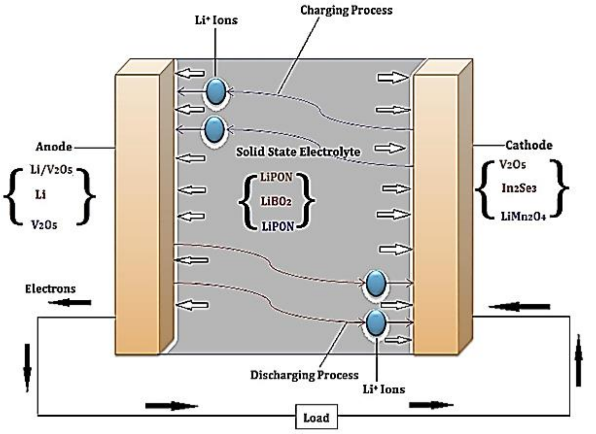


Fig. 2 A schematic representation of a representative lithium based solid state battery

3.4 Advantages of Solid State Batteries

Solid state batteries are more efficient and Advantageous than Liquid state Batteries. Below are some advantages of Solid-State Batteries :

1. High Energy (Higher voltage cathodes possible)
2. High Power (Large discharge rates possible)
3. Low Mass (Less inert material)
4. High cycle number (10 times life cycle than typical Liquid)
5. Compact Geometry (Require less space in a vehicle)
6. Environment Friendly
7. Cell Separator will not break at higher temperature (165) in contrast to liquid batteries.
8. Leakage of Electrolyte is not happened (Because of Solid Electrolyte).

3.5 Disadvantages

1. High Cost
2. Temperature Sensitive (not easy to operate at low temperature)
3. Ceramic electrolytes involve elevated pressure to keep the electrodes in touch.

IV. CHALLENGES AND SOLUTION

4.1 Material Composition:

Interfaces are always a challenge for solid-state systems. It is difficult to interface between cathode, anode and solid electrolyte due to their different chemical properties and physical structure. The proposed solution is Thick composite positive electrode layers (high active mass loading) and thin solid electrolyte layers need to be considered for all-solid batteries so as to achieve favourable energy and power.

4.2 Temperature

At low temperature, below 0°C flow of ions is irregular resulting in less energy and power. Companies are currently researching this problem.

The proposed solution for this problem is that we require a separate lithium-ion battery which heats the heater around the solid-state battery to preheat solid battery to its operating temperature range.

4.3 Cost

Cost is the measure drawback in the development of SSB. According to research at the University of Florida using current thin-film technology, the cost of a single 20Ah battery would be $100,000 A high range EV will require 800-1000 20Ah cells.

To reduce the cost, the following solutions are proposed:

a) Avoid semiconductor grade chemicals

Develop process around inexpensive chemicals

b) Avoid Vacuum technologies

1. Slows Manufacturing
2. High Capital expense

c) Develop high throughput process

e.g. roll to roll

V. COMPARISON OF LIQUID BATTERY USED IN ELECTRIC VEHICLE 'NISSAN LEAF' WITH STANDARD SOLID STATE BATTERY

Currently, 'Nissan' is using liquid-state batteries for their vehicles but they are also planning to move on solid-state batteries in upcoming years because the researches on SSB has proved that, it is way more efficient in every aspect except operating temperature.

Here, the given table proposed by us is focusing on some key aspects to differentiate between LSB used in one car segment "Leaf" of Nissan & standard SSB.

Table No. 2

Parameters	Solid	Liquid
Capacity	24 KWh	24 KWh
Energy Density	350 Wh/kg	140 Wh/kg
Nominal Voltage	360V	360V
Number of Cells	80 (according to calculation)	192

Rated Capacity	80Ah	32.5Ah
Operating Temperature	0-150* ° C	-20 to 60 ° C
Range	We can achieve the existing range of 150km in only 80 solid battery cells, and this range can be increased also by increasing the no. of cells.	150 km

*data obtained from Solid Power company, Canada.

The above comparison is based on our calculations and the data given on Solid Power, Canada website.

After studying the comparison table, we concluded that Solid battery will be more efficient than Liquid Batteries based on Energy Density and also the geometry is compact due to less number of cell, which provides the require Nominal Voltage with Higher Rated Capacity.

5. 1 Thermal Management System

Battery thermal management system always improves the battery behaviour and also plays indispensable role in increasing battery life cycle. Thermal management of the batteries can be done by several means like air, refrigerant, water etc. More appropriately it is termed as;

1. Air Cooling System
2. Liquid Cooling System
3. Direct Refrigerant Cooling System
4. Phase Change Material (PCM) Cooling System
5. Thermo-Electric Cooling System

Due to inefficiency, battery cells will not only generate electricity but also heat. This heat should be moved from the battery pack when the battery temperature reaches the optimum temperature or even in advance. Thus, a cooling function is required in Battery thermal Management system (BTMS).

Here we used Air cooling system in our experiment and also showed how free convection and forced convection can enhance the cooling efficiency.

5.2 Air Cooling System

Air systems use air as the thermal medium. The intake air could be direct either from atmosphere or from the cabin and could also be conditioned air after a heater or evaporator of an air conditioner. The former is called passive air system and the latter is active air system. Active systems can offer additional cooling or heating power. A passive system can offer some hundreds of watts cooling or heating power and an active system power is limited to 1 kW.

Because in both cases the air is supplied by a blower, they are also called forced air systems. The following figure shows a schematic description of systems.

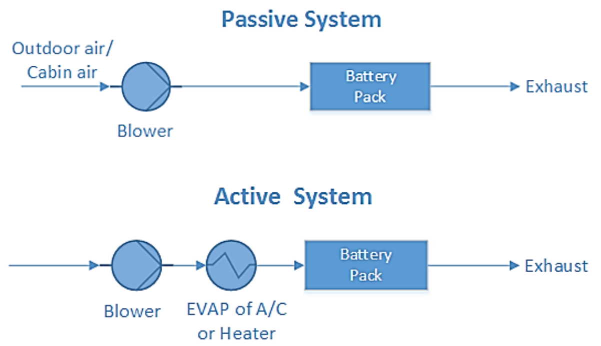


Fig.3 Active & Passive System

Our simulation results shows how important thermal management is in order to control the battery behaviour for better performance and also to enhance the efficiency. One can also do further experiments by combining the our simulation model with electric vehicles or may be any CFD simulation models.[5]

5.3 Battery Thermal Management Model

This model is composed of Lithium Cell 1RC (Resistance Capacitor), one thermal management block. We are using the inbuilt library of thermal systems to do the thermal management of the battery and to control the battery temperature in its optimum working range.

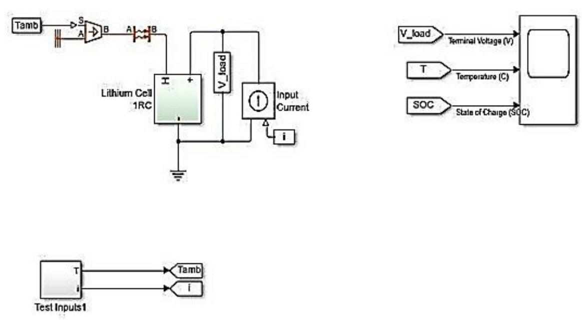
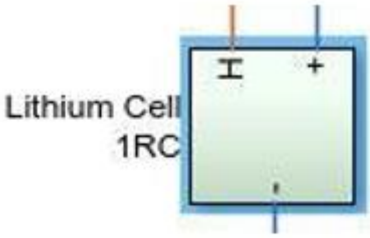


Fig. 4 Thermal Model[6]

1. Lithium Cell 1RC
2. Test Inputs (For Ambient temperature 20 and Current)
3. A Heat Convective Transfer
4. Input Current Sensor
5. Voltage Sensor (V_Load)
6. Scope (It shows Terminal Voltage, Temperature and State of Charge)

Lithium Cell 1 RC

In this model we are using a standard cylindrical Lithium Cell, which consist of a thermal management block, one capacitance block and two resistance block.



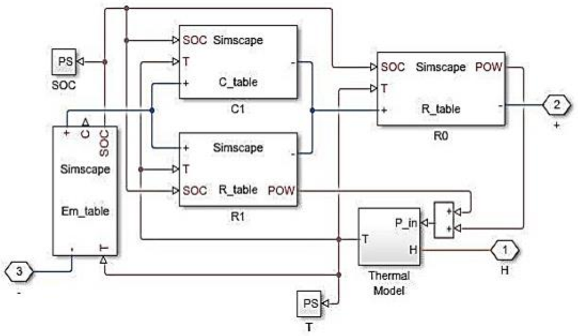


Fig.5 Inside Electrical Model

For Lithium Cell terminal voltage calculation, we are using component block of Em_table. In the component block there is equation on the basis of lookup table of SOC(State of Charge) and Temperature. The system calculates the nominal and terminal voltage of the battery according to the current drawn from it on the load.

According to those calculations the Cell SOC is .5 at the beginning, but when the load is connected, the cell voltage as well SOC of the system changes.

During that time the Cell Nominal Voltage is 3.75 Volts and Peak Voltage is 4.5 at SOC

All calculations are done by the equations that are used in component block source code. We connect the Em_Table (Cell) to the RC circuit to optimize the working and charging.

R_table value is calculated by SOC and the temperature in the MATLAB lookup table and also the amount of heat generated i.e power (temperature) is transferred to thermal management block.

Thermal Model

The thermal model is used to control the temperature range of battery when load is applied.

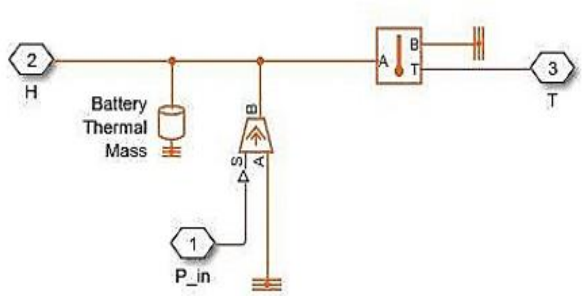


Fig. 6 Thermal Model

In the above model we consider Battery Thermal Mass, Ideal Heat Flow, Temperature Sensor. These component are predefined in Thermal Library of Simscape.

a. Battery Thermal Mass

This block models internal energy storage in a thermal network. The rate of temperature increase is proportional to the heat flow rate into the material and inversely proportional to the mass and specific heat of the material. [6]

b. Ideal Heat Flow

This block represents an ideal energy source in a thermal network that can maintain a controlled heat flow rate regardless of the temperature difference. The heat flow rate is set by the physical signal port S. A positive heat flow rate flows from port A to port B. In this block physical signal i.e. P_in (sum of power generated in battery resistor and load) is connected to port S and consider A as ground reference or thermal reference. [6]

c. Temperature Sensor

This block measures temperature is a thermal network. There is no heat flow through the sensor. The physical signal port T reports the temperature difference across the sensor.

The measurement is positive when the temperature at port A is greater than the temperature at port B. [6].

Parameter that we consider and put in the work space of model is in the following table:

Table No. 3		
Parameter	Value	Units
Nominal Voltage	3.75	Volts
Peak Voltage	4.5	Volts
Cell Mass	1	Kg
Cell Specific Heat(cell_Cp_heat)	850±5	J/kgK
Ambient Temperature	20	°C

Battery Initial Temperature	20	°C
Convective Heat Transfer (h_conv)	5,25,500	W/m2K
Area of Cell	.06	m2

These are the parameters that are used in this model. Someone can edit in the work space of MATLAB of this model and change the parameters according to their requirement without changing the lookup tables. We also did some calculations on thermodynamic behaviour of the system, here are as follows:

First, we calculated the heat generated by battery in the temperature range of (20-45 ° C) Mass of lithium ion battery = 1kg, Specific heat of lithium ion battery (Cp) = 850 J/kgK ±5, Thermal mass = m*Cp

= 1*850= 850 J/K

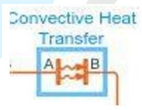
Heat = m*Cp*(delta T) Heat = 1*850*(25)

Heat = 21.25 KJ

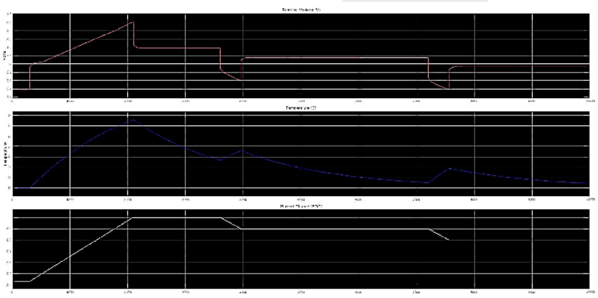
Now, for cooling we are using ambient air by convection method. We are using Convective Heat Transfer Block (From Simscape Thermal Library)

Convective Heat Transfer

This block models heat transfers in a thermal network by convection due to fluid motion. The rate of heat transfer is proportional to the temperature difference, heat transfer coefficient, and surface area in contact with the fluid. [6]



For Heat Flow rate by Free convection



Heat Transfer Coefficient(h) for Ambient air (20 ° C) = 5 W/m^2K Area(A) = 0.06 m^2

Heat Transfer Rate = h*A*delta (T)

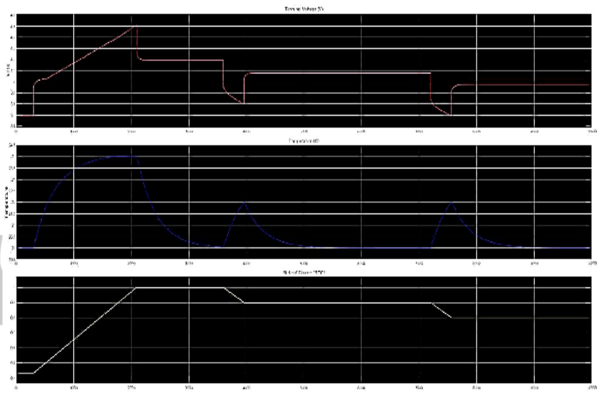
Heat Transfer Rate = (5 W/m^2K) * (0.06 m^2) * (18.4 K) Heat Transfer Rate = 5.52 W

At heat transfer coefficient = 5 W/m^2K

So, at heat transfer coefficient of 5 W/m^2K. we observed following things;

1. We observed that at very first, temperature of the battery is rising (When it is connected to the load, firstly it reaches to the peak voltage and then comes back to certain optimum level, resulting in sudden rise in temperature) from 20 C to 38.4 C.
2. We employed free convection system here which is responsible for cooling down the battery, and it brings the temperature down from 38.4 C to 29 C and then finally around 23 C.
3. System takes 1.804 Ksec. (i.e. 30 min.) to reach to its maximum temperature i.e.
4. 38.4 C from 20 C.
5. Cooling System (Free convection) takes 1.494 Ksec (25 min.) to cool down the battery from 38.4 C to 29.5 C.

For Heat Flow Rate by Forced Convection



Heat Transfer Coefficient(h) for Ambient air (20 ° C) = 25 W/m2K Area(A) = 0.06 m^2

Heat Transfer Rate = h*A*delta (T)

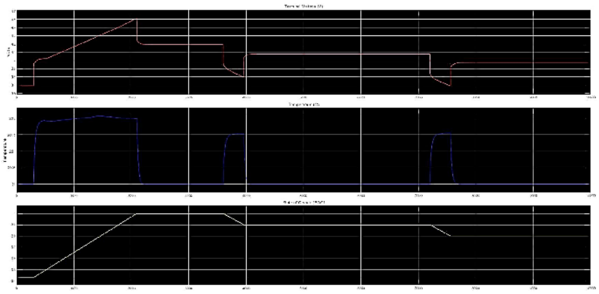
Heat Transfer Rate = (25 W/m^2K)* (0.06 m^2)*(18.4 K) Heat Transfer Rate = 5.52 W

So, at heat transfer coefficient of 25 W/m^2K we observed following things;

a) We observed that at very first, temperature of the battery is rising (When it is connected to the load, firstly it reaches to peak voltage and then come back to certain optimum level, resulting in moderate rise in temperature) from 20° C to 24° C.
b) We employed forced convection system here which is responsible for cooling down the battery, and it brings the temperature down from 24° C to 20° C.
c) System takes 1.785 Ksec. (i.e. 29.75 or 30 min.) to reach to its maximum temperature i.e. 24° C from 20 °C.

d) Cooling System (Free convection) takes 1.499 Ksec (25 min.) to cool down the battery from 24 °C to 20 °C.

For Heat Flow Rate by Force Convection



Heat Transfer Coefficient(h) for Ambient air (20 ° C) = 500 W/m^2K Area (A) = 0.06 m^2

Heat Transfer Rate = h*A*delta (T)

Heat Transfer Rate = (500 W/m^2K)* (0.06 m2)*(.4 K)

Heat Transfer Rate = 12 W

So, at heat transfer coefficient of 500 W/m^2K we observed following things;

a) We observed that at very first, temperature of the battery is rising very slowly and very less from 20° C to 20.2° C.

b) We employed forced convection system here which is responsible for cooling down the battery, and it brings the temperature down from 20.2° C to 20° C.

c) System takes 1.696 Ksec. (i.e. 29 min.) to reach to its maximum temperature i.e. only 20.2° C from 20 °C.

d) Cooling System (Forced convection) takes 108.418 seconds to cool down the battery from 20.2 °C to 20 °

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VII. CONCLUSION

After many experiments, calculations, and research we came to an end where we can put a prominent statement that solid-state batteries are way more batter than currently used liquid state batteries. Above all life risk in liquid state batteries (LSB catches fire) can be eliminated by replacing it with solid-state batteries. We found solid-state batteries better in terms of energy density, life cycle, safety, etc. One problem with the solid-state battery is, it cannot perform efficiently at very low temperature (e.g. negative temperature).

We found a very satisfactory result in the thermal management of the batteries using simulation also. Hence, we can conclude that forced convection is better and should be deployed to achieve better temperature control. We tested our Simulink model on three different values of heat transfer coefficient, where at very first we used free convection but the results are not implementable in every battery pack of electric vehicles. Hence we switched to another one, which is forced convection and the results are under control and implementable in any battery pack of any vehicle for its thermal management.

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[4] Fig. (2) A schematic representation of a representative lithium based solid state battery", A review of lithium and non-lithium based solid state batteries Joo Gon Kim a, 1, Byungrak Son a, **, 1, Santanu Mukherjee b, 1, Nicholas Schuppert b,Alex Bates b, Osung Kwon c, Moon Jong Choi a, Hyun Yeol Chung d, Sam Park b,

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