SSRG International Journal of Electrical and Electronics Engineering
ISSN: 2348-8379/ https://doi.org/10.14445/23488379/IJEEE-V11I10P1113

Volume 11 Issue 10, 122-139, October 2024

Original Article

Investigative Approach to Thermal and Electrical Synergy of Lithium Ion Battery and Supercapacitor Hybrid Energy Storage Systems

Ravikant Nanwatkar[1], Deepak Watvisave[2], Aparna Bagde[3]

[1]*Department of Mechanical Engineering, SCOE, Savitribai Phule Pune University, Maharashtra, India.*
[2]*Department of Mechanical Engineering, CCOEW, Savitribai Phule Pune University, Maharashtra, India.*
[3]*Department of Computer Engineering, JSPM NTC, Savitribai Phule Pune University, Maharashtra, India.*

[1]*Corresponding Author : ravikant.nanwatkar@sinhgad.edu*

Received: 09 August 2024 Revised: 08 September 2024 Accepted: 10 October 2024 Published: 30 October 2024

Abstract *- Hybrid Energy Storage Systems (HESS), composed of lithium-ion batteries and supercapacitors, may provide an excellent alternative for the state-of-the-art in terms of modern energy applications. This paper adopts an investigative approach to reveal the interaction between thermal and electrical properties of hybrid systems using experimental analysis and simulation models. By combining the high energy density of lithium-ion batteries with the fast-charging and discharging ability of supercapacitors, their HESS has the potential to solve the structural and thermal issues of energy storage systems. While most studies concentrate on the single device properties and pay little attention to how thermal constraints affect electrical performance in hybrid configurations, with very little work on integrated models. Complete models capable of predicting and controlling the thermal-electrical coupling in the mentioned hybrid systems do not exist yet, and this fact is a bottleneck for practical applications in EV applications. Further, several roots were uncovered that determine how well a lithium-ion battery combines with supercapacitors, such as charge/discharge rates, thermal management, and energy density. A computational fluid dynamics model has emerged to simulate the compartments' thermal effects and surrounding airflows. These results show that effective thermal management is critical for the performance and longevity of electrical devices in hybrid systems. This paper offers a detailed study of the thermoelectric synergies in HESS using lithium-ion batteries and supercapacitors. The results could lead to powerful new pathways for designing cheaper, longer-lasting energy storage solutions vital in renewable and electric vehicle technologies.*

Keywords *- Structural Analysis, Hybrid Electric Vehicle, Pack of Lithium-ion battery, Pack of Supercapacitor, Structural integrity, Thermal analysis, Computational Fluid Dynamics.*

1. Introduction

Lithium-ion batteries and supercapacitors are both commonly used in Hybrid Electric Vehicles (HEVs) due to their high energy and power density, respectively. In this paper, electrical and thermal investigations are performed considering a hybrid electric vehicle system that combines both technologies so that it can benefit from the advantages of both and overcome some of their individual drawbacks.

The lithium-ion battery is a hybrid electric vehicle's primary energy storage system. It comprises numerous battery cells linked in series, parallel, or both arrangements to make a battery pack. Every battery cell comprises an anode, cathode and an electrolyte solution. The electrodes are made up of a thin layer of active material made of oxides such as lithium cobalt, lithium manganese oxide, or lithium iron phosphate coated on a conductive substrate such as copper or aluminium. The electrolyte is typically a lithium salt dissolved in an organic solvent. The supercapacitor, also known as a supercapacitor or a double-layer capacitor, is a device that stores energy electrostatically. It is made up of two electrodes that are separated by an electrolyte, which acts as a charge separator. The electrodes are made of a high-surface-area material such as activated carbon, allowing a large amount of charge to be stored in a small volume.

In the proposed Lithium-Ion Battery and Supercapacitor hybrid electric vehicle, the lithium-ion battery and supercapacitor are connected in parallel with a power electronics module, as shown in Figure 1. The power electronics module manages the power flow between the battery, the supercapacitor, and the electric motor. During acceleration, the supercapacitor can discharge quickly to provide an additional burst of power, while the battery can provide sustained power. During regenerative braking, the supercapacitor can quickly absorb the energy from the motor and store it for later use.

In contrast, the battery can absorb the remaining energy at a slower rate. The power electronics module can also control the charging of the battery and the supercapacitor to ensure optimal performance and longevity. Overall, the hybrid system can provide the high energy density of the lithium-ion battery and the high power density of the supercapacitor, resulting in a more efficient and responsive hybrid electric vehicle, as shown in Figure 2. One of the key areas for HEV design is thermal analysis, aspired by designing and developing Lithium-Ion Battery (LIB) and Supercapacitor Hybrid Electrical applications.

In order to achieve that, a thermal management system for EVs has become mandatory to control the battery temperature between an operational ranges, help prolong the life of batteries and thus optimizing vehicle performance. LIB has other physical and chemical properties than SC; this is reflected in the thermal behaviour trends of each electrochemical storage alternative.

In this context, LIBs give off heat as they charge and discharge because electrochemical reactions occur within the cell. If left unchecked, thermal runaway can allow a battery to fail catastrophically from the heat. SCs, however have low energy density compared to LIBs but generate less heat during operation per unit power and also provide higher Power Density. For the thermal study of LIB and SC-based HEVs, the following techniques have been employed, including numerical simulations, experimental measurements etc.

- Thermal Modeling: A numerical simulation can predict the temperature distribution inside the battery pack and SCs. It can be useful for designing an effective thermal management system to keep the temperature from exceeding a safe range.
- Thermal imaging: This can be used to evaluate temperature distribution on the battery pack and SCs surface. This will allow the identification of hotspots and thus work on managing thermals.
- Calorimetry: Measures the heat production from battery packs and SCs while operating. This pen recorder allows us to forecast the temperature rise and develop a functioning thermal management strategy.
- Thermal Cycling: It is used to mimic the actual working scenarios of battery packs and SCs. This can provide an assessment of the performance and reliability of thermal management systems.

1.1. Problem Definition

Hybrid Energy Storage Systems (HESS) that combine Lithium-Ion Batteries (LIBs) and Supercapacitors (SCs) are increasingly seen as promising solutions for applications requiring both high energy density and high power output, such as Electric Vehicles (EVs) and renewable energy systems. While lithium-ion batteries excel in energy storage, their power delivery and lifespan can be compromised by thermal stress, particularly during high-demand conditions. On the other hand, supercapacitors, known for rapid charge/discharge cycles and high power density, struggle with long-term energy storage and thermal stability.

The interaction between these two components, specifically their thermal and electrical behaviours, poses significant challenges in optimizing the performance, efficiency, and safety of HESS. Currently, the lack of a comprehensive understanding of the thermal-electrical synergy between LIBs and SCs limits the effective design and implementation of HESS. An imbalance in the thermal performance can lead to inefficiencies, reduced lifespan, and potential safety risks. Moreover, inadequate management of electrical performance under variable load conditions hinders the practical application of these systems in high-demand environments like EVs. Therefore, addressing the thermal and electrical interactions in a hybrid setup is critical to advancing this technology.

1.2. Research Gap

While significant progress has been made in improving the individual performance of lithium-ion batteries and supercapacitors, little research has been devoted to understanding the detailed thermal and electrical interactions within a hybrid system. Existing studies often focus on the optimization of either the thermal or electrical performance but fail to explore their interplay comprehensively. Moreover, the current models that exist for thermal management and power delivery in HESS are largely theoretical, lacking validation through real-world applications or experimental data.

This research aims to fill this gap by conducting an in-depth investigation of the thermal and electrical synergy between lithium-ion batteries and supercapacitors in hybrid energy storage systems. By focusing on how these systems perform under varying load and temperature conditions and developing integrated thermal-electrical models, this study will provide valuable insights for optimizing HESS design and operation for enhanced efficiency, safety, and longevity. It is crucial to perform thermal analysis of the lithium-ion battery and supercapacitor-based HEV to guarantee the safety and proper performance of the vehicle. Together, numerical simulation and experimental testing assist in designing a functional thermal management system that keeps temperature in check with safe operating limits.

This study confirms that identifying and analysing the cooling system of a battery pack structure for an electric drive vehicle to establish excellent control over this decoder also plays a key role in reducing safety issues, increasing the life cycle time of cell packs, and costs should be carried out. When choosing cooling and emerging approaches, adjustments must be established among expenses, complexity, mass production, refrigeration attributes, temperature profile with good reproducibility and scavenging energy.

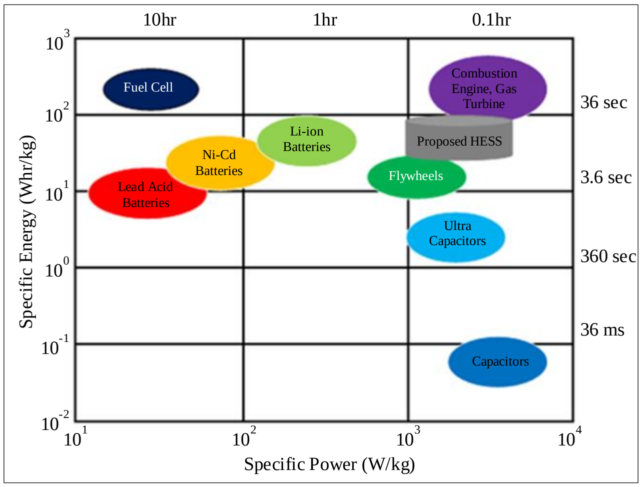

Fig. 1 Proposed hybrid energy storage system

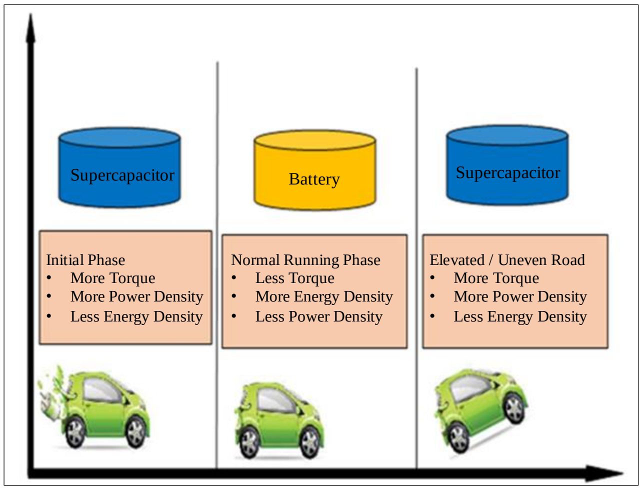

Fig. 2 Working mechanism of the proposed hybrid energy storage system

2. Literature Survey

Marek Michalczuk et al. [1] has worked on energy recovery through regenerative braking, and the effects are simulated using the Matlab/Simulink PLECS toolbox. Jian Cao et al. [2] demonstrated a the Power System Analysis Toolbox (PSAT) controlled compact dc/dc converter acting as an energy-limited pump contributing to cool battery reserves for HESS restorative mode on road conditions with data from drive cycle experiments.

Rebecca Carter et al. [3] worked on the novel HESS of lead acid batteries and supercapacitors with regenerative braking. It focused on supercapacitor behaviors and energy conversion using regenerative braking circuits. A. Ostadi et al. [4] the literature related to RA Technologies was covered by connecting the HESS of the battery and supercapacitor, which were tied with DC sources to connect with energy (NEDC mode) and power demands of the vehicle, including management about these energies. Experimentation clearly reveals, among all associating organized in EV/HEV applications, The dissociate arrangement wherein the supercapacitor cell conjoined to the DC bus and battery cell supplying output power from/to bidirectional DC-DC converter is effective.

Di.wu. et al. [5] conducted a brief review about lithium-ion batteries thermal management in electric and hybrid vehicles. The paper detailed different thermal management techniques and their effects on the battery performance, making it safe to operate across wide ranges of temperatures. Seyed Hamidi et al. [6] worked on Lithium-ion Batteries and Supercapacitors for Network applications with different materials for cathode, anode, and lithium-ion Battery output characteristics that will vary based on Equivalent Electrical Circuits. Their work connects Li-ion and supercapacitors for high power density w/ prolonged ARD app. to overcome Li-ion doors (high cost in production, and highly sensitive for thermal runaway).

C. Cao et al. [7] the paper reviewed supercapacitor modeling, estimation and control in the context of its employment in hybrid electric vehicles. This paper introduces some modeling methods and control strategies to enhance the power delivery performance of a hybrid system. Wu et al. [8] conducted a research study that explored the mechanical performance of a LIB pack in HEV subjected to various loading conditions. Based on this study, the shear stress and von Mises stress mainly influenced the mechanical behavior of the LIB pack. The paper also suggests using low-modulus and high-strength materials for ESS housing to reduce the stress concentration.

Clemente Capasso et al. [9] worked on Na-Cl batteries and the EDLC DC/DC bi-directional power converter. Using Simulation and experimental investigation with HESS of lithium-ion AND supercapacitor. Similarly, a study by Liu et al. [10] investigated the structural behavior of an SC pack in HEV. This study concluded that the SC pack tended to deform and fail under prolonged mechanical load (stress).

The use of a housing designed to prevent deformation around the SC pack was also suggested by paper A. Bhatt et al. [11] in this paper, a design and thermal analysis of lithium-ion battery modules for Hybrid Electric Vehicle (HEVs) is presented. The first part is devoted to developing a numerical model for simulating the dynamics and thermal behavior of the battery, from which benchmarking is done under various stressful operating conditions. A study by HE et al. [12] determined the thermal behavior of a LIB pack in an HEV for different operating conditions. Study: LIB pack temperature spiked with fast charging and discharging; this study suggested that an effective cooling method was required to stabilize the temperature of the LIB pack in safe regions.

Wu et al. [13] studied the thermal characteristics of a SC pack in an HEV. The SC pack was less vulnerable to thermal runaway than the LIB pack. The research suggested implementing an improved cooling system to extend a longer time for SC pack temperature in a normal operating zone. Wenhua Zuo et al. [14] developed a number of HESS configurations using high-rate-capable batteries and power-rated capacitive electrodes. Additional works were conducted on BSH with a smooth high voltage window and 3D electrodes integrated system.

Anuradha Herath et al. [15], refined battery and supercapacitor charge-discharge algorithm based on acceleration or deceleration. Among that work was a concerted effort to alleviate the burden on the batteries and increase the overall vehicle range to be next to traditional all-battery BEV operation. Mahdi Soltani et al. [16]: Lithium-ion Capacitors (LICs) with an output behavior suitable for high-power MLTB driving cycle. Additional work on the lithium-ion battery and capacitor unit would make it more cost-effective, faster recharging for smaller sizes, and with much higher energy and power densities.

Lip Sawa et al. references [17] investigated the different ways thermal and electrical performance parameters can be assessed with respect to various driving cycles for an HESS utilizing Lithium-ion batteries alongside that of an equivalent supercapacitor-based model. The dynamic stress and thermal performance under peak power demand are improved due to the short battery life span, which will also enhance reliability in HESS by simulation. Only the setup formation of an electric propulsion test bench to finalize the simulation results and incorporate an intelligent energy management system in the model is pending work. Md. Arman Arefin et al. [18] worked on Simulations of HESS with battery and supercapacitor new and used (degraded) battery cells. The efficiency of the hybrid system was inversely proportional to temperature. This hybridization is beneficial since it will improve the battery life and efficiency of energy storage systems and powertrains. Advantages of this HESS include reduced battery aging, max battery current and the size to up more cycle counts executed at an increase in power preserving for a longer period, which includes cell life accruing but simultaneously rising overall pack dimensions.

Lia Kouchachvili et al. [19] studied the battery and supercapacitor HESS, where a modified cell is coupled with a supercapacitor that has an identical basic electrochemical architecture but benefits in terms of specific discharge capability rate as well as cyclability. Basically, the basic principle was that the supercapacitor supplies an excess amount of energy while the battery does not provide it. Various configurations, designs, and performance characteristics of HESS have been discussed, as well as active, passive, and semi-active types of HESS. The paper outlines the application areas of HESS, such as mobile charging stations and hybrid electric racing cars with different combinations of batteries and supercapacitors; issues related to all application aspects have been discussed along with future research prospects. M. Palma et al. [20] this paper focused on a structural analysis of lithium-ion battery modules developed for electric vehicles. The authors develop a finite element model of the module to analyze the mechanical behavior of the battery in various loading situations.

S. K. Lee et al. [21] described the work that consists of an analysis of the structural and thermal behavior of a battery pack Li-ion for electric vehicles. They create a finite element model of the pack and study how the battery behaves thermally for various driving profiles. Immanuel N. et al. [22] suggested a synergistic blend of battery, supercapacitor and hybrid capacitor to realize environmentally friendly energy utilization in EV applications. The work mitigates the problem of autonomy deficit between two supercapacitor recharge points. The experimental study employed simulation of different inputs for the DC-DC converter and the electric vehicle profiles to get the recommended HESS. This effort could be extended to different load profiles with peak crest factors.

S. Devi Vidhya et al. [23] Hybrid energy storage system for a light electric vehicle based on Indian driving cycle, simulation study of the lithium-ion battery and supercapacitor bank using bi-directional converter to reduce overuse, thereby enhancing life. The potential of the proposed system, accompanied by modelled prototype components, was explored by simulation and experimental analysis in line to keep its effectiveness.

A.Bharati Sankar et al. [24] smart power converter for an electric bicycle, powered hybridization of lead acid battery and supercapacitor. The power converter is based on an Arduino controller that adapts micro application processes to judge the energy exchange between the two systems for both linear and fuzzy logic control strategies by connecting a supercapacitor in parallel with the battery pack. experimental results showed an improvement in completion grade times for events with positive elevation w. r. to time from undeviatingly reducing discharge depth magnitude cycles frequency x battery cells count, significantly extending battery life without decreasing top speed. The life cycle of the main battery pack was improved by designing an over-current protection scheme for high discharge currents.

Walvekar A. et al. [25] investigated the hybridization of Li-ion batteries and supercapacitors for lightweight electric vehicles. The impact of hybridization is mainly on current, voltage and State of Charge (SOC) for different combinations of Hybrid energy storage systems. Results indicated that using HESS reduces the Current Battery peak in pure battery EV 2-wheelers and thus improves their range.

3. Materials and Methods

The experiment set shows hybrid connectivity of a Lithium-ion battery pack of 11.1Volts and 20 Amperes and a supercapacitor pack of 13.5 Volts and 100 Faraday. The HESS power supply is controlled by 12Volts, 10 Ampere Switched Mode Power Supply. Two shunt resistors control the current and voltage supply on both ends of the input and output for display devices. During experimental testing, the battery and supercapacitor are connected individually and, in HESS mode, are connected to three separate switches (Battery pack, supercapacitor pack and HESS of both) through a switch.

The experiment is conducted here by taking two four-wheeler headlights, each of 100 watts for independent load and combining load for different drive cycles to check the charging and discharging characteristics of energy storage systems in individual and hybrid modes. Block Diagram of Connections made for Experimental Investigation is shown in Figures 3 and 4. The component specifications for the experimental setup can be seen in Table 1. At higher temperatures, molecules vibrate and move more quickly in an area through conduction by Heat flows from hot to cold.

A comparative analysis of the above four types of cooling systems, i.e., air, liquid, fin cooling, and phase change methods, is done. For this project, a form of non-direct cooling with shell and tube is used. Lithium-ion battery is packed using copper tubes and acrylic sheets placed on both sides of the lithium-ion cell to get more cooling effects, using propylene glycol as a coolant. The coil has one end connected to the pump and installed inside the sump.

The other end is also located in the sump or cooling system. Coolant begins flowing inside the copper tubes when the battery pack's temperature increases beyond the ideal range, causing heat transfer. Since this reduces the battery pack temperature, a benchmarked Non-direct liquid flow cooling vs. forced airflow cooling is shown below. Once the load is ensured to the battery pack, a temperature change occurs. These two battery packs end up getting hotter than either of them copes well with. At this point, the two cooling air flows are implemented, and liquid flow approaches for 55 minutes; through all observations and calculations, how efficient non-directed fluid liquid-cooling can be over airflow.

The model used in this work consists of two 14.8Volts and 10 Ampere battery packs. Each cell is rated at a voltage level of 3.7 Volts and able to supply the required power over up to currents that reach as high as their limits, which are always defined by the thickness of every cell manufactured from the beginning (each pack contains x16-cells). Both battery packs are then subjected to a 100 Watts load bulb. After 55 minutes, both battery packs heated up to only 39°C when the room temperature was no more than a chilly day at just over 27°C. However, any temperature change results in less performance of your batteries and shortens their overall life. The battery is best maintained for 15°C-35°C with a cooling or heating effect.

4. Structural Analysis

Table 1. Specification for structural analysis

Experimental Set-Up Components	Requirements
HESS Controller (SMPS)	12V, 10A
Pack of Li-ion Battery cell (each of 3.7V and 2.5 A))	11.1V, 20Ah
Pack of Supercapacitor cell (each of 2.7 V and 500 F)	13.5V, 500F
Display Unit for Voltage	0-200 V
Display Unit for Current	0-75A
Resistor Used for HESS Pack	470KΩ, 2W
Shunt Resistor for Display Unit	75mV
Power Switches	3
Applied Load (headlight bulb)	200W
Other Components i.e. Solder Gun, Wire, Pump, Speed Controller, Cooling Fan, Propylene Glycol, Copper Coil with U Bent, Insulating Sheet, and Thermocouple.	As per Requirement

4.1. Energy and Power Calculations of the Hybrid System for Generating Approx. 100-Watt Energy for Approx. 2 Hours

- Total Energy generated by battery pack:
  VA/100 = (11.1 x 20)/ 1000
  = 0.222 Kwh = 222 watts/hr
- Total Power generated by battery pack:
  VA = 11.1 x 20
  = 222 watts.
- Total capacitance of supercapacitor pack (CT)
  CT= $\frac{1}{C_T}=\frac{1}{C_1}+\frac{1}{C_2}+\frac{1}{C_3}+\frac{1}{C_4}+\frac{1}{C_5}=\frac{1}{500}+\frac{1}{500}+\frac{1}{500}+\frac{1}{500}+\frac{1}{500}=\frac{5}{500}$
  $C_T = 500/5 = 100\text{Faraday}$
- Total Energy by supercapacitor pack (E)
  E = $\frac{1}{2}C_T V^2 = \frac{1}{2}\times 100 \times 13.5^2 = 9112.5\text{joules} = 2.53125\text{w/h}$
- Total Power generated by supercapacitor pack
  = $E/(t_2-t_1)$
  = (2.53125 / 3) = 843.75 watts

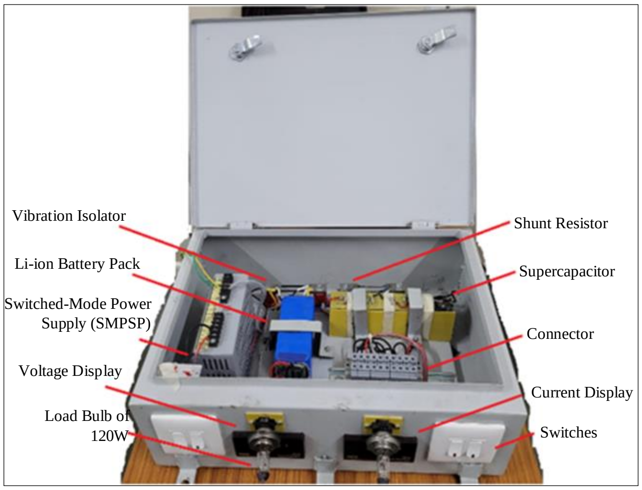

Fig. 3 Experimental setup

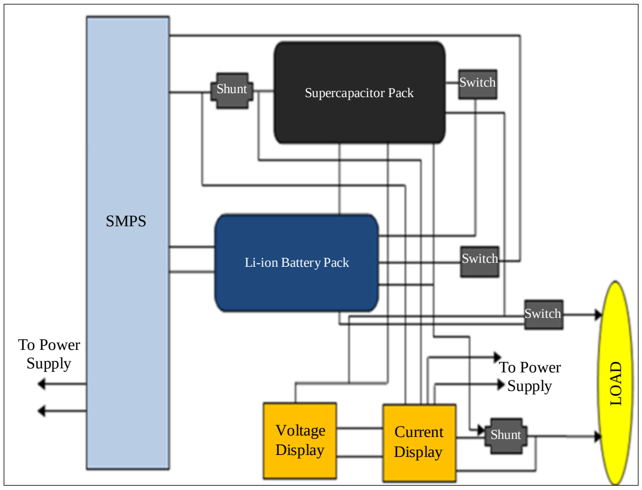

Fig. 4 Experimental set up block diagram

5. Thermal Analysis

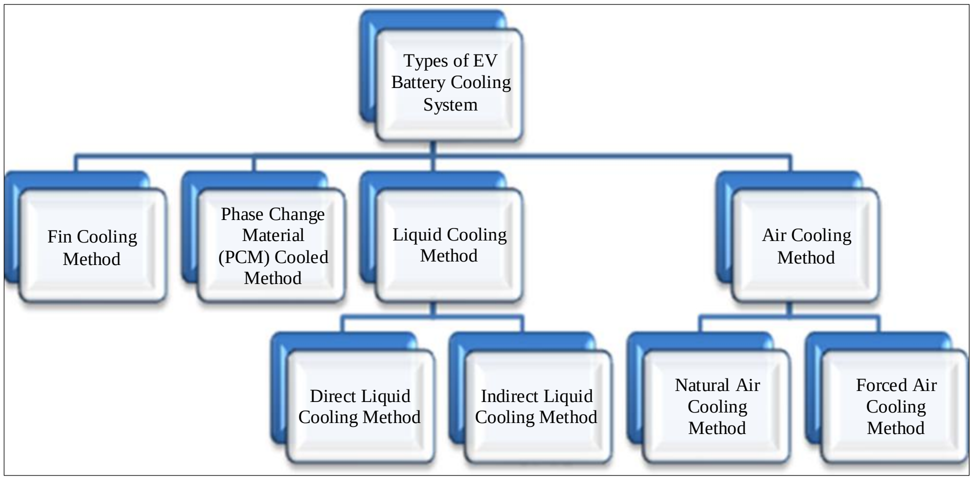

Fig. 5 Classification of cooling systems for automobiles

Table 2. Comparative analysis of cooling methods

Sr. No.	Parameters	Air Cooling	Liquid Cooling	Fin Cooling	Phase Change Material
1.	Medium	Air (Atmosphereic Air)	Liquid (Water, Ethylene, Propylene Glycol)	Metals (Copper, Aluminium)	Semi-Solid (Al-Foam)
2.	Cooling Capacity	Medium	High	Very low	Very low
3.	weight	Light	Medium	Heavy	Heavy
4.	Cost	Low	Medium	High	Medium
5.	Size	Large	Compact	Very compact	large
6.	Complexity	Simple	Complex	Medium	Medium
7.	Life	Medium	Medium	Long	Less

8.	Leakage & Safety	More Butless Risk	Less than Air but more Risk	No & no risk	More fin but more Risk
9.	Efficiency	Medium	More	Less	less
10.	Temperature Distribution	Uneven	Uneven	Medium even	Even
11.	Energy Consumption	High (Fan)	High (Motor)	None	None
12.	Maintenance	Medium	Medium	Less	High

Table 3. Specifications for thermal analysis

Sr. No.	Particulars	Specifications	No. of Components Required	Approximate Cost
1	Water pump	12V	1	100/-
2	Battery	18650 X.T.T manufacturer, 3.7V,2.6A	16	2000/-
3	Fan	Size: 3 × 3-inch (80 x80 x 25mm) DC: 12V 0.20A. Speed: 3000 RPM	1	300/-
4	Voltmeter	Input Voltage - 4.5V to 30V DC Input Current - <= 20mA Measuring Voltage Range - 0V to 100V DC Measuring Current Range - 0A to 10A	1	400/-
5	Current Display	Display ON Voltage (V) 2.5 Operating Voltage (VDC) 3.6 ~ 28 Current Consumption (mA) 15 Refresh Speed (ms) 200 (one time) Minimum Input (V) 3.6 Highest Input (V) 28 Operating Temperature (C) -10 to 60	1	400/-
6	Shunt Device	100 mV.	2	375/-
7	Metallic Fins	Aluminum, Copper		3000/-
8	Coolants	R134A	1	650/-
9	M. S .Box	500 x 300	1	2000/-
			Total	9600/-

Here, an experiment is performed to evaluate the effects of thermal fin cooling with a modified cooling mechanism as proposed in the work to get improved cooling with maximised contact area with the battery cell of the lithium-ion battery pack. The cooling methodology for the given setup is performed for air, water, and phase change material cooling methods, as shown in Figure 5.

Table 2 indicates the comparative analysis for the same methodologies. Figure 10 indicates the block diagram for connecting the different components of the experimental setup. Table 3 specifies the different components required for the experimental setup.

Figures 6 and 7 show the proposed fin cooling design modification for battery pack fabrication to get a maximum contact area for improved cooling. Figure 8 shows a lithium-ion battery pack without cooling, and Figure 10 indicates it with cooling methodology per the proposed idea. Figure 11 shows the experimental set-up for the aforesaid analysis to compare the thermal cooling with and without the proposed cooling system. A battery pack setup is also taken here using the 18650 Battery cells. According to the above, a hole of 7 mm has been designed from copper wire.

- The copper coil is placed on the battery gap for better thermal insulation and contact area.
- Temperature coolant flows through a coil as Fans on the rear assist in further temperature drops.
- The battery is back at room temperature.
- An ideal temperature of 15^0C -35^0C.
- Two battery packs with lithium ion-based battery cells were investigated here: one without coolant and one with cool ability air and water (through direct contact). Further, the experimental results were confirmed by CFD analysis.

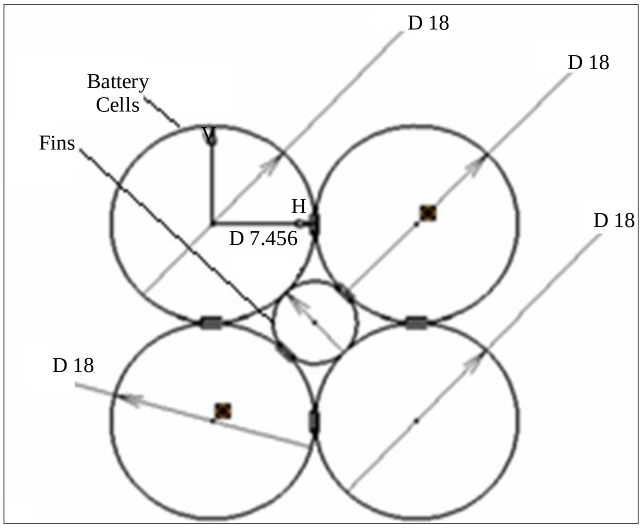

Fig. 6 proposed design for HESS thermal analysis

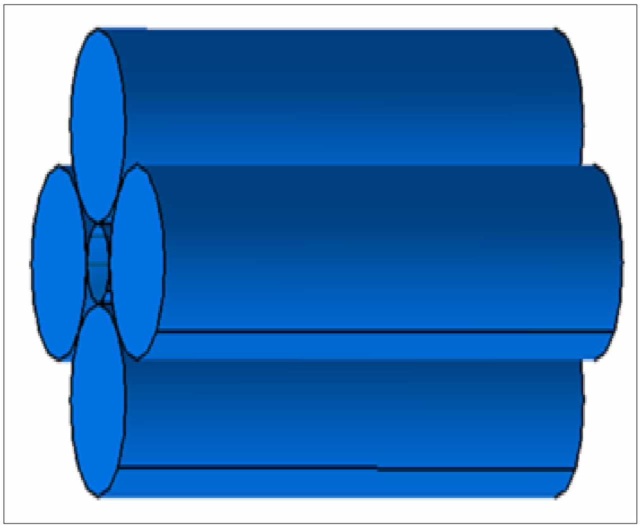

Fig. 7 CAD Model for battery pack

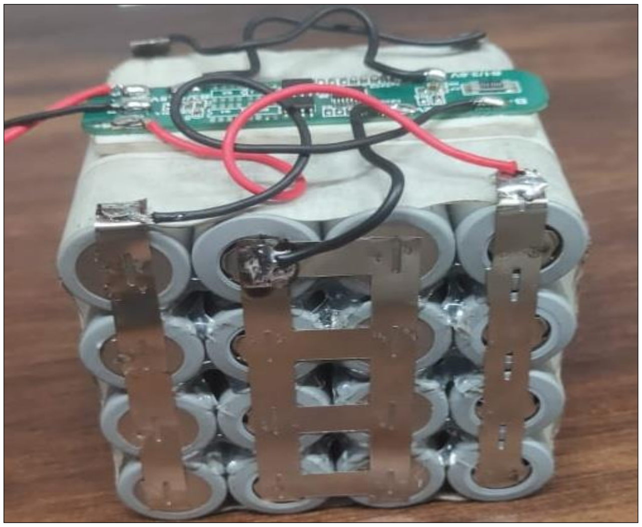

Fig. 8 Li-ion cell battery pack

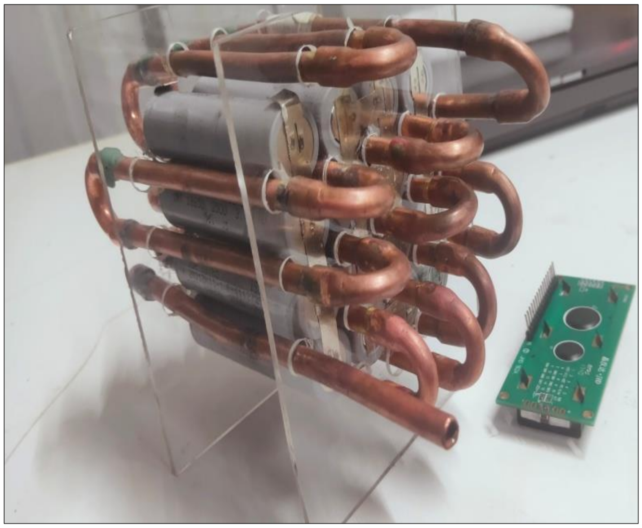

Fig. 9 Li-ion cell battery pack with fins

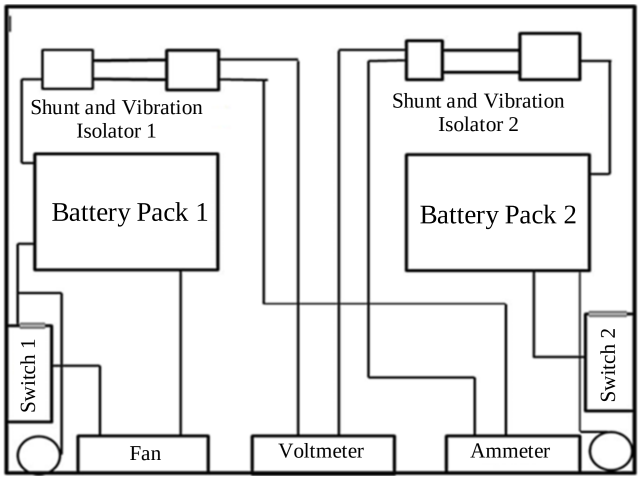

Fig. 10 block diagram for set up for thermal analysis

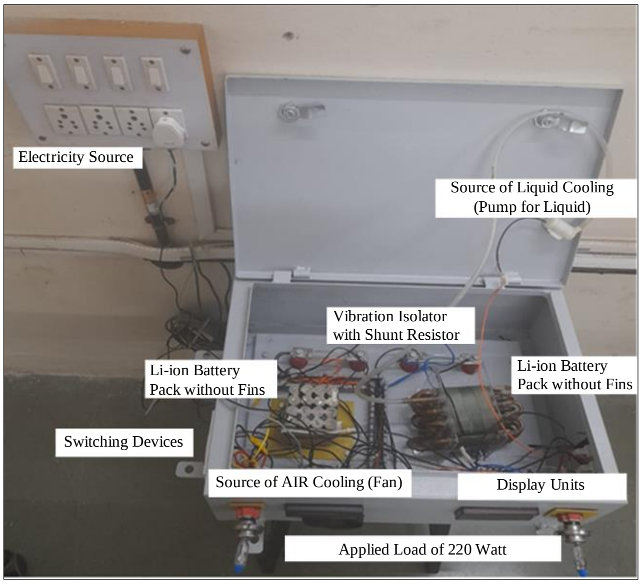

Fig. 11 Experimental set-up for thermal analysis

6. Simulation and CFD Analysis

Here, the supercapacitor working as secondary energy storage for the battery (primary device) effect is verified by taking a Simulink circuit. Nominal voltage 11.1 V, rated capacity in AH-20 and Initial SOC=80%, whereas the latest version of EDLC Supercapacitor, which could be considered here, has rates capacitance =100 faradays and a rating voltage of is14V taken for this study. This figures out to around 3.6 seconds per supercapacitor, allowing everything a good apx-mainboard-20sec, as shown in Figure 12.

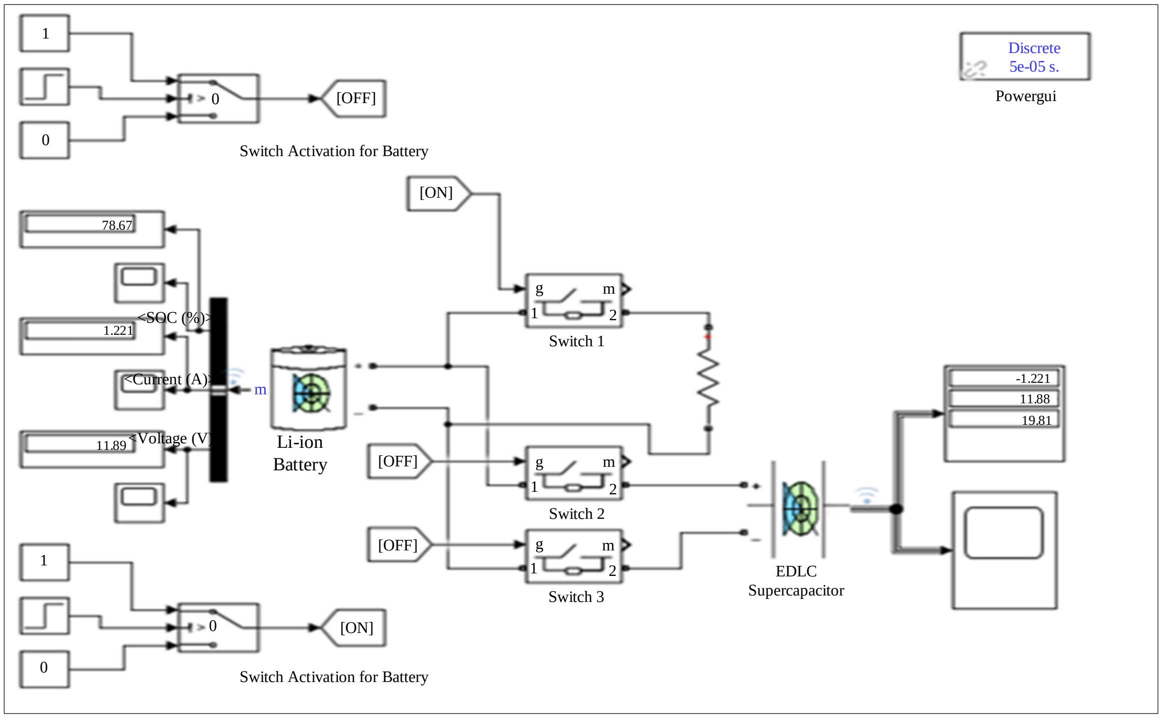

Fig. 12 Simulation circuit for li-ion battery and supercapcitor

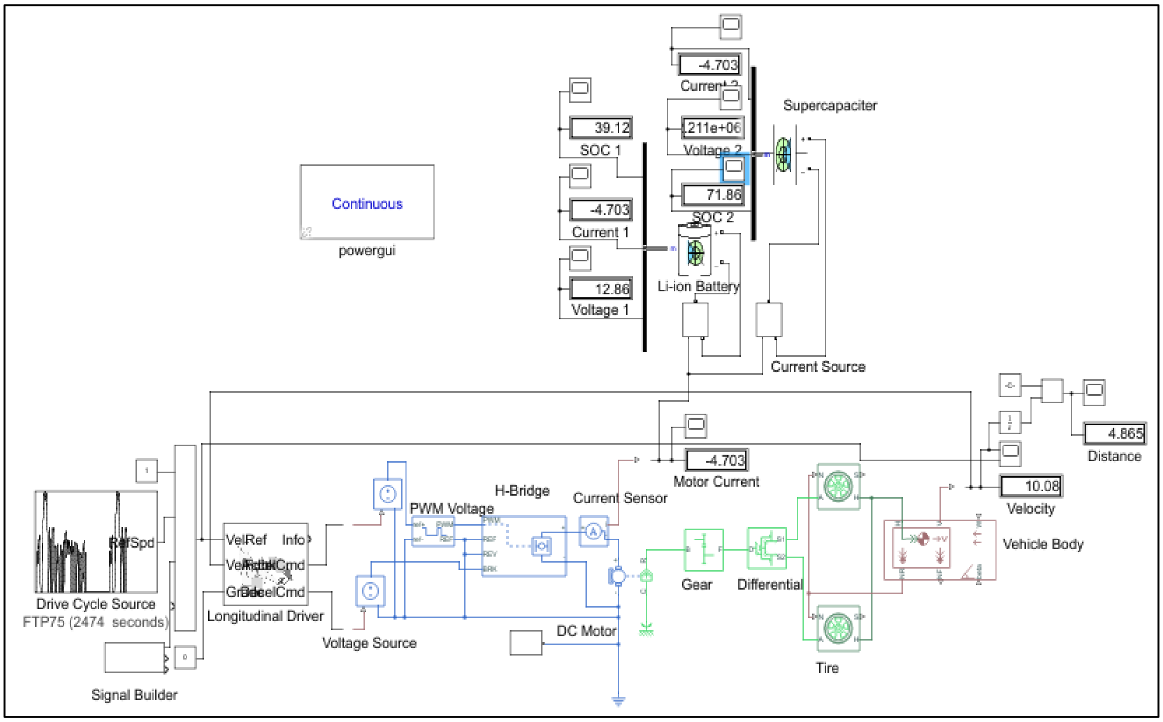

Fig. 13 Simulink model of electric vehicle

- Battery SOC is reduced from 80% to 78.67 after 4 seconds
- Battery Current is constant upto 4 seconds; at the same time, it raises to its peak value and starts reducing upto zero with r.t.to time.
- Battery Voltage is constant upto 4 seconds; at the same time, it reduces to its 8 V (Nominal value) and starts increasing to rated capacity with r.t.to time.
- Supercapacitor shows an increase in current after 4 seconds, whereas voltage and state of charge show approximately 10 units.

Further, using the above mechanism, a simulation for an electric vehicle to evaluate the battery parameters is performed here. The simulation was carried out using MATLAB/Simulink software, considering the hybridization of lithium-ion batteries and supercapacitors, initially charged at 100% as an energy source. Results are further evaluated by simulating the hybridization of lithium-ion battery and supercapacitor using Simulink circuit design as shown in Figure 13, with FTP 75, 2474 seconds, drive cycle for an electric vehicle with specification and parameters as shown in Table 4.

Table 4. EV parameters for simulation

Battery Parameters		**Vehicle Parameters**	
Nominal Voltage of Lithium-Ion Battery	12 V	Mass of Vehicle	100 kg
Rated Capacity	20Ah	No of Wheels per Axle	2
Initial State of Charge	100%	Horizontal Distance from the Front Axle to CG	1.4 m
Battery Response Time	10sec	Horizontal Distance from Rear Axle to CG	1.6 m
No. of Batteries in Series (each of 3.7V)	3	CG Distance above Ground Level	0.5 m
No. of Batteries in Parallel (each 2.5A)	8	Frontal Area	2m^2
Supercapacitor Parameters		Drag Coefficient	0.25
Rated Capacitance	500F	Air Density	1.18kg/m^3
Equivalent DC Series Resistance (Ohms)	470kΩ	**Vehicle Tyre Parameters**	
Rated Voltage	13.5V	Rolling Radius of the Tyre	0.3 m
Number of Series Capacitors	5	Rated Vertical Load	3000 N
Number of Parallel Capacitors	1	Peak Longitudinal Force at Rated Load	3000 N
Initial Voltage	0	Slip at Peak Force at Rated Load	10%
Operating Temperature	25deg	**DC Motor Parameters**	
Gear and Differential Parameters		Rated Speed (at Rated Load)	5000 RPM
Carrier (C) to Driveshaft (D) Teeth Ratio	4	Rated DC Supply Voltage	50V
Follower (F) to base (B) Teeth Ratio (NF/NB)	2	No-Load Speed	7500 RPM
		Rated Load (Mechanical Power)	200W

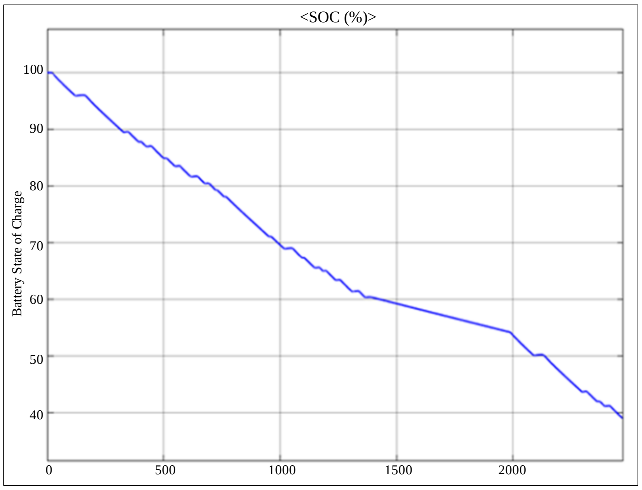

Fig. 14 Battery state of charge vs time

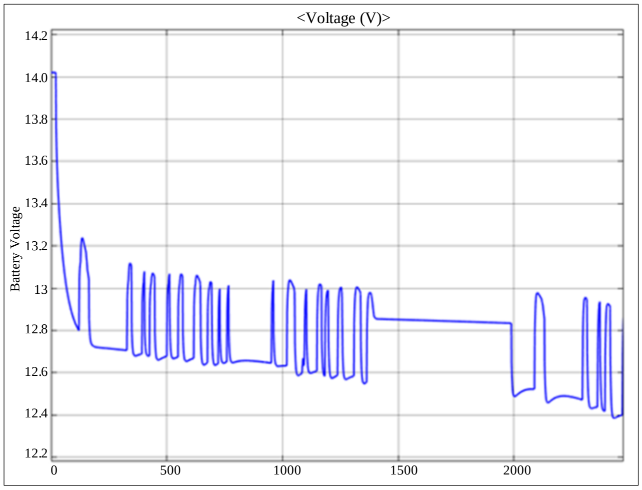

Fig. 17 Battery voltage vs time

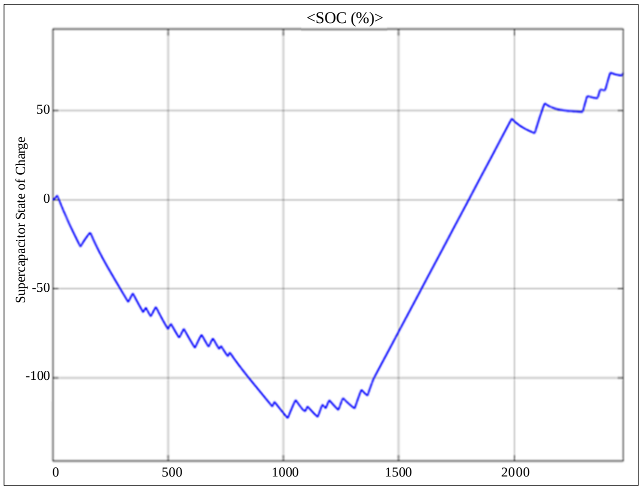

Fig. 15 Supercapacitor state of charge vs time

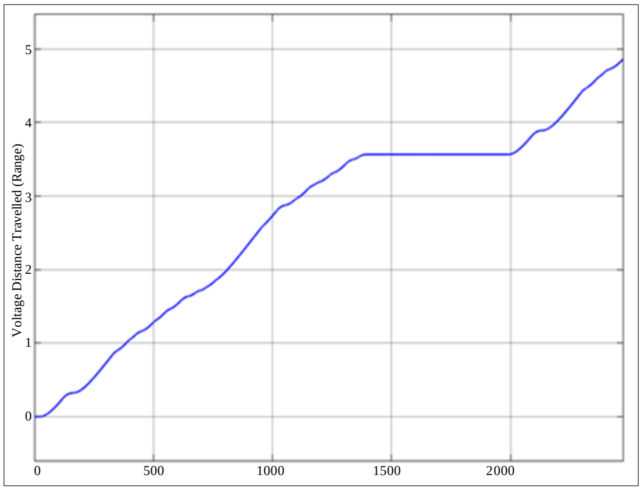

Fig. 18 Vehicle distance covered vs time

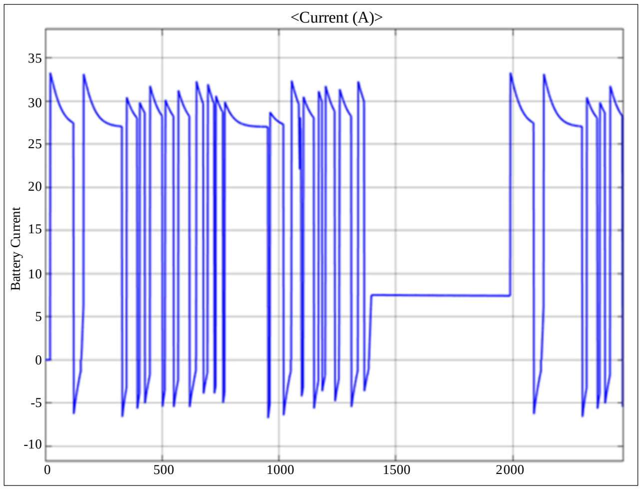

Fig. 16 Battery and Supercapacitor current vs time

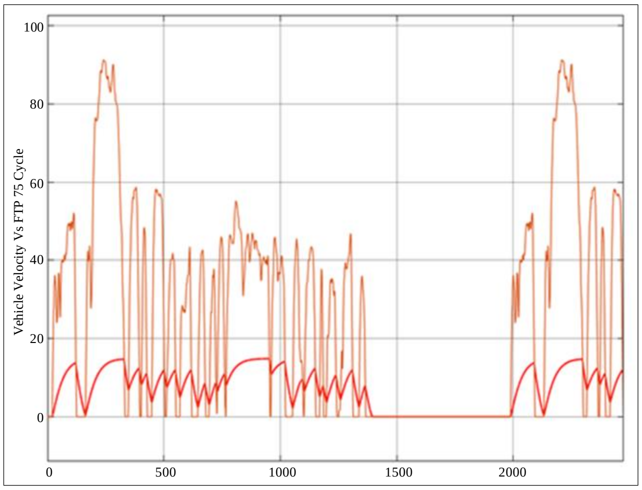

Fig. 19 Vehicle velocity covered vs time as per FTP 75 drive cycle

Table 5. Specifications for CFD analysis

Compressive Ultimate Strength MPa	
Total Heat	4.06e+02 W/m³
Flow Time	1500 S
Maximum Temperature	306.00 K
Area Weighted Average ofPassive Zone Potential	12.36 V
Static Temperature	3.06e + 02 K
Current Magnitude	3.19e+02 A/m²

Table 5 indicates input parameters and boundary conditions for computational fluid dynamics study using ANSYS fluent software using the following inputs.

- The water flow rate was 100 watt
- Conventional rate 10 w/mm2
- Ambient temperature 22 degree
- Material aluminium box, pipe copper

Figure 20 shows the CAD model used for CFD analysis, whereas Figure 21 indicates the copper fin shape model for analysis. Figure 22 indicates the CFD model for battery simulation with internal fins with boundary conditions, whereas Figure 23 shows the Mesh CFD model for battery simulation with internal fins with boundary conditions. Figure 24 indicates the CFD model for battery simulation with internal fins boundary conditions for air cooling, whereas Figure 25 shows the Mesh CFD model for battery simulation with fins boundary conditions for liquid cooling.

Figure 26 CFD model for battery simulation for stresses with maximum stresses as 55.628 N/mm^2 and minimum with a value of 21.787 N/mm^2, which shows that stresses can be reduced to much significant value to control the voltage variation and control other electrical parameters like current and state of charge etc. Figure 27 shows the temperature variation from 55.58^0 to 26.85^0 without cooling. Further, Figures 28 and 29 indicate the temperature variation with air cooling achieved in a range of 55.52^0 to $19.85^{0,}$ whereas liquid cooling shows 55.58^0 to 26.85^0.

This shows the temperature has reduced by approximately 75% reduced with air cooling considering the proposed mechanism compared to liquid cooling. As air is available in ample amounts, this mechanism was found to be cooling efficient and reduce the thermal runaway of the battery pack.

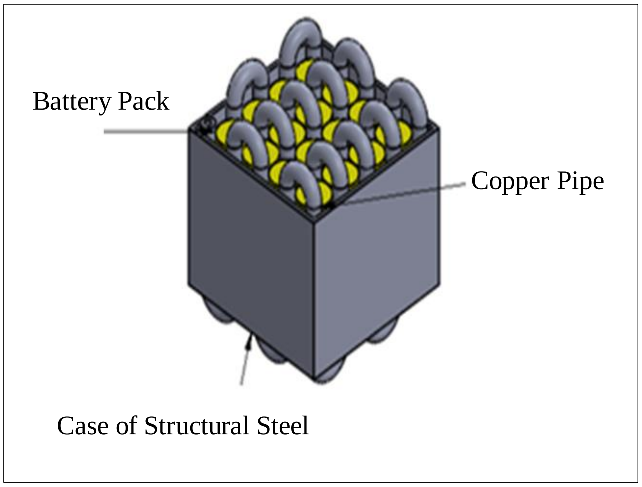

Fig. 20 CFD model for battery simulation with internal fins

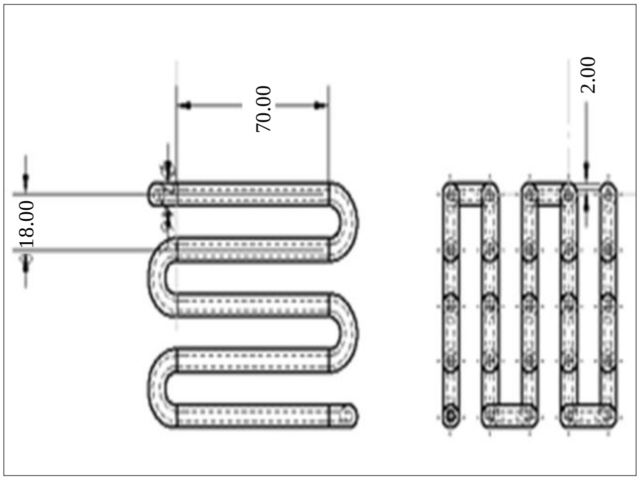

Fig. 21 Copper fin shape model for analysis

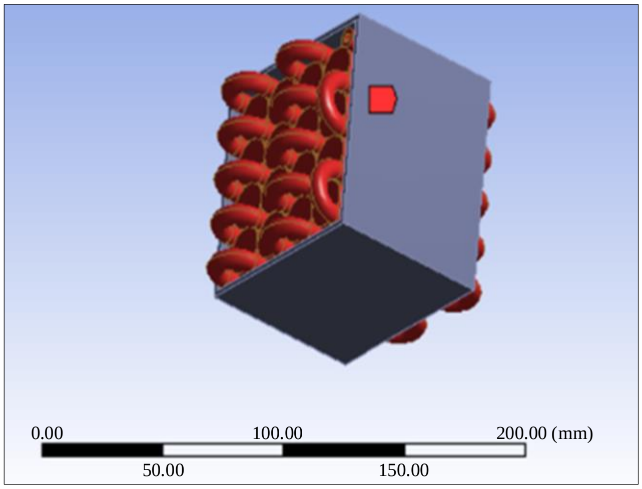

Fig. 22 CFD model for battery simulation with internal fins with boundary conditions

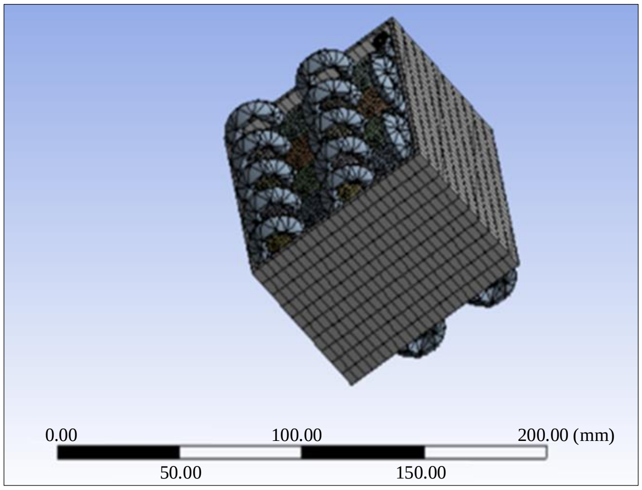

Fig. 23 Mesh CFD model for battery simulation with internal fins with boundary conditions

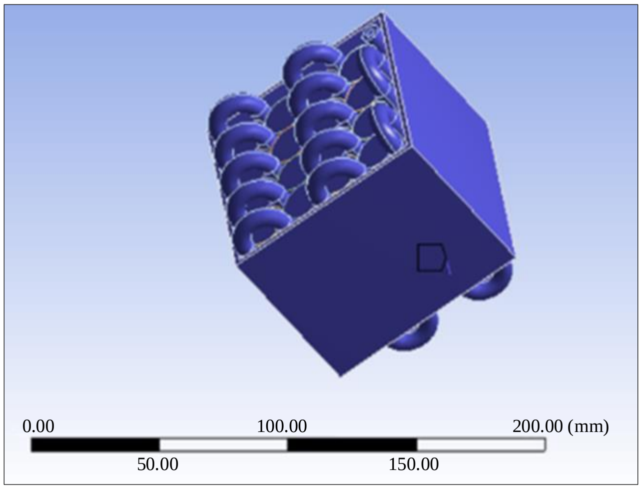

Fig. 24 CFD model for battery simulation with internal fins boundary conditions for air cooling

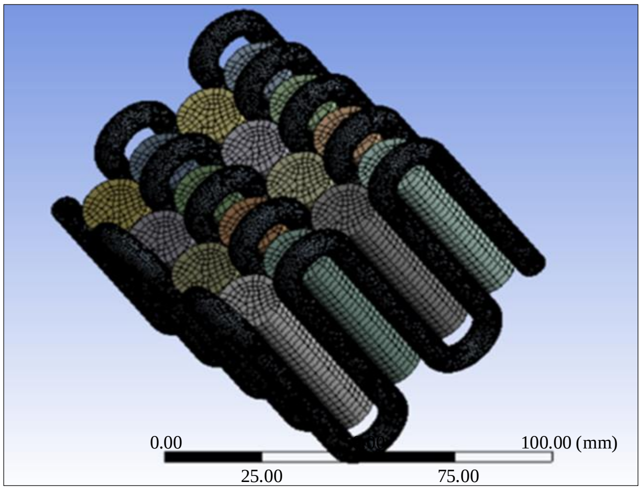

Fig. 25 Mesh CFD model for battery simulation with fins boundary conditions for water cooling

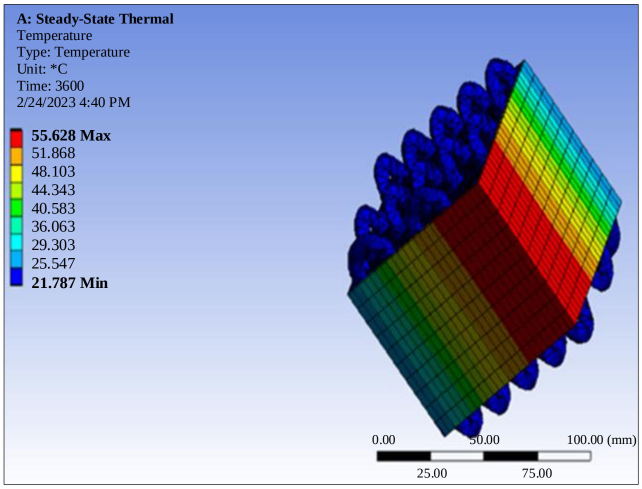

Fig. 26 CFD model for battery simulation for stresses

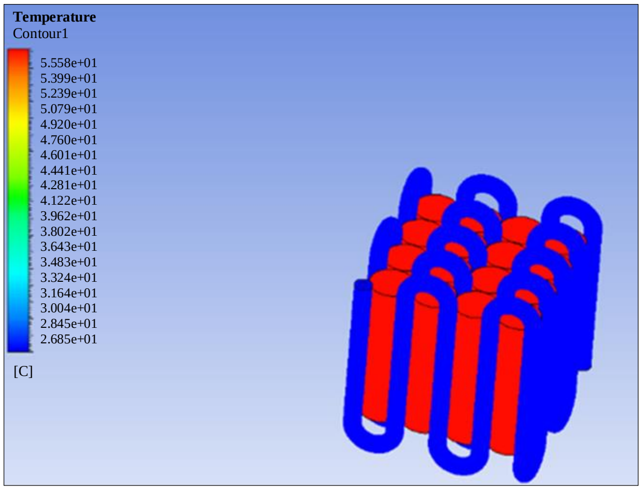

Fig. 27 CFD model for battery simulation for temperature stresses

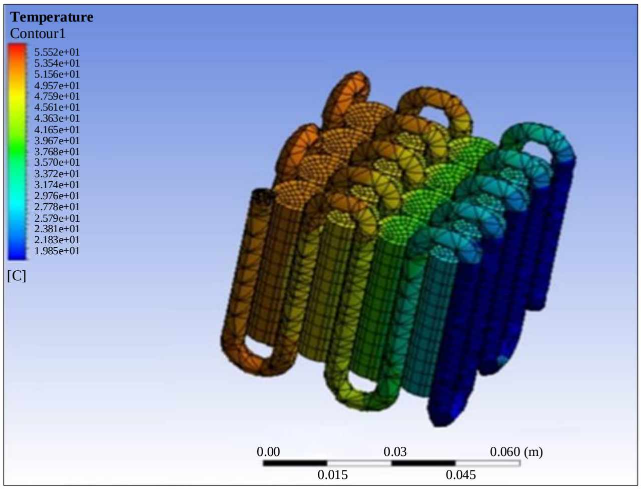

Fig. 28 CFD Analysis of the battery pack by air cooling

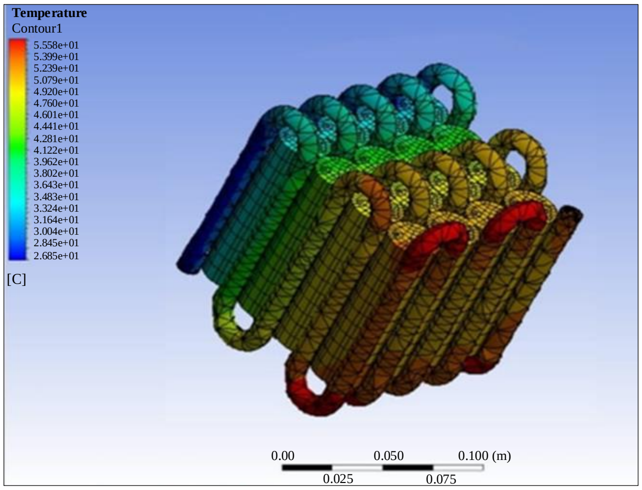

Fig. 29 CFD Analysis of the battery pack by liquid cooling

7. Results and Discussion

Figure 30 shows the voltage variation, whereas Figure 31 indicates the state of charge variation of the hybrid energy storage system w.r.to time. It reflects both aforesaid properties reduced to a significant value of 11 volts from 13.5 volts for 15 seconds with an applied load of 200 watts.

- Initially, the HESS was tested without any load to check for impact on the supercapacitor, and it was seen that Voltage capacity at constant has been affected negligibly on Li-ion battery pack but significantly in the case of supercapacitor packs, as shown in Figure 32.
- Next, the HESS is examined under 200 watts (four-wheeler headlight load) for an hour,
- The loading current of HESS decreased stepwise with the initial jerk for 2 minutes, as shown in Figure 33.

7.1. Structural Analysis

Simulation of electric vehicle shows a graphical representation of variation in different parameters of an electric vehicle, and it seems that,

- Battery state of charge decreases linearly w.r.to. Time with some interruption, whereas that of supercapacitors decreases up to 1400 seconds and suddenly rises linearly till 2000 seconds, with some interrupted variation for further time cycles.
- Battery current and supercapacitor current variation is nearly the same with approximately step variation.
- Voltage variation for the battery suddenly decreases for the first 100 seconds with interrupted variation for further time cycle.
- Distance covered by vehicle shows increasing linear relation for first 1300 seconds, for next 700 seconds it is constant whereas again increase linearly further till cycle completion.
- Vehicle Velocity – 10.08 Km/hr and Distance Travelled – 4.865 Km.
- Battery state of charge is 39.12, whereas supercapacitor state of charge is 71.86.

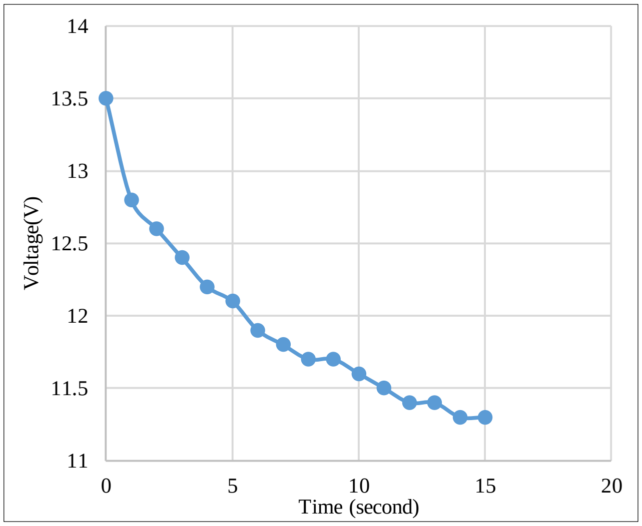

Fig. 30 HESS voltage variation w.r.to time at no load condition

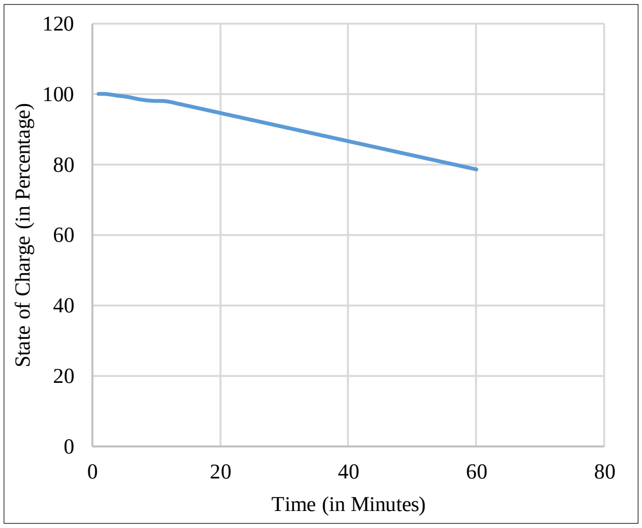

Fig. 31 HESS SOC variation w.r.to time at a load of 220W

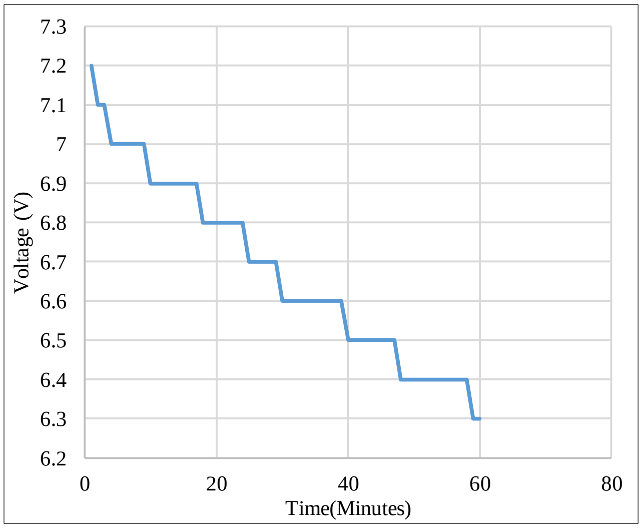

Fig. 32 HESS voltage variation w.r.to time at a load of 220W

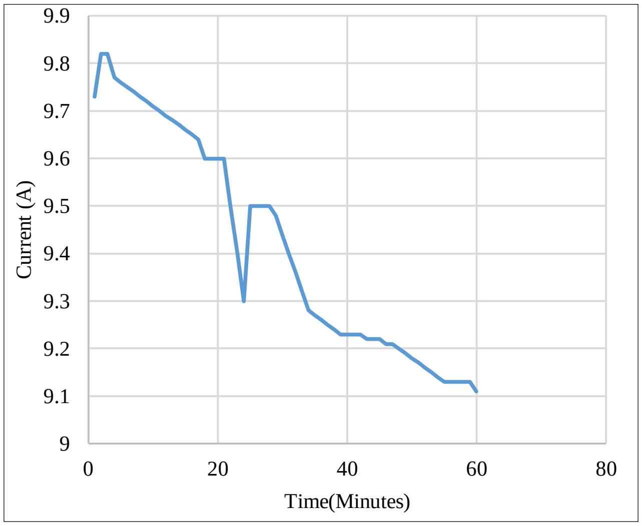

Fig. 33 HESS voltage variation w.r.to time at a load of 200W

1) The current variation: It is discrete, with the initial jerk for 2 minutes, a linear increase of up to 18 mins, and constant for the next 2 mins. It then drops down significantly to 9 amperes for the following 2-3 minutes. Safeguards - 9.6 amperes. Other use only: During operation, the current suddenly increases to 9.6 amps and then drops again. Till now, the supercapacitor is in an ON state; its OFF mode is shown by supercapacitor operation as defined before in Figure 24. Linear Variation of HESS SOC with time.
2) For the supercapacitor, it takes around 3 minutes to charge and discharge for this setup, which takes up to approximately 2.5 hrs in case of battery.

7.2. Thermal Analysis

It is found that, in a comparative study of different cooling systems, air and water, as shown in Figure 35, are available in abundance from nature. However, the only con they have is their little chance for corrosion as and when compared to any other system. It is not a problem for a long-term scoop, but if we make some proper refrigerant area in that cooling region, a refrigerant cooling system can be found to be a desirable solution.

Figures 34 and 35 show the variation of HESS working parameters, i.e. temperature, voltage, current and state of charge w.r.to time. Figures 36 and 37 validate the CFD results, which show that air cooling was found to be a better solution for the proposed hybrid energy system with an inside-fin cooling method.

Figures 38 and 39 indicate the temperature variation of the experimental set-up w.r.to to time, which shows approximately 10 % reduction in temperature w.r.to air cooling, which is not much deviation considering other benefits of air cooling systems.

The conclusion was drawn that an air-cooling strategy required two to three more energy to be spent than the same control temperature. Liquid Direct cooling system has the lowest maximum temperature rise, and the fin-cooling structure saves 40% of the weight of the cell in most cases as long as a homologous sized volume sure, when our four types have an identical total volume. Indirect liquid cooling than direct liquid cooling with a less useful. Percentage Effectiveness of Liquid Cooling compared to air cooling = 6.70%.

Compared with the non-direct liquid cooling system, the study has shown that water cools more efficiently and is better than air because of its high specific heat capacity, density, and thermal conductivity.

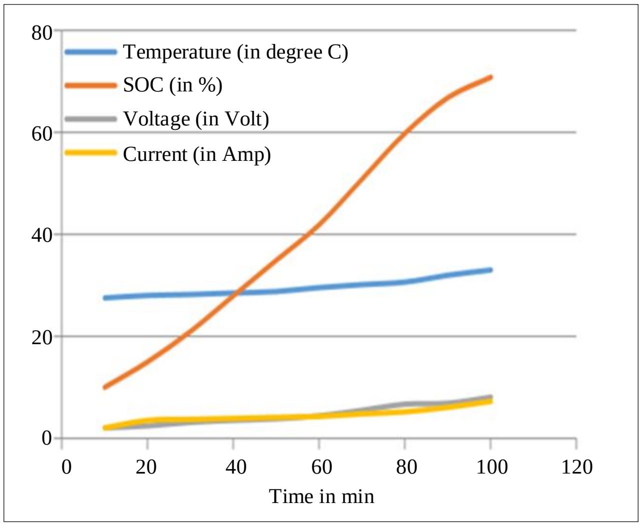

Fig. 34 Battery parameter variation w.r.to time without the cooling system (HESS)

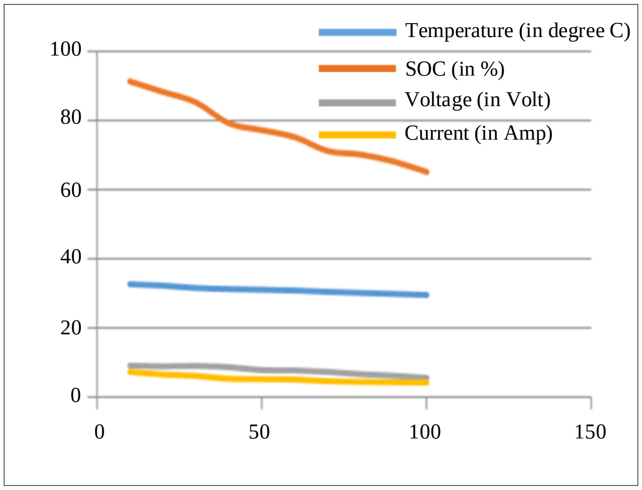

Fig. 35 Battery parameter variation w.r.to time with air cooling system (HESS)

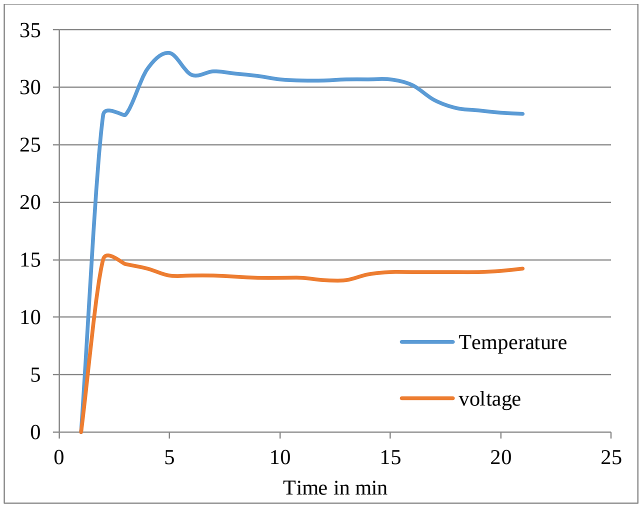

Fig. 36 Battery parameter variation w.r.to time without the cooling system (CFD results)

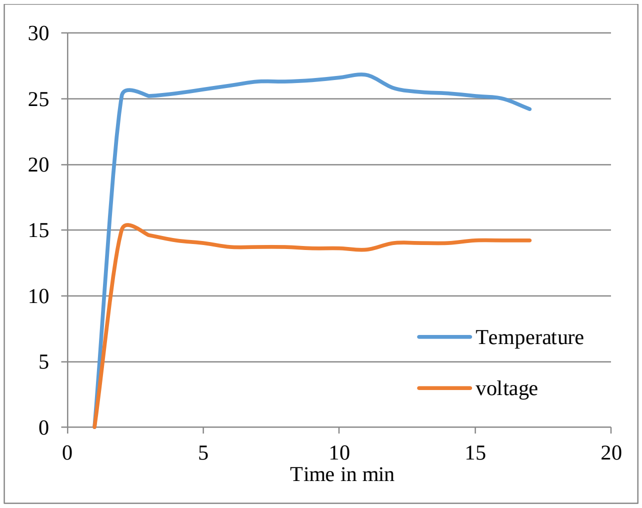

Fig. 37 Battery parameter variation w.r.to time with the liquid cooling system (CFD results)

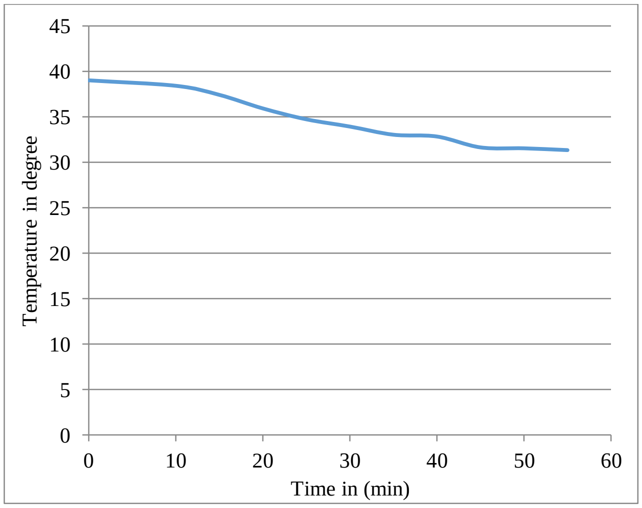

Fig. 38 Battery parameter variation w.r.to time with air cooling system (temperature variation)

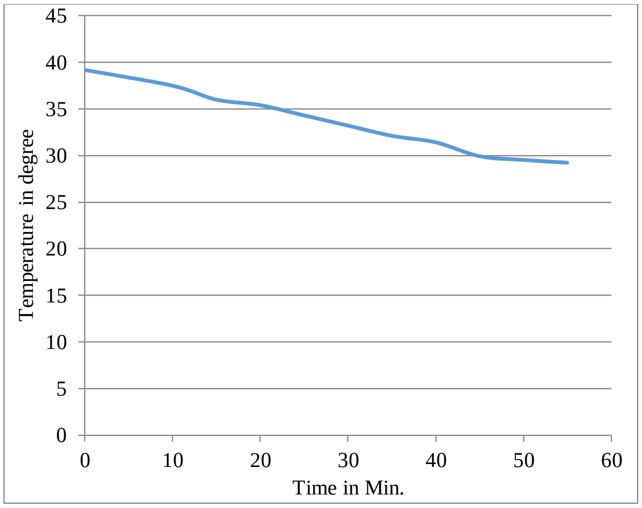

Fig. 39 Battery parameter variation w.r.to time with the liquid cooling system (temperature variation)

8. Conclusion

- Structural analysis of the hybridization proposed between the lithium-ion battery and supercapacitor proposed a novel solution to find that under a given load, detailed results indicate that the only action on the supercapacitor when it requires additional power; otherwise, it is idle.
- The development demonstrates a large-scale solution for effective hybridizing of automobiles (to satisfy the present needs for both energy and power in inter-part surface applications from renewable sources) with powered part surfaces as an important breakthrough at bay.
- In light of the above, this paper aims to perform a structural analysis on an energy storage system with a lithium-ion battery/supercapacitor hybrid configuration (HESS) to achieve better performance and prolong the service life. Factors such as mechanical stability, thermal expansion and material compatibility can be examined for key success for several reasons through Structural Analysis. Real-world corrugations, surface changes, and vibrations felt by onboard human passengers or even freight in an electric vehicle during transit will never allow your system for a housing-mounted meter to work. A proper structure design of walls can absorb mechanical stress, including temperature variation, better than its rigid counterpart.
- These results significantly improve the HESS's overall efficiency, durability and energy density by addressing these structural challenges. Ultimately, this will result in more optimal charge-discharge cycles, improved power delivery, and longer system life. The results underline the significance of judicious design in structural details for a synergistic integration between high-energy capacity lithium-ion batteries and supercapacitors, rendering their hybrid system an attractive, practical solution to high-power applications within contemporary sustainable energy storage scenarios.

- Despite the fact that both components are temperature-sensitive in terms of their electric performance, LIBs suffer from massive levels of degradation at extreme temperatures. Thermal management, both active (liquid or air cooling) and passive cooling (phase change material functionality or thermal insulation), leads to higher working temperature efficiency, meaning better battery life combined with lower inner resistance allows for more charge/discharge cycles while ensuring optimal operating temperatures.
- The performance of the LIB and SC is that of energy storage in HESS while dealing with a relatively slow charging (or discharging) process against high-power delivery involving a supercapacitor. Inefficient thermal regulation can cause inefficient energy distribution, reduced voltage stability and other system performance problems. AI-powered thermal management systems optimize cooling capacity and energy yield for safe, efficient operation. In addition to improving electrical performance, these strategies extend the lifetimes of both energy storage components by maintaining thermal stability and ensuring reliability and efficiency in applications such as electric vehicles. CFD analyses have been made at 21^0C to 56^0C, and thermal stresses are within safe limits for both air and water cooling.
- The simulation results were also validated with experimentally obtained data, which confirmed the accuracy and reliability to some extent because it showed acceptable deflection in time versus current/voltage/state of charge characteristics.

8.1. Limitations and Future Scope

- Materials parameters in lithium-ion batteries and supercapacitors are often input parameters, subject to simplifying assumptions employed by structural or thermal models. Such simplifications could reduce the validity of simulations under real-world operating conditions such as high currents, rapid cycling or high temperatures.
- The temperature inside each HESS may have a uniform distribution, but it might not fully consider localized hot spots or non-uniform cooling in real applications that are densely packed.
- Validating the findings over an industrial scale may be something of a challenge. The limitations of prototyping, the verifiability of long-term ageing, and wear under varying conditions are limited.
- The inherent limitations of the study may not capture all such complex interactions that could arise between lithium-ion batteries and supercapacitors during dynamic load conditions.
- The analysis sought to describe only the slowest possible chemical processes at room temperature and may not have adequately accounted for environmental influences, such as humidity invading a material or external shock vibrations during operation, which cause an incomplete understanding of degradation.
- In the future, advanced materials such as solid-state electrolytes could offer improved structural integrity and thermal stability at higher temperatures. The new predictive models would be more accurate and should incorporate non-linear, time-dependent material properties.
- Multi-physics simulations for the coupling of electrical and thermal problems with mechanical stresses should be considered in future research to understand practical interactions within HESS.
- Understanding the long-term structural and thermal degradation of both battery and supercapacitor to assess real-world cycling/aging conditions for system reliability is an important point in EVs/grid storage applications that requires further study.
- The research investigated hybrid cooling strategies that use an active and passive approach to cool the components more efficiently. For example, researchers might consider using AI and machine learning algorithms to dynamically adjust cooling based on load conditions.
- In the future, such structural and thermal models must be experimentally validated under real operating conditions. This further refined the models and validated them in predicting large-scale system-level hybrid performance.

Funding Statement

This work is funded by Savitribai Phule Pune University, Pune, India, under the ASPIRE Research Mentorship Scheme, sanctioned by the Internal Quality Assurance Cell of SPPU, India.

References

[1] Marek Michalczuk, Lech M. Grzesiak, and Bartłomiej Ufnalski, “A Lithium Battery and Ultracapacitor Hybrid Energy Source for an Urban Electric Vehicle” *Przegląd Elektrotechniczny (Electrical Review)*, vol. 88, no. 4, pp. 158-162, 2012. [Google Scholar] [Publisher Link]

[2] Jian Cao, and Ali Emadi, “A New Battery/Supercapacitors Hybrid Energy Storage System for Electric, Hybrid, and Plug-In Hybrid Electric Vehicles,” *IEEE Transactions on Power Electronics*, vol. 27, no. 1, pp. 122-132, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[3] Rebecca Carter, Andrew Cruden, and Peter J. Hall, “Optimizing for Efficiency or Battery Life in a Battery/Supercapacitor Electric Vehicle,” *IEEE Transactions on Vehicular Technology*, vol. 61, no. 4, pp. 1526-1533, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[4] A. Ostadi, M. Kazerani, and Shih-Ken Chen, “Hybrid Energy Storage System (HESS) in Vehicular Applications: A Review on Interfacing Battery and Ultra-Capacitor Units,” *2013 IEEE Transportation Electrification Conference and Expo (ITEC)*, Detroit, MI, USA, pp. 1-7, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[5] Wei Xiong, Yimin Mo, and Cong Yan, “Online State-of-Health Estimation for Second-Use Lithium-Ion Batteries Based on Weighted Least Squares Support Vector Machine,” *IEEE Access*, vol. 9, pp. 1870-1881, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[6] Seyed Ahmad Hamidi, EmadManla, and Adel Nasiri, “Li-Ion Batteries and Li-Ion Ultra Capacitors: Characteristics, Modelling and Grid Applications,” *2015 IEEE Energy Conversion Congress and Exposition (ECCE)*, Montreal, QC, Canada, pp. 4973-4979, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[7] Jiahao Li et al., “A Comparative Study of State of Charge Estimation Algorithms for LiFePO4 Batteries Used in Electric Vehicles”, *Journal of Power Sources*, pp. 244-250, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[8] Huanyu Wang et al., “Online State of Health Estimation for Lithium-Ion Batteries Based on a Dual Self-Attention Multivariate Time Series Prediction Network,” *Energy Reports*, vol. 8, pp. 8953-8964, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[9] Clemente Capasso, and OttorinoVeneri, “Integration between Supercapacitor and ZEBRA Batteries as the High-Performance Hybrid Storage System for Electric Vehicles,” *Energy Procedia*, vol. 105, pp. 2539-2544, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[10] Haitao Wang et al., “Cooling Capacity of a Novel Modular Liquid-Cooled Battery Thermal Management System for Cylindrical Lithium Ion Batteries”, *Applied Thermal Engineering*, pp.1-31, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[11] Anshuman Bhatt, Rajeev Sharma, and Anil Gupta, “Thermal Management of Lithium-Ion Batteries Using Phase Change Materials: A Review”, *Journal of Power Sources*, 2017.

[12] Peizheng Li et al., “Design and Optimization of a Liquid Cooling Thermal Management System with Flow Distributors and Spiral Channel Cooling Plates for Lithium-Ion Batteries,” *Energies*, vol. 16, no. 5, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[13] Huanwei Xu et al., “Optimization of Liquid Cooling and Heat Dissipation System of Lithium-Ion Battery Packs of Automobile,” *Case Studies in Thermal Engineering*, vol. 26, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[14] Wenhua Zuo et al., “Battery-Supercapacitor Hybrid Devices: Recent Progress and Future Prospects,” *Advanced Science*, vol. 4, no. 7, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[15] Anuradha Herath et al., “Conversion of a Conventional Vehicle into a Battery-Supercapacitor Hybrid Vehicle,” *American Journal of Engineering and Applied Sciences*, vol. 11, no. 3, pp. 1178-1187, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[16] Mahdi Soltani et al., “Hybrid Battery/Lithium-Ion Capacitor Energy Storage System for a Pure Electric Bus for an Urban Transportation Application,” *Applied Sciences*, vol. 8, no. 7, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[17] Lip Huat Saw et al., “Numerical Modelling of Hybrid Supercapacitor Battery Energy Storage System for Electric Vehicles,” *Energy Procedia*, pp. 2750-2755, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[18] Md. Arman Arefin, and Avijit Mal, “Hybridization of Battery and Supercapacitor for Low Weight Electric Vehicle,” *Journal of Mechanical and Energy Engineering*, vol. 2(42), no. 1, pp. 43-50, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[19] Lia Kouchachvili, Wahiba Yaïci, and Evgueniy Entchev, “Hybrid Battery/Supercapaciter Energy Storage System for the Electric Vehicles,” *Journal of Power Sources*, vol. 374, pp. 237-248, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[20] Mohammad Shahjalal et al., “A Review of Thermal Management for Li-Ion Batteries: Prospects, Challenges, and Issues,” *Journal of Energy Storage*, vol. 39, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[21] Xinyang Zhu et al., “Optimization Design of Lithium Battery Management System Based on Z-F Composite Air Cooling Structure,” *Journal of Energy Storage*, vol. 102, part A, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[22] Immanuel Ninma Jiya, Nicoloy Gurusinghe, and Rupert Gouws, “Hybridization of Battery, Supercapacitor and Hybrid Capacitor for Load Applications with High Crest Factors: A Case Study of Electric Vehicles,” *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 16, no. 2, pp. 614-622, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[23] S. Devi Vidhya, and M. Balaji, “Modelling, Design and Control of a Light Electric Vehicle with Hybrid Energy Storage System for Indian Driving Cycle,” *Measurement and Control*, vol. 52, pp. 1420-1433, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[24] A. Bharathi Sankar, and R.Seyezhai, “Super capacitor/Battery based Hybrid Powered Electric Bicycle,” *WSEAS Transactions on Power Systems*, vol. 14, pp. 156-162, 2019. [Google Scholar] [Publisher Link]

[25] Akshay Sanjay Walvekar, Yogesh Krishan Bhateshvar, and Kamalkishore Vora, “Active Hybrid Energy Storage System for Electric Two Wheeler,” *SAE Technical Paper*, 2020. [CrossRef] [Google Scholar] [Publisher Link]