Enhancing electric car lithium-ion batteries by using adaptive materials to improve heat transfer and reduce fatigue.

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ABSTRACT

The success of electric vehicles (EVs) depends mainly on the efficiency of their battery. However, EV batteries still have many issues, mostly in terms of quantity, storage efficacy, charging speed, lifespan, and security, particularly, temperature variations, which can cause accidents that can lead to losses of products and persons. Hence, any advancement in the field of EV batteries would boost their performance and thus, enable daily usage of EVs that would reduce the pollution caused by traditional cars. For this purpose, studies have been conducted to improve the performance of EV batteries. In this study, we developed a novel way to boost the performance of EV batteries by enhancing their aforementioned qualities, through the incorporation of multifunctional materials into the batteries. On the one hand, utilizing phase-change materials can increase the battery capacity by regulating its temperature variation, which will improve the charge–discharge cycle, extend the battery life, and prevent overheating, all of which will increase safety from explosions and unexpected stops during the EV operation. On the other hand, integrating smart materials, such as shape memory alloys, can protect the battery system and guarantee the mechanical stability and flexible management of heat transfer between the EV battery cells, which can protect the battery from thermomechanical fatigue and thus, improve its lifespan. Moreover, adaptable and intelligent materials can be flexibly integrated into the battery without influencing the overall design of the EV nor of the battery, and the additional weight of these materials is too low to affect the entire weight. Therefore, a systematic study to improve lithium batteries was conducted and is presented in this paper to show the need to integrate multifunctional adaptive materials into EV battery storage systems. The results of this study showed an unprecedented improvement in the thermomechanical stability level of the battery that improved its storage performance, quality, and charging speed. Furthermore, the temperature fluctuation of the battery was stabilized for a long time around 23% to boost the battery's performance while minimizing its mechanical fatigue. Finally, the results revealed that the proposed adaptable materials are the most stable for car batteries even during fast charging while driving. These materials can also support alternative ways of charging, such as using solar sources.

Keywords: *Shape memory alloy, phase change material, Lithium-Battery, Adaptive material, fatigue, heat transfer, safety…*

1. INTRODUCTION

In the last few years, the use of electric vehicles has made significant progress and been extensively researched to reduce the significant pollution produced by thermal vehicles. In terms of efficiency and price, yet, EVs and HEVs still have a long way to go before they can compete with thermal vehicles. EVs are driven by electric motors, unlike traditional vehicles that depend on thermal motors. In contrast to the vehicles mentioned above, HEVs are designed to use both a thermal engine and an electric motor. EVs require electric batteries, which are the core of their operation and must function perfectly under different circumstances. Although EVs can use various types of batteries to generate electricity, lithium-based storage systems are the most widely used type due to their excellent capacity, low self-discharge rate, and long life cycle. Recently, Sayem *et al.* [1] presented an overview of Li-ion battery materials and discussed their challenges and opportunities. Their investigation focused on improving the battery's energy density and safety by utilizing new and adaptable materials. Hence, the practicality of lithium-ion (Li-ion) batteries is due to their high energy density, low weight, high efficiency, availability, and storage power. They have many advantages, despite some drawbacks that must be considered. More specifically, damaged or incorrectly charged batteries can lead to overheating or fire. Lately, Zeng [2] discussed thermal management in Li-ion batteries, emphasized factors that impact heat generation and dissipation, and demonstrated that temperature variations have a major impact on the battery discharge rate, power density, capacity, and lifespan. Consequently, thermal effects in Li-ion batteries must be controlled to make them suitable for various applications, including for EVs. Despite the longer lifespans of Li-ion batteries, they are degraded over time, which reduces their storage capacity, and replacing them can be costly. Therefore, their weight, vibration, and operating temperature must be particularly considered.

In fact, any thermomechanical variation that exceeds the normal thermal running can cause internal cell damage, which would disrupt the power available for discharging and charging, as energy from the cell quickly flows to nearby cells. Araki *et al.* [4] discussed the significance of comprehending these processes and the impacts of different factors, such as the thermal expansion coefficient and elastic modulus of the materials, on the stresses in the thin-electrolyte plate. The findings indicate that control of the temperature impact and stress variations on EV batteries is crucial to improve their performance. Therefore, several thermal management systems exist for controlling the temperature of battery systems, and employing adaptive materials as phase change materials (PCMs) could be a suitable solution for this purpose [8], [9]. Indeed, PCMs operate as a reliable thermal management system that can control the thermal flow in electrical battery systems [10], [11]. Their incorporation into the battery architecture ensure the absorption and storage of extra heat as latent heat, which prevents overheating. Recently, Javani *et al* [14] verified that incorporating PCM in the passive thermal management of electric cars decreases the maximum temperature and temperature excursion within the cell. Yu *et al.* [13] studied the various approaches to enhance the PCM heat transfer and analysed their advantages and disadvantages. They show that combining different thermal management systems, such as coupled heat pipe and PCM systems can improve operational performance, which signifies an innovative avenue for future research.

On the other hand, Shukla *et al.* [5] measured the temperature of a Li-ion battery cell under diverse levels of vibration. The findings revealed that the vibration in the battery area significantly affected the temperature of the Li-ion battery cell. Hence, the thermal field of the battery cell can be affected by the amplitude and frequency of vibrations, and larger amplitudes and frequencies result in higher temperature rises. In fact, even indirect stress and vibration can affect EVs, including their battery. This is why many researchers have studied the influence of stress variation on EVs and HEVs. Kulkarni *et al.* [6] investigated the fatigue behavior of a suspension system used inside an EV wheel and found that exposing the system to cyclic loading can cause fatigue failure in its components, including in its battery storage system. Consequently, the critical areas of the suspension system that are most susceptible to fatigue failure were identified, which can be used to guide design improvements and optimization. However, to prevent mechanical fatigue in electric car batteries, the researchers employed various methods to improve system stability and reduce mechanical vibration. Recently, Liu *et al.* [15] discussed the different safety issues and different mechanisms that associated with lithium-ion battery that subjected to cyclic mechanical loading, which potentially leads to thermal runaway and serious safety risks. Li [16] conducted research to minimize vibration and mechanical stress, which enhances battery life and offers additional security in case of shock or overheating.

Therefore, several studies have successfully developed algorithms to integrate adaptive systems, merging diverse components with a specific emphasis on optimizing efficacy. Hence, the integration of mechanical dampers reinforces the safety, lengthen the life of the storage system, and avoid the sudden rupture during operation. As heat and vibration are unavoidable in electric batteries, the use of adaptive materials such as shape memory alloy (SMA) is capable of handling these challenges. The most important that SMAs are suitable with PCMs that can work together to limit heat and mechanical fatigue. Recently, Yin *et al.* [17], [18] proposed a co-design optimization with evolutionary algorithms, achieving optimal efficacy in dynamic conditions. In emerging tech, choosing adaptive materials is crucial. Integrating SMA with PCM goes beyond temperature control and thermal energy management. Indeed, this dynamic combo promises competitive thermal management, adaptability, safety enhancements, fatigue reduction, and cost-effectiveness for advancing EV batteries in various conditions, thus playing a significant role in the evolution of EV technology [19].

In this research, a systematic study to improve lithium batteries by integrating multifunctional adaptive materials has been presented. The use of these materials makes it possible to manage the temperature and reduce stresses during operation, which ensures the needed safety. The results of this study show an unprecedented improvement in the level of stability and performance of autonomy and charging speed. Thus, the thermo-mechanical management system warrants the car battery to operate at peak performance by providing a balanced temperature, secure against overheating and vibration, shock and fatigue. Moreover, the new developed design has incorporated SMA and PCM to control the thermal and mechanical management system. Then, a numerical study was conducted to analyse the behaviour of both adaptive materials in the electrical storage system in order to manage its temperature and mechanical fatigue. The results obtained are analysed and compared with results from the literature in order to show the efficiency of the proposed management system.

2. PROPOSED SYSTEM FOR THERMAL MANAGEMENT:

2.1. The proposed PCM -SMA

Electric and hybrid cars naturally operate in ways that expose their battery components to temperature and stress variations, which obviously affect their performance. This study has developed an adaptive system that incorporates the lithium battery system in electric cars to prevent thermo-mechanical challenges. Besides, it is crucial to create an optimal design that ensure to simplify the integration of adaptive materials into the car battery system. Accordingly, the proposed system is based on previous systems that can complement them for controlling temperature and stress variation then be protected and optimize the battery system [20]–[24]. Hence, Both PCM and SMA systems cooperate with each other to control and manage the temperature variation and stress variation as shown in the figure 1:

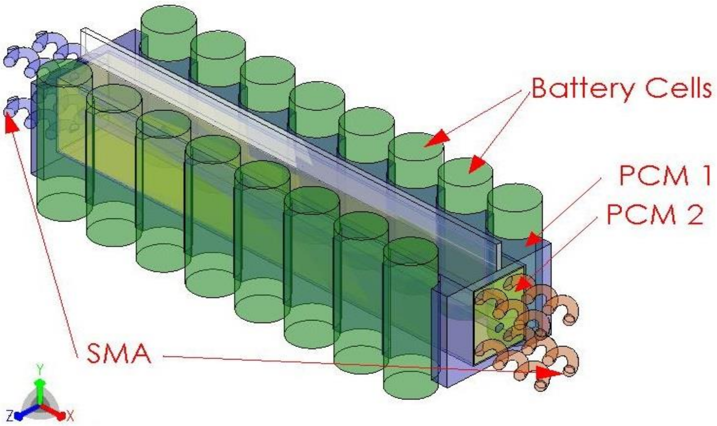


Fig. 1 : The proposed electrical storage system with the integration of adaptive smart system.

The proposed adaptive system benefits from the temperature variation to change the phase in the PCMs and in the SMA. As the SMA component heats up, it changes its shape, effectively separating the heated part from other components. This mechanism facilitates heat evacuation and ensures a balanced distribution of heat among the battery cells. The proposed battery management system (BMS) designed with robust heat and fatigue dissipation capabilities and a compact construction that eliminates the need for additional energy input. The battery system is made up of two parts: A fixed part, which is the electrical storage system, and a flexible part is responsible for managing mechanical and thermal energy. Therefore, the PCM is able to manage thermal energy in the system, and the SMA can supervise the PCM's distribution in different parts of the system and dissipate mechanical stresses [25].

2.2. Physical principle of the proposed PCM -SMA

The proposed actuator in this study is based on two adaptive materials that the SMA and the PCM that can be adapted to temperature variation and stress variation. Due to their ability to absorb heat and stress over time, both materials can handle thermal variation through the phase change principle. Typically, phase changes typically occur when heat is added or taken away at a specific value and can switch between different states (solid-liquid, liquid-gas or gas-solid). Solid-liquid phase change stands out as the predominant mechanism employed in thermal energy storage systems and thermal management. This phase transition is distinguished by its capacity to absorb or release substantial latent heat, making it a widely utilized choice in various applications.

SMAs are metallic materials that exhibit a unique property known as shape memory effect (SME), which allows them to return to their original shape after being deformed under certain conditions. This effect is due to a reversible phase transformation between martensite and austenite. When an SMA is deformed at low temperature, it can change from its original austenitic crystal structure to a more flexible and easily deformable martensitic crystal structure. When SMA is heated above a specific temperature, it undergoes a phase transformation to the austenitic crystal structure, allowing it to return to its original shape even it has been deformed fig.3). Hence, the SMA in this case can operate as an excellent damper that absorbs stresses that dissipate mechanical energy and return to its original shape. Hence, the phase transformation in SMAs is driven by a change in temperature or stress, while in PCMs the transformation occurs due to a change in the thermal energy of the material.

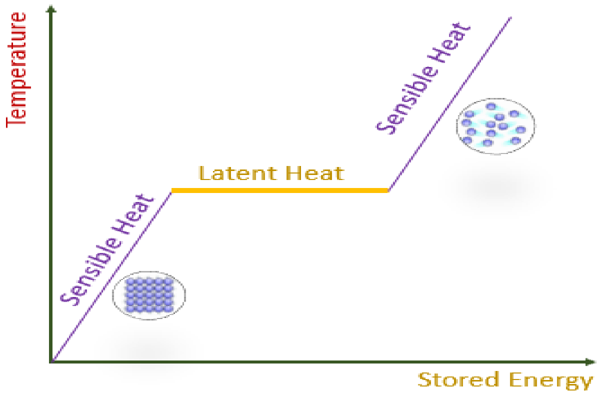


Fig. 2 : Evolution of phase change material as a function of temperature variation.

On the other hand, there could be a solid-solid phase change as found in SMA materials [26], [27]. Otherwise, shape memory alloy absorbs thermal energy to change phase from crystal structure at low temperature (martensite phase) to another one at high temperature (austenite phase) [28].

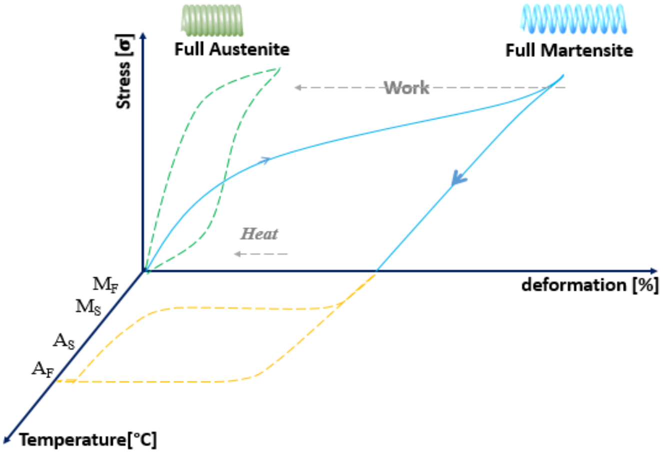


*Fig. 3 : T*hermo-mechanical behaviour of the Shape memory alloy.

It has been indicated that the SMA and PCM react to temperature variations. Consequently, PCM and SMA are two different types of materials with distinct temperature-responsive behaviours that make them complementary properties. As a result, the PCM and SMA combination can offer a mutually beneficial system in which the PCM can absorb and release thermal energy while the SMA can do mechanical work, and the two materials can cooperate to efficiently regulate temperature.

The adaptive actuator outlined in this study ingeniously combines between the PCM and SMA in a complementary manner, which will exploit almost all the properties of both materials. On the one hand, the PCM characterized by the change of phase that can absorb a significant heat in order to pass from the solid phase to the liquid phase, while it will ensure a constant temperature throughout around the transition region [29], [30]. Hence, the lithium battery can dismiss the overheating over the storage operation, which allows the PCM to act as a heat sink, absorbing excess heat generated by the system and preventing the temperature from rising. As the system cools, the PCM solidifies and releases the latent heat of fusion into the system, maintaining a constant temperature. This process is known as thermal energy storage and can be used to regulate the temperature of a system, reducing the need for active cooling or heating.

3. THERMO-MECHANICAL MODELLING:

The modelling of the proposed system can be divided into two types of modelling; the SMA modelling and PCM modelling. Subsequently, both models can reveal the variables that are connected between the two materials, resulting in a coupled system that combines the characteristics of the two materials into a single equation that can definitely represent the combined behaviour of PCM and SMA.

3.1. The SMA thermo-mechanical model

In this part, the mathematical description of the SMA aims designing the material to exhibit a specific superelastic and shape memory effect in response to environmental stimuli. The proposed study can capture these thermomechanical behaviour and adjust the proposed actuator to the surrounding. The actuator applied the superelasticity and the memory effect, which is reply to temperature variation and stress. The SMAs comportment can be studied by studying their total deformation, which is the sum of elastic deformation and transformation deformation. We can understand how these materials behave and create new SMAs with certain qualities by investigating the total deformation of SMAs. In light of this, the current modelling based on a total deformation that may be separated into partial deformations as shown in the equations (1) and (2) [31], [32]:

$$\mathcal{E}^{Tot} = \mathcal{E}^{elas} + \mathcal{E}^{Th} + \mathcal{E}^{plas} \qquad (1)$$

$$\mathcal{E}^{Tot} = {}^{\sigma}/_{Y} + \delta.(\theta - \theta_0) + \text{ƒ}\,\bar{\mathcal{E}}^{Tr} \tag{2}$$

with, $\mathcal{E}^{Tot}$, $\mathcal{E}^{e}$, $\mathcal{E}^{Th}$, et $\mathcal{E}^{Tr}$ are the strain total, elastic, thermal and transformation

$$\mathcal{E}^{Tr}(x,t) = \text{ƒ}(t) \cdot \xi^{sat} \tag{3}$$

The amount of transformation deformation depends on the transformation strain and the volume fraction of martensite. The volume fraction can be written as shown in the equation (4):

$$\text{ƒ}(x,t) = n \tag{4}$$

The irreversible deformation that happens when a material goes through a phase transformation is referred to as transformation deformation. Transformation deformation associates with the irreversible deformation that takes place when the SMA go through the creation of martensite variants that occur in a modification in the material shape. The accumulation of infinitesimal deformations succeeded in a state of saturation in which the martensite fraction is entirely acquired (n=1) in the material that leads to the saturation strain (ξ^{sat}).

The model equation has been thought to be generated from the studied deformations that considered various interactions and the have the ability to connect the variation in global deformation to the temperature and stress variations. The free energy of Helmholtz energy associated with the entire deformation can eventually be obtained by adding together every partial deformations and each of its associated energy as can be written below:

$$\psi_{tot} = \frac{1}{2\rho}(\xi^{e}):Y:(\xi^{e}) + C_v[(\theta - \theta_{moy}) - \theta ln\frac{\theta}{T_{moy}})] + \alpha(\theta - \theta_{moy}).\text{ƒ} + \frac{1}{2}\psi: \textstyle\sum_n \sum_k((I - S^{K}):(\xi_k^{Tr} - \xi_n)\text{ƒ}.\xi_{sat} + \chi \tag{5}$$

Where the following two-dimensional heat diffusion equation can describe the source of heat energy χ is written:

$$\rho c.\frac{dT}{dt} = div(\lambda grad\theta) + \chi \tag{6}$$

The greatest benefit of SMA is its ability to adapt to the environment, allowing our system to take advantage of any temperature change. Since the heat equation may reflect all the different heat transfer modes across the whole system, the SMA may function as both a sensor and an actuator with perfect responsiveness to the PCM. Hence, a significant degree of design and application flexibility in this study is provided by the fact that thermal activation of the SMA may be triggered by direct conduction via phase change material or either by indirect exposure to temperature variation expected from the battery system.

3.2. The PCM thermomechanical model

The PCM incorporated in the battery system is designed to surround the cylindrical battery cells in order to absorb the generated thermal energy. The descriptive equation of PCM system combines the heat transfer equation with the Navier-Stokes equations in order to connect the internal variables with the thermomechanical behaviour of the material. Accordingly, the system's energy balance is related the energy equation of heat transfer, while fluid circulation and momentum are governed by the Navier-Stokes equations.

The thermomechanical equation of PCM is a three-dimensional model can capture the PCM behavior when the phase change in the system and can describe the temperature variation and the thermal energy exchanged during phase change between the surrounding and the PCM as shown below:

$$\frac{\partial[(\rho\int c_p d\theta)+\text{ƒ}l]}{\partial t} + U_x\frac{\partial[(\rho\int c_p d\theta)+\text{ƒ}l]}{\partial x} + U_y\frac{\partial[(\rho\int c_p d\theta)+\text{ƒ}l]}{\partial y} + U_z\frac{\partial[(\rho\int c_p d\theta)+\text{ƒ}l]}{\partial z} = k\left(\frac{\partial^2\theta}{\partial x^2} + \frac{\partial^2\theta}{\partial y^2} + \frac{\partial^2\theta}{\partial z^2}\right) + \chi \tag{7}$$

The PCM surfaces are in contact with a source of heat flow. Therefore, the thermal system's final equation is:

$$\rho c_p\left(\frac{\partial\theta}{\partial t} + U_x\frac{\partial\theta}{\partial x} + U_y\frac{\partial\theta}{\partial y} + U_z\frac{\partial\theta}{\partial z}\right) = k\left(\frac{\partial^2\theta}{\partial x^2} + \frac{\partial^2\theta}{\partial y^2} + \frac{\partial^2\theta}{\partial z^2}\right) - \rho\, l\left(\frac{\partial\text{ƒ}}{\partial t} + U_x\frac{\partial\text{ƒ}}{\partial x} + U_y\frac{\partial\text{ƒ}}{\partial y} + U_z\frac{\partial\text{ƒ}}{\partial z}\right) + \chi \tag{8}$$

It is implied that the proposed model, which depicts the phenomena and thermo-fluidic assumption described by the equilibrium equations coupled and the heat energy equation, is capable of simulating the thermal heat behaviour and its relationship between the PCM and battery system.

- *Coupling SMA-PCM*

The relationship between the PCM and SMA in the system is associated with the variation of temperature in the battery system that evacuates the heat to the PCM then to the SMA. Consequently, the heat transfer in the system can be ensured the phase change in the SMA and the PCM. The coupling thermomechnical in the SMA material can be Respond to the thermal energy and mechanical energy as shown in the below equation:

$$\psi_{tot} = \frac{1}{2\rho}\,(\xi^{e}):Y:(\xi^{e}) + C_v[\,(\theta-\theta_{moy}) - \theta ln\frac{\theta}{\theta_{moy}})\,] + \alpha(\theta-\theta_{moy}).\mathfrak{f} + \frac{1}{2}\psi:\sum_n\sum_k(\,(I-S^{K}):(\xi_k^{Tr}-\xi_n)\mathfrak{f}\,.\,\xi_{sat} + \chi \quad (9)$$

The system is pushed to switch from a liquid to a solid state and vice versa by the temperature variations in the phase transition material. As a result, as shown by the equation, the energy that has been realized or stored will change into SMA material, which can govern the martensitic transformation:

$$\psi_{tot} = \frac{1}{2\rho}\,(\xi^{e}):Y:(\xi^{e}) + C_v[\,(\theta-\theta_{moy}) - \theta ln\frac{\theta}{\theta_{moy}})\,] + \alpha(\theta-\theta_{moy}).\mathfrak{f} + \frac{1}{2}\psi:\sum_n\sum_k(\,(I-S^{K}):\left(\xi_k^{Tr} - \xi_n\right)\mathfrak{f}\,.\,\xi_{sat} + \rho c_p\left(\frac{\partial\theta}{\partial t} + U_x\frac{\partial\theta}{\partial x} + U_y\frac{\partial\theta}{\partial y} + U_z\frac{\partial\theta}{\partial z}\right) - k\left(\frac{\partial^2\theta}{\partial x^2} + \frac{\partial^2\theta}{\partial y^2} + \frac{\partial^2\theta}{\partial z^2}\right) + \rho\, l\left(\frac{\partial\mathfrak{f}}{\partial t} + U_x\frac{\partial\mathfrak{f}}{\partial x} + U_y\frac{\partial\mathfrak{f}}{\partial y} + U_z\frac{\partial\mathfrak{f}}{\partial z}\right) \quad (10)$$

4. RESULTS AND DISCUSSION:

4.1. Validation

In order to verify the adaptability of SMA-PCM multifunctional material's in the battery system, a numerical analysis that compares and analyses numerical results with experimental findings published in the literature was carried out. The SMA actuator and the PCM material used in the references are regenerated using the same thermo-physical characteristics and operating circumstances in the validation investigation. The selection of Ni-Ti and Paraffin RT28 for electric vehicle battery applications based on their unique properties. Ni-Ti is the best choice that addresses challenges, related to vibration, fatigue, and shape memory, ensuring the structural integrity of the battery. Paraffin RT28 is the most effective choice to manage thermal energy by stabilizing the temperature at around 28°C, which improves the electric battery's overall performance and safety. The specific properties of adaptive materials like NiTi and Paraffin RT28 play a crucial role in improving lithium-ion batteries in electric vehicles. So that, they address challenges related to vibration, fatigue, and thermal management, ultimately contributing to enhanced durability, safety, and overall performance of EV batteries.

Table.1: The specification of SMA actuator

SMA actuator specifications	
start critical stress $\boldsymbol{\sigma_s^{cr}}$ (MPa)	0
Final critical stress $\boldsymbol{\sigma_f^{cr}}$ (MPa)	200
C_A Transformation Factors	4
C_M Transformation Factors	2
Max residual deformation (%)	$\varepsilon_L \approx 2$
The SMA actuator	
spring diameter (mm)	4
The max strain $\boldsymbol{\varepsilon}$ (%)	5
Austenite temperature (°C)	> 30
Maximum stress (MPa)	≤400
Martensite temperature (°C)	< 10

According to Fig. 4, which depicts Yoo [33] experimental investigation of the thermo-mechanical behaviour of the SMA actuator, the numerical results of the reference are in excellent agreement with those of the current model. We find the same results for Sobrinho [34] and Yoo [33]. Indeed, the model can capture other characteristics and behaviour as shape memory effect and damping effect as shown in the Fig.4:

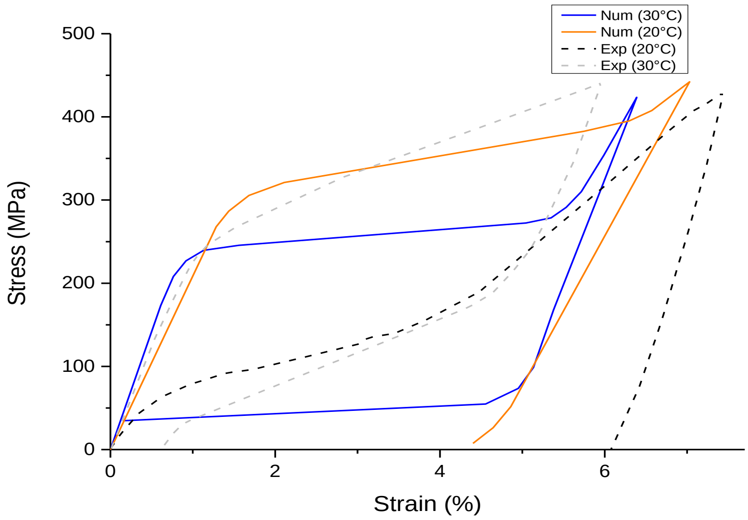


Fig. 4: Variation of strain as a function of stress

As revealed in Fig. 4, the current model shows suitable agreement with the numerical results of the reference. The obtained results show that the behaviour of SMA is dependent on the temperature variation, which means the SMA behaves as damper superelasticity respond to stress variation at high temperature above 28°C. On the other hand, the SMA behave memory effect under 28°C. Consequently, these results can make sure that the proposed system can work in harmony with the battery system to prevent stress variation and temperature.

In fact, the martensite transformation can be controlled by the temperature variation through PCM material in order to ensure a heat evacuation and mechanical safety. PCM absorbs thermal energy from the battery system, consequently the temperature decreases compared to the system without PCM, as displayed in Fig.5:

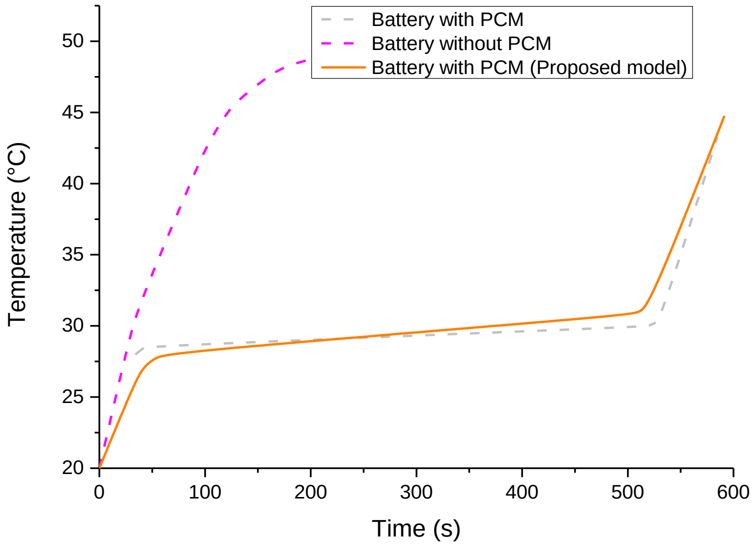


Fig. 5 : Phase change materials fusion front relationship time

Fig. 5 demonstrates that the battery system's temperature is continuously rising in the absence of a PCM. In comparison, a system with a PCM layer maintains its temperature at 28 °C for half of the research duration. Additionally, the suggested system's temperature is always maintained at 28 °C since the system's Airflow absorbs the generated thermal energy [35].

4.2. PCM material and thermal management in lithium battery system

A comparison of the projected numerical simulation and the experimental data has been done to validate the numerical research. Utilizing a successful cooperative control strategy from literature, this study adopts a proven approach to enhance the synergy between two systems [36]. The methodology's feasibility is confirmed through simulations, verifying its effectiveness in improving energy production in the studied context [37]. In Table 1, the characteristics and settings of the materials under consideration that will be used for simulation are shown.

Table.2: The specification of Aluminium, Air and Paraffin RT28 [38]

property	***Unity***	***Paraffin RT28***	***Air***	***Aluminium***
Specific heat	(J/Kg.K)	2890	1	871
Thermal conductivity	(W/m.K)	0.2	0.0242	202.4
Melting temperature	(°C)	28	-	-
Liquidus temperature	(°C)	27	-	-
Solidus temperature	(°C)	26	-	-
Melting heat	(kJ/kg)	160	-	-

Since all heat transfer in different geometries was taken into account as an additional thermal energy, it was possible to compare the modelling's ability to describe PCM behaviour, which largely agrees with the references [39]–[42] with a noticeable increase in the present results.

➢ *Heat transfer in the system with and without PCM*

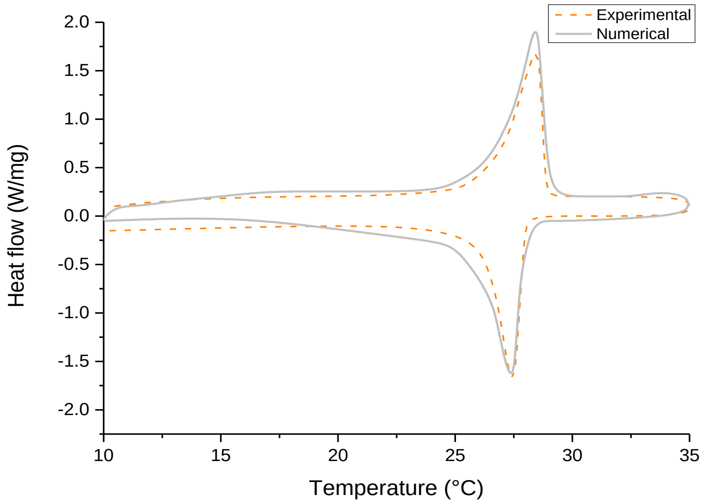


Fig. 6 : Heat transfer in the battery system with and without PCM

As can be observed in Fig. 6, when the battery performs at a temperature higher than the melting point of the PCM, the material gathers the extra heat generated by the battery and changes from a solid to a liquid state. Indeed, the amount of PCM used and its specific heat capacity determine the amount of heat it can absorb. Until all of the PCM melts, it may continue to absorb heat without experiencing a major temperature increase.

➢ *Temperature variation as a function of time with and without PCM*

In a battery with PCM, the temperature variation over time will depend on several factors, including the specific properties of the battery and PCM, the ambient temperatures, and the rate of energy input and removal from the system.

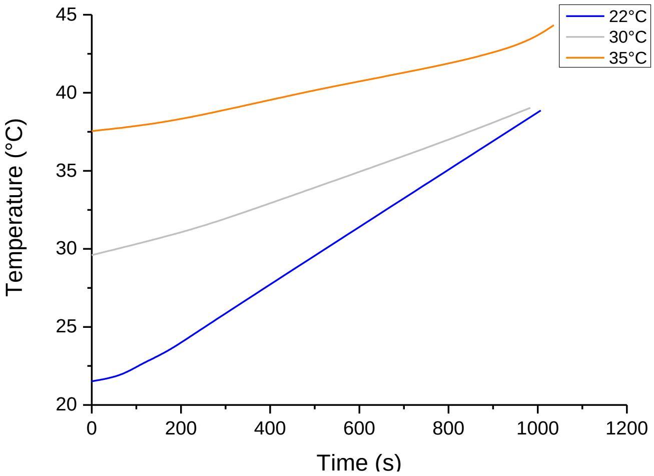


Fig. 7 : Temperature variation as a function of time with and without PCM

When a battery is being charged, it generates heat due to internal resistance and other factors. If the ambient temperature is relatively high, the heat generated during charging can change the battery temperature to rise rapidly. As can be seen in Fig. 7, at ambient temperatures of 30 °C and 35 °C, the maximum battery heat of the modules changed little. In this way, even if the system is equipped with the PCM the temperature can increase to even exceed the melting point. This is due to the fact that, at the end of discharging at the first ambient temperature of 22°C, the PCM is not totally heated, it however, at the next ambient temperature, each of the temperatures of the battery module varies mainly within the PCM melting temperature range. In a battery system, the presence of the PCM can help to reduce temperature fluctuations and maintain a more stable temperature, which can improve safety, performance, and lifespan of the battery.

➢ *Cycle life of lithium ion cells by partial state of charge cycling*

As shown in the Fig. 8, the variation of voltage in lithium battery as a function of electrical charge, whichever discharging to an inferior discharge or charging to an inferior maximum voltage provides for an extended cycle life. As a consequence, it was shown that by discharging from the fully charged level to smaller levels, the length of a cycle is determined by the total quantity of transferred energy. Running a constant amount of energy from a barely charged state prolongs cycle life since the beginning level of charge is lower.

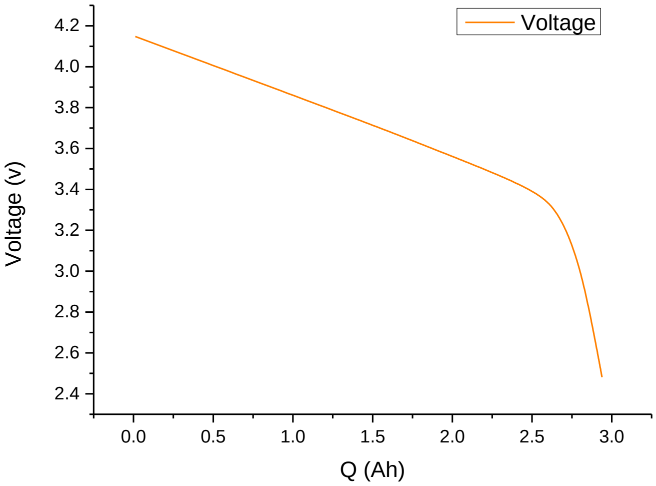


Fig. 8 : Variation of voltage in lithium battery as function of electrical charge

4.3. SMA material and thermo-mechanical behaviour in lithium battery system

- ***Volume fraction as a function of time***

The rate of change of the volume fraction with time depends on the kinetics of the martensitic transformation, which is influenced by several factors, including the temperature, stress, and composition of the alloy. In general, the transformation is faster at higher temperatures and under higher stresses.

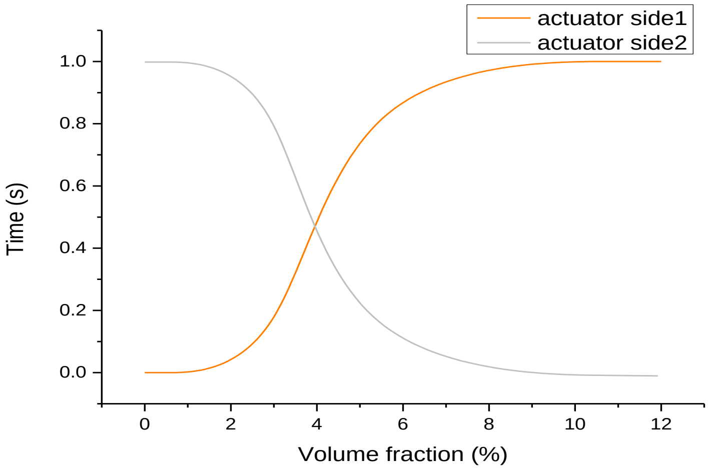


Fig. 9 : The volume fraction as a function of time

Generally, the volume fraction of the SMA actuator increases with time as the material undergoes the martensitic transformation. Initially (fig.5), the SMA actuator is in its austenitic phase and the volume fraction of martensite is zero. As the actuator is subjected to a stimulus, the temperature or stress may cause the austenite to transform into martensite, resulting in an increase in the volume fraction of martensite.

- ***Heat transfer in the system with and without SMA***

The heating and cooling of SMA actuators through heat transfer as a function of temperature is a critical process that enables the actuator to perform mechanical work. By controlling the heat transfer process, it is possible to optimize the actuator's performance, including its response time, efficiency, and reliability.

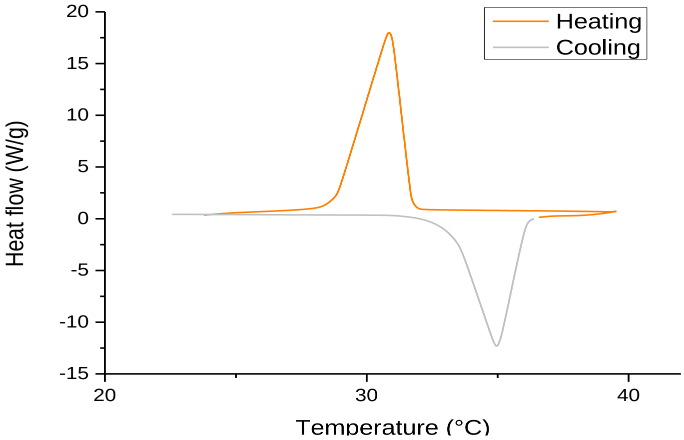
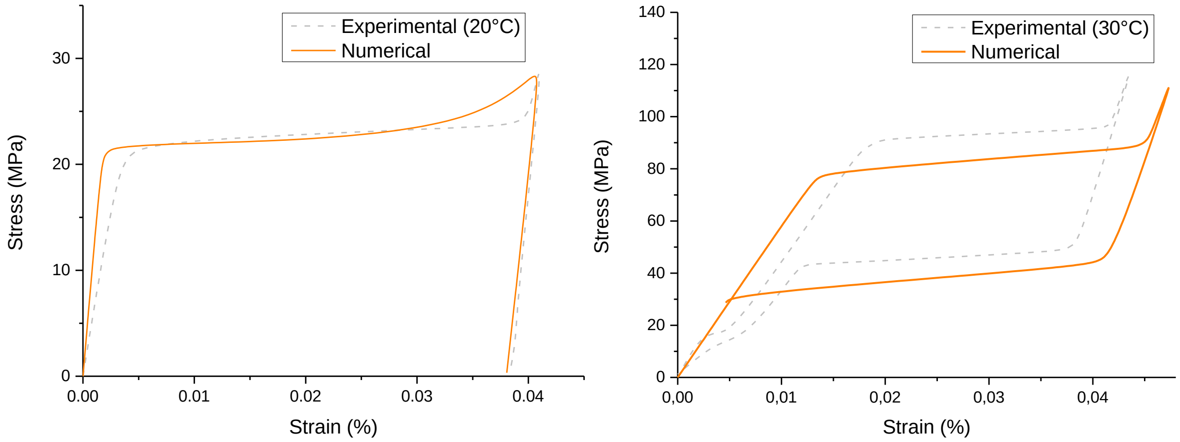


Fig. 10 : The evolution of heat flow as function of temperature

As shown in the figure 10, the endothermic process (a downward peak) seen during the cooling cycle was the evolution of the forward (A to M) transformation and the reverse (M to A) heat output, whereas the exothermic process (an upward one) recorded during the melting process respectively. The numerical study evaluated how much the thermal energy that the alloy captures or loses during phase changes.

➢ *Variation of strain as a function of stress*

The variation of strain as a function of stress in SMA actuators is a critical aspect of their operation. The stress-strain behaviour of an SMA actuator is influenced by various factors, including the composition of the SMA, the processing conditions, and the temperature (Fig. 11).



➢ *Fig. 11 : Variation of strain as a function of stress*

Fig.11 illustrates how the loading procedure takes into account a mechanical loading from zero to the maximum amount and after which an unloading back to zero. The stress drive situation is used for all studies, along with steady temperature and the stress variation. According to the results, a rise in temperature encourages a vertical shift of the hysteresis loop, which encourages a switch from the shape memory effect (*Fig. 11.a*) to the pseudoelastic effect (Fig.12 (b)).

➢ *Variation of strain as a function temperature*

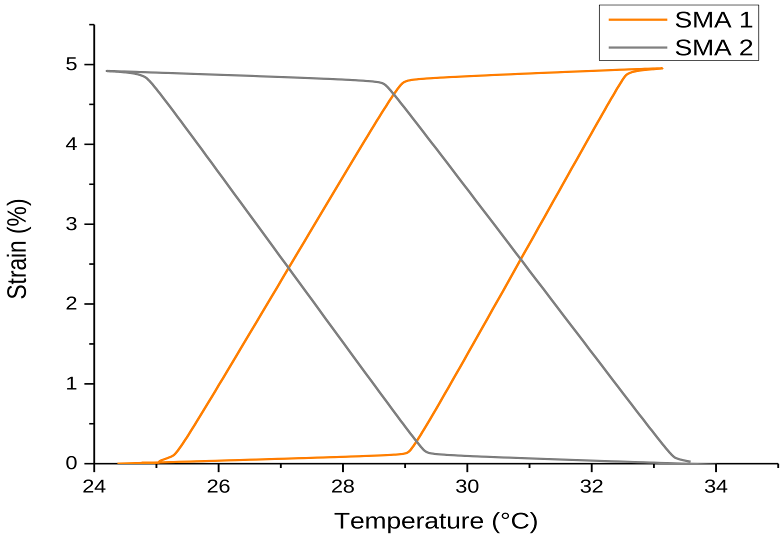


Fig. 12 : Variation of strain as function temperature

In SMA actuators, the variation of strain as a function of temperature is influenced by their unique properties, such as the shape memory effect and superelasticity. During heating, the SMA actuator undergoes a phase transformation from austenite to martensite, which is associated with a significant increase in strain (Fig.12). The amount of strain generated during heating is influenced by the thermal expansion coefficient of the SMA, as well as the transformation temperature and the amount of stress applied to the actuator.

4.4. Heat transfer in the battery system:

To exploit the storage potential of PCMs, a 3D encapsulated PCM numerical study is performed for a cylindrical system of an RT28 PCM. This study allows us to follow the evolution of the volume variation induced by the phase change, which will allow us to account for the associated mass in the system. Fig.13 show the density distribution and location of liquid-solid interfaces over time. Here again, our model reproduces the results of the previous simulation well. This why it is important to understand and control the density distribution and location of the liquid/solid interfaces is an important aspect of lithium-ion battery design and engineering.

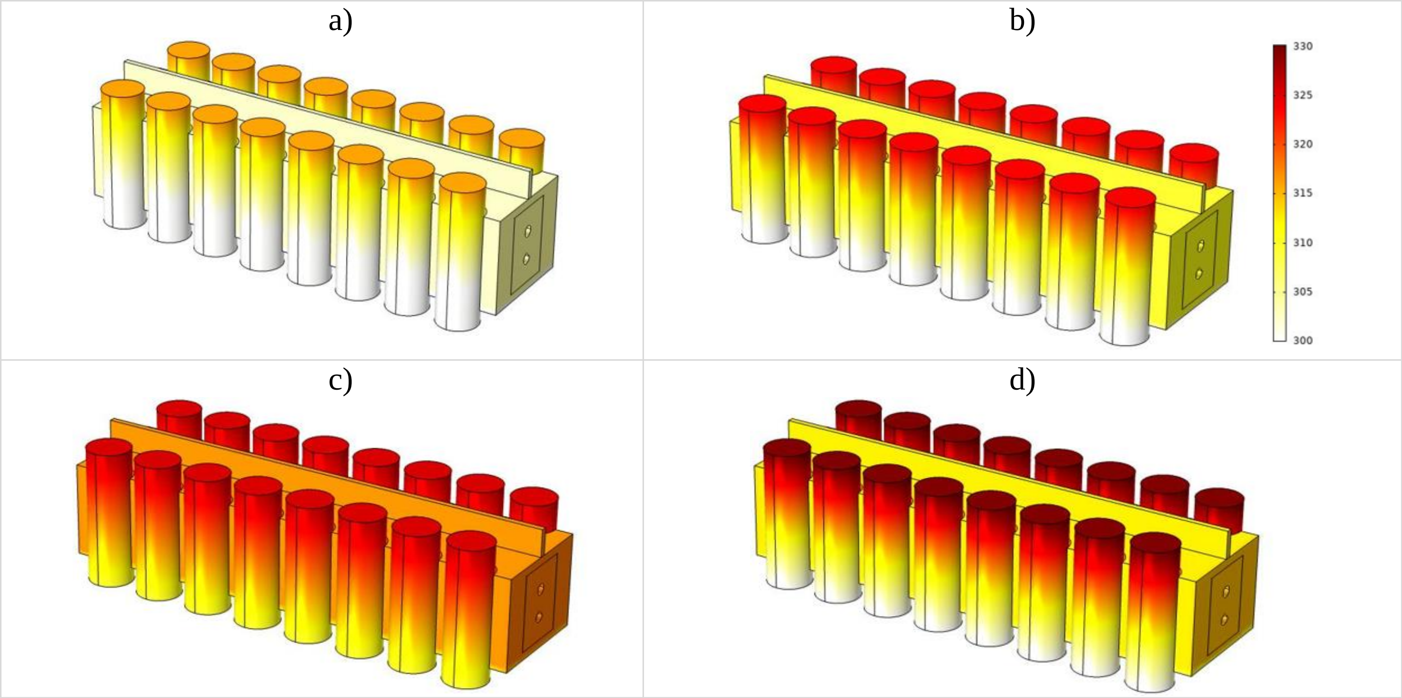
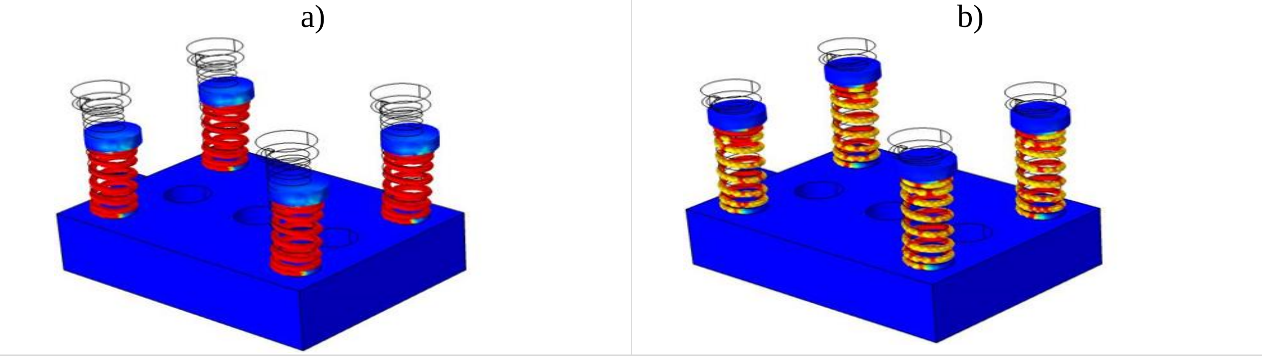


Fig. 13 : Temperature distribution as a function of time (step 30min) between battery components and PCM

The variation in temperature in the battery system depends on the utilisation process and the charge-discharge cycle. As the temperature increases, the ions become more mobile, which can cause them to diffuse faster and redistribute more evenly across the electrodes. In the Fig.13, the proposed design of Battery-PCM provides good conductivity that ensures excellent heat transfer between the both systems. PCMs can be an effective solution for mitigating the impact of temperature on the performance and safety of lithium-ion batteries, when the temperature rises above a certain threshold, the PCM will absorb heat and undergo a phase change. During this process, the PCM will absorb a large amount of thermal energy while keeping the temperature of the battery cells relatively constant. As the temperature of the battery cells falls below a certain threshold, the PCM will solidify and release the stored energy, which will help to keep the temperature stable.

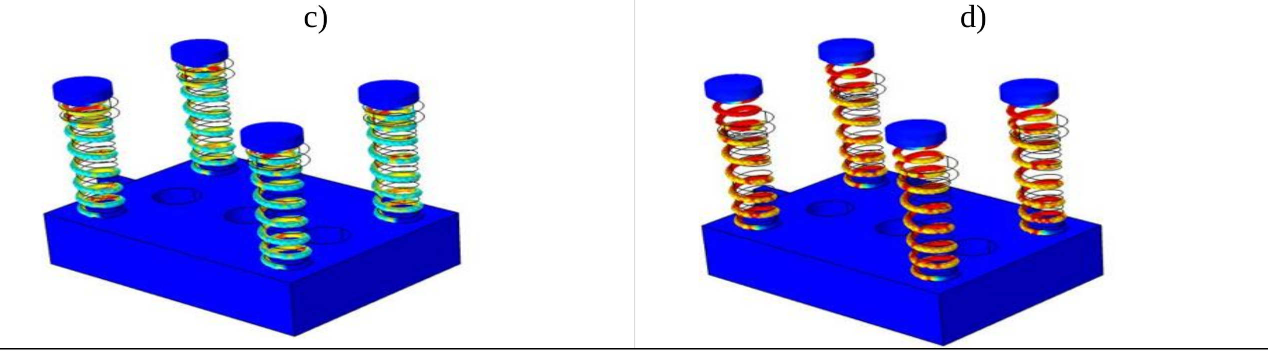
On the other hand, the transferred thermal energy from the battery-PCM system to the SMA material increased gradually related to the heat transfer between the PCM and SMA actuator as shown in Fig.14. The increase of the material temperature is able to activate the SMA actuator progressively in the face connected to the battery-PCM. The system has been designed and studied in in COMSOL software as a spring with a radius $R_{tube} = 20$ m, length $L = 100$ cm and thickness E=1cm. A good accuracy and good results are provided by the approximately 34500 elements in the suggested actuator's mesh.

Compression (SMA_1)



a) b)

Tension (SMA_2)



c) d)

Fig. 14: The variation of stress and deformation as a function of tension- compression loading and thermal energy

The SMA system is working on temperature variation, which is the actuator on the first state at lower temperature work on the shape memory effect that can absorb any vibration on the system and submit a variable deformation that can evacuate and damping the stress. At the temperature increase the SMA actuator operate at second state which the austenite state the SMA work with superelastic effectively that the battery pack is more sensitive to the stress therefore the SMA is extending and minimize the battery-PCM vibration (Fig. 14). The finite simulation successes to capture the thermo-mechanical behaviour that can respond to heat transfer by conduction between SMA and battery-PCM system, which induces the martensitic transformation.

Advanced engineering and optimization techniques play a key role in mitigating potential drawbacks and maximizing the positive contributions of adaptive materials in electric vehicle design. Integrating adaptive materials with their environment goes beyond merely enhancing battery performance. By seamlessly integrating these materials with renewable energy sources such as solar or wind power [43], efficiency is optimized, waste is minimized, and sustainability goals are aligned. This strategy not only harnesses renewable energy but also optimizes resource usage and promotes eco-friendly practices across industries.

5. CONCLUSION:

Enhancing electrical storage batteries is crucial for achieving increased autonomy and improved energy storage, particularly in the automotive sectors. In this regard, the development of batteries is still encountering several kinds of issues, especially in terms particularly concerning storage quantity and efficiency, storage speed, and security. Hence, the variation in heat and stress over time that can result in losses of both persons and commodities. Therefore, the incorporation of adaptive materials that guarantee heat and stress stability in electric storage batteries can improve performance and upgrade safety, autonomy, and quick charging. In this investigation, a systematic study was conducted to optimize lithium batteries by strategically integrating multifunctional adaptive materials as the PCM and the SMA into the storage system. The proposed methodology aims to adapt these materials to the battery system in order to maintain a constant temperature, and a reduced stress that optimizes its performance and lifespan. The findings of this study demonstrate a remarkable improvement in the performance of autonomy, charging speed, and autonomy level. Particularly, the use of PCM has the potential to ensure a 23% increase in the duration of temperature stability, while the use of SMA can reduce mechanical vibration by 79%. These materials show resilience and durability under varying stress and temperatures, but real-world conditions pose significant challenges. Therefore, fatigue in SMAs and PCMs is unavoidable, although degradation may only become apparent after many years of use. This phenomenon can affect phase change, affecting heat absorption in PCMs and the memory effect in SMAs, respectively. It is vital to ensure that both PCMs and SMAs operate within defined temperature and stress ranges. On the other hand, integrating adaptive materials into battery and electric car design is challenging that may limit the incorporation of these materials, requiring careful positioning of PCM and SMA for effective interaction. Despite higher initial costs, long-term benefits contribute to cost-effectiveness. Consequently, addressing factors like battery design, adaptability, weight balance, and costs is crucial for seamless adaptation to various EV models. Therefore, our upcoming research focuses on optimizing materials, design factors, and regular monitoring to enhance reliability across diverse applications.

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