Journal of Research and Applications in Mechanical Engineering
ISSN: 2229-2152 (Print); 2697-424x (Online)
(2025) Vol. 13, No. 2, Paper No. JRAME 25-13-030
[DOI: 10.14456/jrame.2025.30]

Research Article

Impact of Battery Pack Shell Materials on Electrical Leakage in Submersion

D.N. Ngo[1]
C. Charoenphonphanich[1]
N. Kunanusont[2]
P. Meelapchotipong[3]
C.T. Vo[4]
T.S.V. Pham[1]
M. Masomtob[2,*]
[1] *Department of Mechanical Engineering, School of Engineering, King Mongkut's Institute of Technology Ladkrabang, Bangkok, 10520, Thailand*
[2] *National Energy Technology Center, National Science and Technology Development Agency (NSTDA), Pathum Thani, 12120, Thailand*
[3] *AMM Research Laboratory, Faculty of Engineering, Thai-Nichi Institute of Technology, Bangkok, 10250, Thailand*
[4] *Faculty of Automotive Engineering Technology, Industrial University of Ho Chi Minh City, Ho Chi Minh City, 727900, Vietnam*

Received 3 September 2024
Revised 29 November 2024
Accepted 2 December 2024

Abstract:
This study investigates the impact of battery pack shell materials on electrical leakage when fully submerged in seawater. Both conductive and insulating materials are utilized for battery pack shells. Simulations are conducted using the Finite Element Method (FEM) and are compared with experimental procedure to validate accuracy and reliability. After validation, the simulations are applied to different accident scenarios to analyze potential outcomes. The results revealed that the choice of materials significantly influences electrical leakage, as evidenced by simulations of various scenarios. Moreover, the voltage distribution changed with different battery pack shell states, indicating that the condition of the battery shell significantly impacts electrical leakage. Additionally, solutions for mitigating leakage were implemented and analyzed. Adding highly conductive materials between leaked positions can also reduce the current density in the surrounding areas. These findings are expected to provide valuable data for designing battery pack shells and enhancing the safety of electric vehicles (EVs) in potential accident scenarios.

Keywords: *Battery submersion, battery pack shell materials, electrical leakage, eletrical behavior, Finite Element Method*

1. Introduction

Electric vehicles (EVs) are currently undergoing robust development, driven by the urgent need to reduce fossil fuel consumption compared to traditional internal combustion engine (ICE) vehicles [1]. Many countries worldwide are planning to phase out internal combustion engine vehicles entirely. In 2023, nearly 14 million electric vehicles were sold globally, with a significant portion in China, Europe, and the United States [2]. Alongsidse the rapid increase in electric vehicles comes inherent risks that have not been fully researched and analyzed. Of particular concern are the battery packs in electric vehicles, which pose potential dangers such as electrical, mechanical, chemical, and explosion hazards that drivers are increasingly worried about [3]. Specifically, one of the cases is the car being submerged in water in an undesirable scenario and that risk actually poses a danger to humans.

High voltage in conductive environments such as seawater and fresh water poses a risk of electric shock and can be dangerous to human life. Additionally, when human skin is submerged in water, it has the lowest electrical resistance

* Corresponding author: M. Masomtob
E-mail address: manop.mas@entec.or.th

in the body [4]. Consequently, with the typical operating voltage of electric vehicles being around 300 V, the current passing through the human body could reach up to 300 mA [5]. Meanwhile, a current of around 20 mA or more can cause muscle spasms and loss of bodily control [6]. This is extremely dangerous when a person is in an entirely submerged environment, with a high risk of drowning.

Therefore, if a battery pack is fully submerged in water, there is a risk of electric leakage into the water environment, particularly if the positive and negative terminals of the power source come into contact with the conductive water.

In practice, most modern electric vehicles are equipped with safety systems that completely disconnect the high voltage in the event of a severe accident, including situations where the vehicle is fully submerged in water [7]. Additionally, the battery pack shell is designed to isolate the inside of the battery pack fully from the external environment. However, specific scenarios where the safety system fails or the battery pack shell is compromised due to collision or accident should be considered. In these cases, the voltage might not be disconnected, allowing water to infiltrate the battery pack, leading to an electrified water environment. This is a significant concern as it represents a potential accident risk associated with current electric vehicles.

In this study, multiple scenarios where the battery pack terminals could come into contact with water were investigated. Furthermore, both insulating and conductive materials were used for the battery pack shell in the corresponding cases. The study aims to highlight the changes in electrical leakage when altering the material of the battery pack shell. The objective of this research is to elucidate the risks associated with potential electric shock hazards when a vehicle is fully submerged in seawater.

2. Methodology

2.1 Experimental setup for validation

In this study, the simulation process was implemented to evaluate the electric behavior of battery packs in seawater by the Finite Element Method (FEM). In order to ensure the reliability of the simulation results, the experimental setup was constructed for validation, as shown in Fig. 1. The 2D model corresponding to the experiment model was built in simulation, and the results of both models were assembled to perform a comparative approach to demonstrate the accuracy of the simulation. From that foundation, more complex geometry was built to analyze the main objects in this study.

In the experiment, the acrylic box was filled with a moderate amount of seawater, and a high voltage of 60VDC was applied to the terminal points. 39x39 points were evenly distributed inside the box, and each point was designated for measuring the voltage distribution in that position. The electrode rods were used as intermediaries to connect with measuring devices for collecting voltage. The experimental process was collected from line 1 to line 20, as marked in Fig. 2. The simulation for this validation will be built as a 2D model corresponding to Fig. 2 to ensure consistency between the experiment and the simulation.

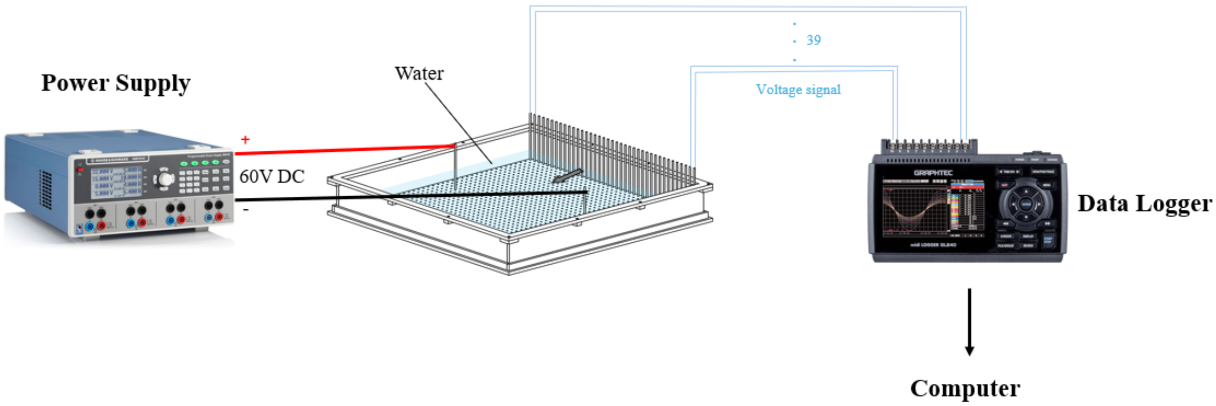


Fig. 1. Experimental setup.

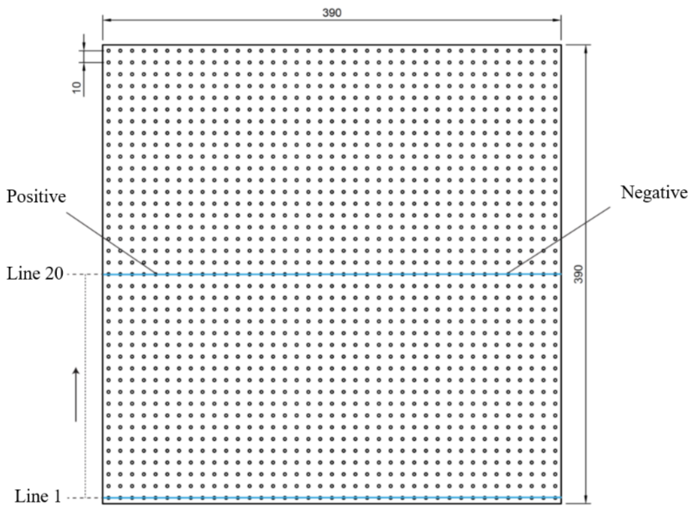


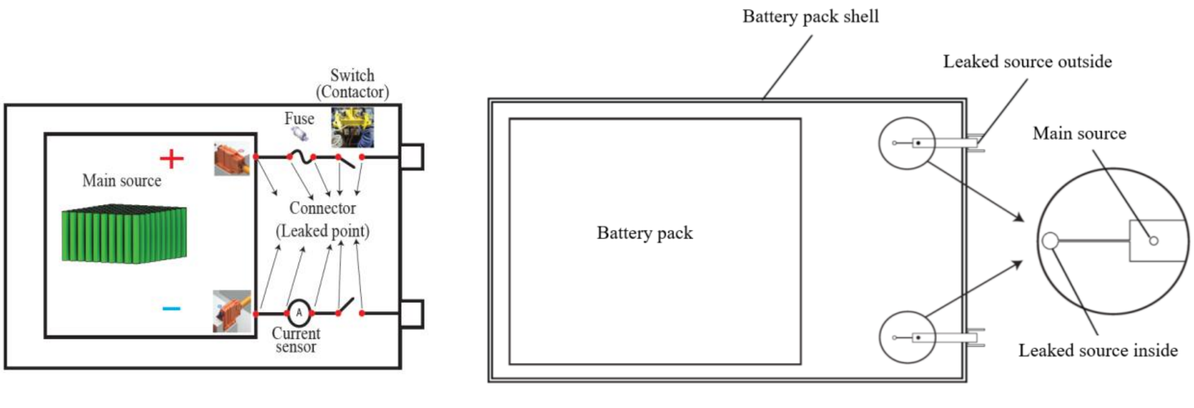
Fig. 2. Experimental measurement surface.

2.2 Simulation conditions

2.2.1. Battery pack model

There are many types of battery packs produced by various different electric vehicle manufacturers. In addition, the dimension of the battery pack depends on properties such as voltage, power and capacity. In this study, the battery pack of the Tesla Model S was chosen to generate the data for dimension in the simulation. Due to complex geometry, the 2D model was simplified and built into a rectangular shape using the length and width of the battery pack of the Tesla Model S, as shown in Fig. 3. The main source was connected by wires to leaked sources outside and inside. The leaked source inside includes points that have the potential to cause electrical leakage, such as the points at the electrical connector illustrated in the Fig.3a, and are assumed as shown in the Fig.3b. This contributes to a clear description corresponding to the simulation conditions established in the section below.

The materials in this study consist of four types, with electrical conductivity parameters used for simulation, as shown in Table 1. The electrical conductivity of aluminum was assigned to conductive material because aluminum is a common material used for battery pack shell [8]. Insulating material is 1e-16 S/m [9]. Both the insulating and conductive materials were applied to the battery pack shell in Fig.3 to compare the two types of materials. The electrical conductivity of seawater is 5.5 S/m at 25°C [10] and was assigned to the water domain and the punctured points in each case in the simulation, while copper for wires was derived from software.



(a) (b)

Fig. 3. Simulation model

Table 1: Simulation parameters.

	Insulating material	Conductive material	Seawater	Copper
Electrical conductivity (S/m)	1e-16	3.4e7	5.5	5.998e7

2.2.2. Simulation conditions

In current practice, nearly all battery packs achieve IP67 or IP68 ratings, indicating waterproof. Furthermore, modern security systems incorporate advanced features; for example, power from the battery will automatically shut off upon detection of the vehicle being fully submerged in water. The applied voltage is 300VDC in the model. This study applied conditions that could lead to electrical leakage based on the battery pack's operational status, aiming to assess potential hazards in accidents. The four cases used in this study were illustrated in Fig. 4 and depicted in Table 2.

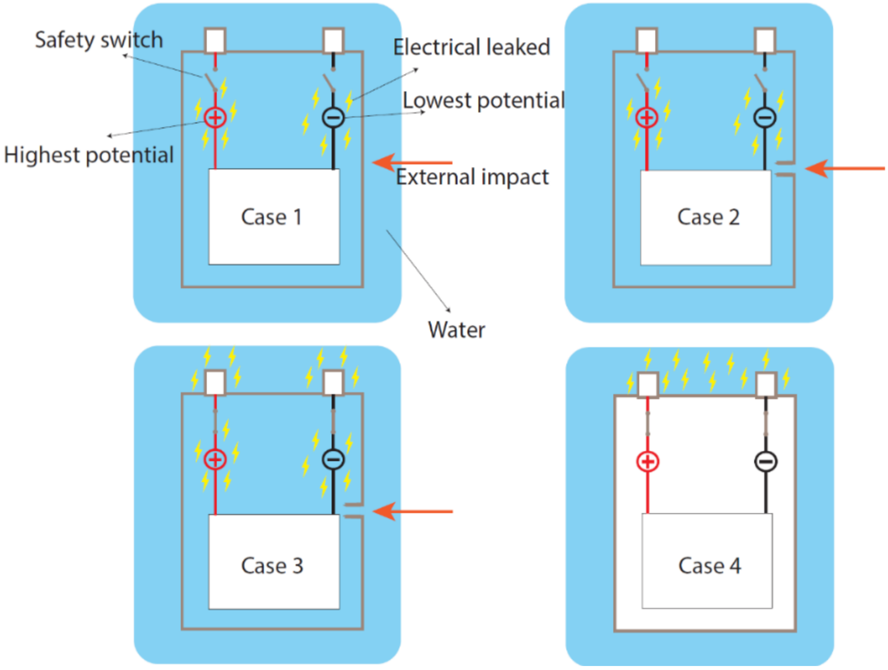


Fig. 4. States of battery pack in simulation.

Case 1: Assuming the safety switch is activated, the battery pack is subjected to external impacts that compromise the IP rating, allowing water to penetrate inside. As a result, water may come into direct contact with the highest potential cell and the lowest potential cell within the battery pack.

Case 2: The safety switch is activated, but water comes into contact with a leakage current inside the battery pack due to the formation of a puncture caused by severe external impact.

Case 3: Similar to case 2, there is a puncture, but in this case, water directly contacts both the internal and external sources of the battery pack because the safety switch fails to operate.

Case 4: The battery pack is not affected by external impacts, and water can only contact the external leakage current because the safety system has been activated.

Table 2: Simulation conditions.

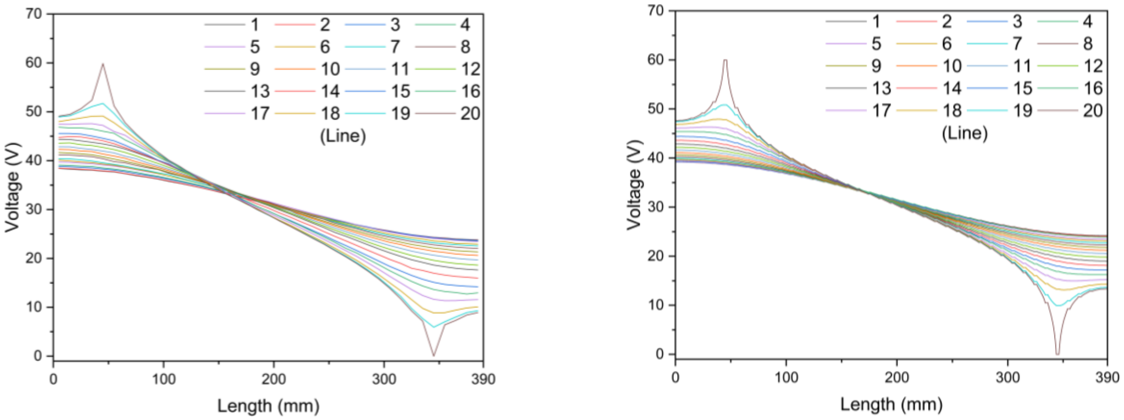
Case	Security system	Seal of terminals (outside)	State of shell
1	Active	Bad	Small crack (water can intrude inside)
2	Active	Bad	Punctured
3	Inactive	Bad	Punctured
4	Inactive	Bad	Normal

The materials will be assigned to the outer shell of the battery by adjusting the electrical conductivity values in the table. In cases with punctures, such as case 3 and case 4, the electrical conductivity at the puncture location will be replaced by the conductivity value of seawater. The puncture size is randomly assigned in terms of length, as the damage to the battery pack in real conditions is unpredictable. Therefore, this study selects a specific case to analyze the overall issue.

In this study, these four cases were assumed to represent realistic scenarios where electrical leakage could occur. Two different materials were applied to the shell for each model to evaluate their differences.

3. Results and discussions

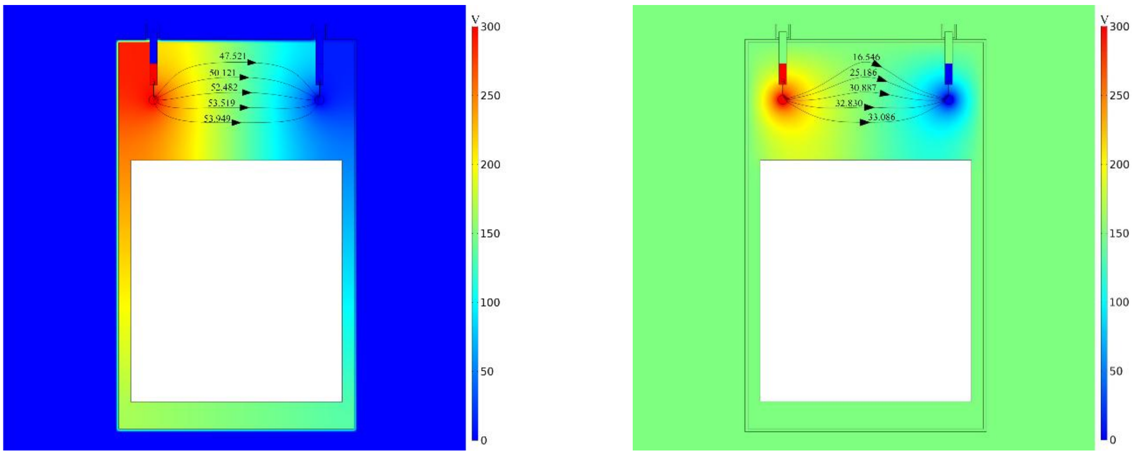
3.1. Validation via experiment



(a) Experiment

(b) Simulation

Fig. 5. Voltage of experiment and simulation model.

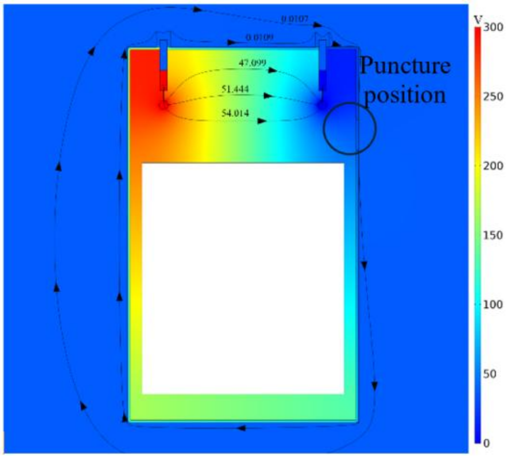


(a) Insulating material

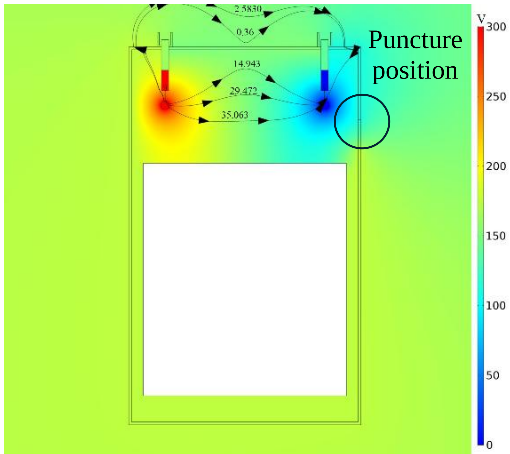
(b) Conductive material

Fig. 6. Voltage distribution of case 1.

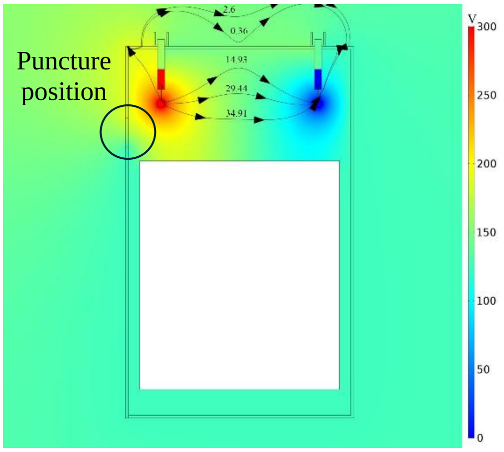
A 2D model with all parameters matching the experiment was designed as Fig.2 to validate the accuracy of the simulation and the reliability of the electrical conductivity parameters. A high voltage of 60VDC was supplied during the experiment, as described in the previous section. The experimental results are shown in Fig. 5a, with each line in the graph representing a measurement position from Line 1 to Line 20 as illustrated in Fig.2. Compared to the simulation results shown in Fig. 5b, both graphs exhibit a similar voltage distribution trend, with high voltage at the anode side and low voltage at the cathode side. However, a slight difference in the magnitude of the distributions between the two graphs was noted. This discrepancy can be attributed to the simulation model, which only considers electrical behavior and in the experiment, all physical phenomena occurring in real-life conditions were applied, one of which is the robust electrolysis process happening in this experiment, affecting the voltage distribution. According to the results, the numerical model of the simulation provides a relatively accurate depiction of the electrical behavior observed in the experiment, as reflected by the similar trends in the graphs.



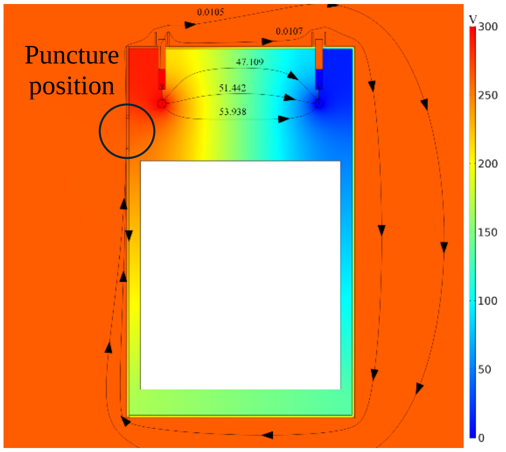
(a) Insulating material (puncture at negative side)



(b) Conductive material (puncture at negative side)



(c) Insulating material (puncture at positive side)



(d) Conductive material (puncture at positive side)

Fig. 7. Voltage distribution of case 2.

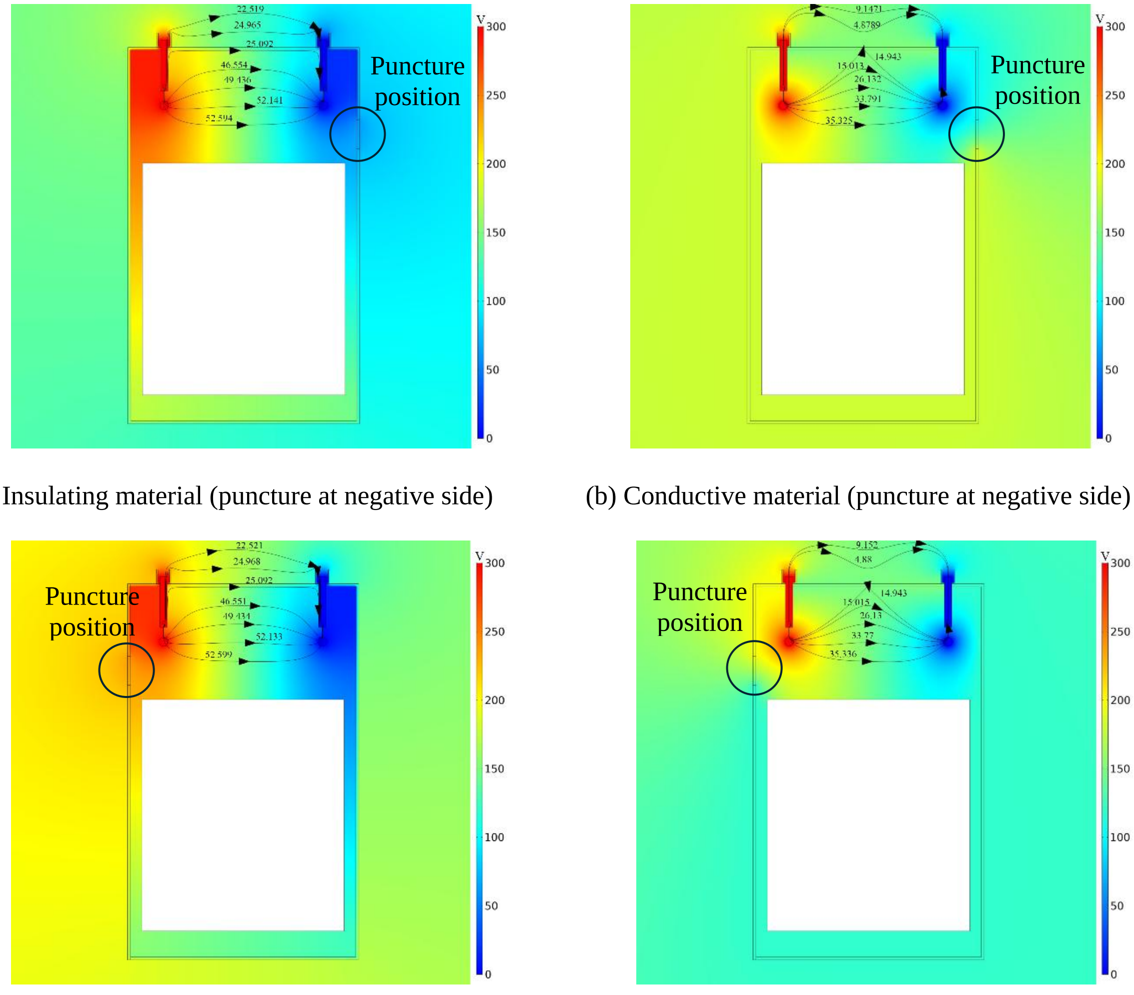
3.2 Case 1

The battery pack was nearly sealed in this case. Fig. 6a illustrated that insulating material completely prevented voltage leakage outside the battery pack due to its significantly lower electrical conductivity compared to seawater. A clear observation of the shell on the positive side revealed that the very low electrical conductivity results in a significant voltage change as it passes through the shell layer. In Fig. 6b, there was leaked voltage outside, and the magnitude of the leakage voltage distribution was almost constant, approximately half of the battery pack voltage magnitude in this study. The results indicated that when the battery pack shell was completely sealed by insulating material, voltage leakage was almost zero. For conductive material, due to their high electrical conductivity, voltage leakage was inevitable. However, the differences in voltage magnitude among various positions of the seawater domain were very small.

Current leakage to the exterior was negligible, confining the current within the battery pack, as illustrated in Fig. 6. The values along the lines represented current density, measured in A/m, and were calculated using an integration method over a 50 mm vertical length for each corresponding line in the figure. These values were presented as reference data to highlight the electrical differences between the two material types. As shown in Fig. 6, the current density decreased when conductive material was used. This phenomenon was attributed to the high electrical conductivity of the conductive material, which directed the current predominantly through the shell. Consequently, the current between the two electrodes decreased. In contrast, with insulating material, the maximum current density occurred in the region between the electrodes, where resistance was lowest.

3.3 Case 2

In this case, the source of the electric leakage was entirely within the battery pack, while the external terminals were completely disconnected by the security system. Additionally, according to the conditions from the table, if a puncture appeared in the battery pack shell, in the simulation at the puncture location, the electrical conductivity of the shell material such as insulating or conductive material was changed to the electrical conductivity of seawater. This illustrated the state of the battery pack, indicating the presence of a puncture in the shell of the battery pack.



(a) Insulating material (puncture at negative side) (b) Conductive material (puncture at negative side)

(c) Insulating material (puncture at positive side) (d) Conductive material (puncture at positive side)

Fig. 8. Voltage distribution of case 3.

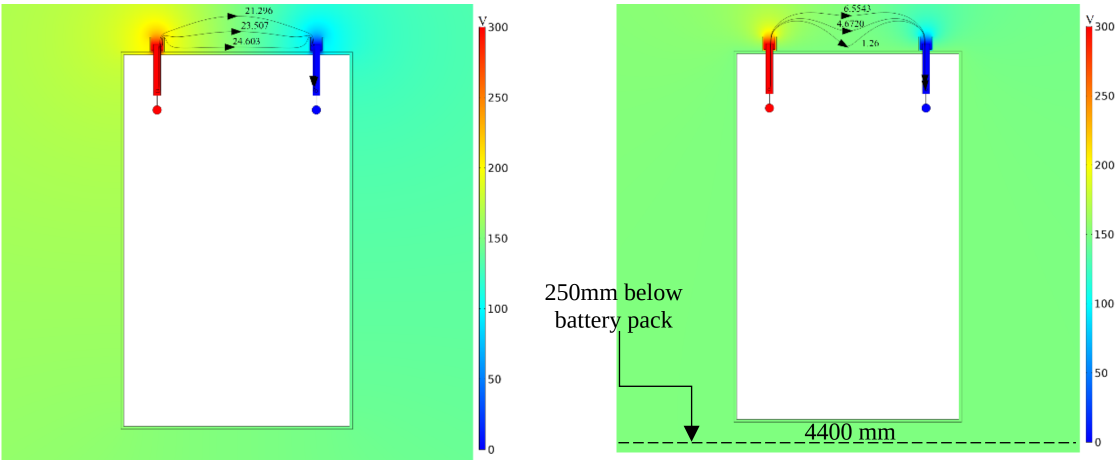
Fig. 7 illustrates the voltage distribution for this case. For the insulating material in Fig. 7a, the results indicated that the leakage voltage outside the battery pack remained almost constant across all positions in the model. The location of the puncture significantly impacted the magnitude of the leakage voltage, as demonstrated in Fig. 7c, which showed the relationship between the leakage voltage magnitude and the puncture position. The leakage voltage was highly influenced by the internal voltage distribution points near the puncture site. The figure revealed that the voltage outside the battery pack and the voltage near the puncture within the battery pack were nearly identical. This observation could be explained by the electrical conductivity of the battery pack shell, which entirely prevented voltage from spreading outside. With the domain change and increased electrical conductivity, the leakage voltage depended on the magnitude at the point closest to the puncture, and there was no influence from other sources outside, resulting in an almost constant voltage value. Observing in Fig. 7a and Fig. 7c, the leakage voltage remains constant at all positions, but the magnitude changes depending on the location of the puncture. Observing the current distribution shown in Fig. 7a and Fig. 7b, although there was some leakage, the voltage difference is minimal, making the leakage current negligible in this case.

Conversely, in Fig. 7b and Fig. 7d, for the conductive material, the voltage distribution exhibited variations and changed with the puncture position. Unlike the insulating material, the domain changed in the shell reduced electrical conductivity at that point and most of the shell had a higher electrical conductivity than seawater. The voltage primarily propagated through the conductive shell of the battery and exhibits a distinct distribution when the puncture position changes. Similarly, the current in this scenario easily flows through the battery pack shell, resulting in a higher tendency for leakage current compared to the use of insulating material.

3.4 Case 3

Based on the conditions in Table 2, in this case, it was assumed that the external terminals were in contact with water and the safety system was inactivated. In Fig. 8a and Fig. 8c, the external voltage distribution is influenced by external and internal leakage sources, leading to a noticeable difference compared to Case 2. However, in Fig. 8b and Fig. 8d, with conductive material, the leakage voltage was quite similar to that of Case 2. The results showed that the external leakage source significantly affects the voltage distribution of the insulating material but had a minimal impact on the conductive material. For the current, this case was entirely opposite to the previous two cases. The use of insulating material results in higher external leakage current compared to conductive material. This can be explained by the presence of an external leakage source, where the current preferentially flowed through the battery pack shell, reducing the overall current magnitude. This case will be explained in more detail in the subsequent sections of this article.

3.5 Case 4



(a) Insulating material (b) Conductive material

Fig. 9. Voltage distribution of case 4.

As shown in Fig. 9, the state of the battery pack shell was completely intact, preventing water from infiltrating inside. The source of electrical leakage was only present outside the battery pack. The results indicated that the voltage distribution in both models exhibited high magnitudes. The difference between the two types of materials was clearly observed in the shell between the two terminals, where a significant change in voltage distribution occurs due to the low electrical conductivity of the insulating materials. In contrast, at the same position, little or no change was observed due to the lower electrical conductivity of the seawater, resulting in noticeable voltage variations only in the water environment. Fig. 10 showed that the voltage distribution of the conductive material was more uniform across various locations in the water domain compared to when using insulating material. The maximum voltage difference for the insulating material was 28 V, whereas for the conductive material, it was less than 1 V. This highlighted that the change in the material of the battery pack shell and the alteration in electrical conductivity parameters significantly affected the voltage distribution. For the current in this case, similar to case 3, it was influenced by an external source. As a result, using insulating material caused higher leakage compared to conductive material, which is the opposite of cases 1 and 2.

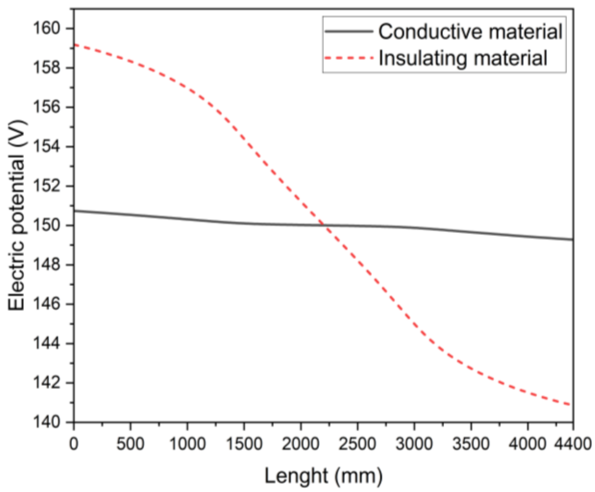
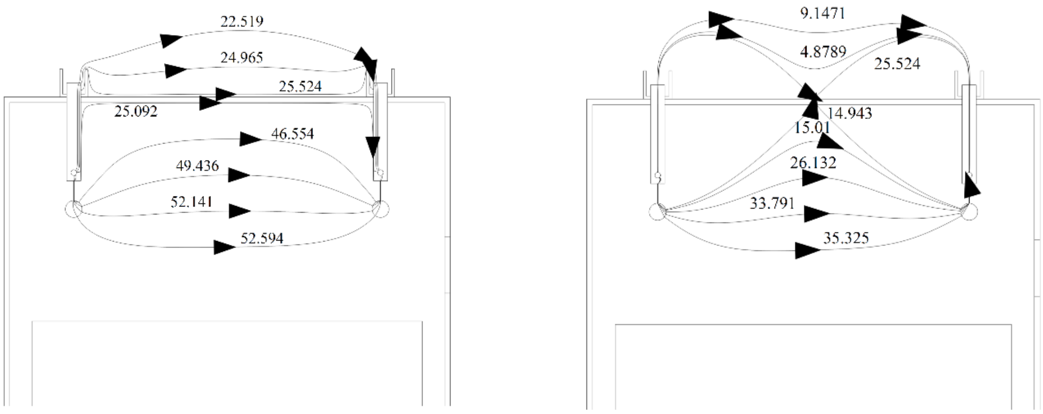


Fig. 10. Horizontal voltage at a position 250mm below the battery pack.

3.6 Leaked current and solution for reducing leakage



(a) Insulating material (b) Conductive material

Fig. 11. Current density and direction of current in model 3.

Fig. 11 illustrates the direction of the electric current in case 3. The direction of the electric current depends on resistance, it flows more readily where there is less resistance. Therefore, the electrical conductivity of the insulating material was much lower than that of seawater, causing the current to flow mainly within the water. Conversely, when using conductive material, the current flowed predominantly through the battery pack shell due to its higher electrical conductivity than seawater.

In both cases, external current leakage was observed. For the insulating material, the leakage occurred at the external terminals of the battery pack and did not penetrate the battery pack shell. This resulted in a significant amount of current leakage in the surrounding areas. In contrast, with conductive material, the leakage current appeared at the external terminals but entered the battery pack shell, leading to a significant reduction in leakage current paths compared to the insulating material. This led to a significant reduction in the leakage current paths within the water domain compared to insulating material. Furthermore, as shown in the figure, the magnitude of the leakage current density (A/m) differed between the two materials. The results confirmed that leakage current was higher for insulating material than for conductive material

Fig. 12 illustrated a solution where high-conductivity material was added to the upper shell section between the two terminals of the insulating material model. This change caused the current to preferentially flow through the newly added component due to its high electrical conductivity. As shown in Fig. 12, the current density (A/m) at this location is significantly higher, while the magnitude of leakage within the water domain decreased considerably. Fig. 13 also illustrates the reduction in current density (A/m²) of the solution model compared to the original model. These findings demonstrated that structural changes to the battery pack can also influence the behavior of electric current.

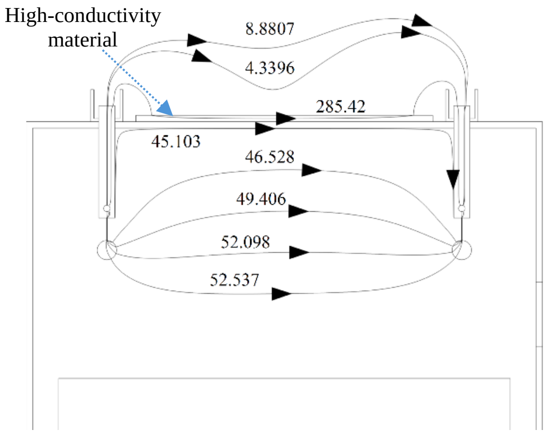


Fig. 12. Solution model for insulating material model in case 3.

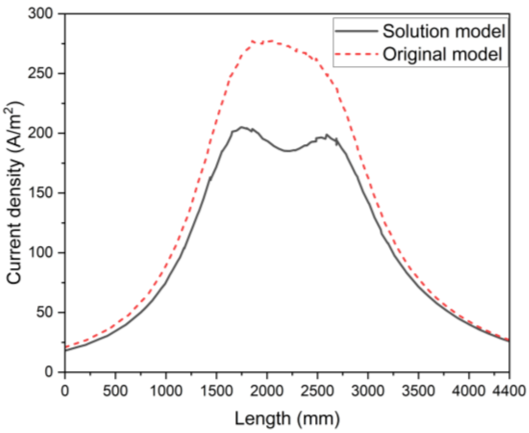


Fig. 13. Magnitude of leaked current on top of the model in case 3.

4. Conclusion

This study has analyzed the electrical behavior of submersed battery packs using the FEM, focusing on the effects of different shell materials. Both insulating and conductive materials were applied to the battery pack shell in the simulation. Results have shown a change in voltage and current density distribution due to varied electrical conductivities of materials. The observed leakage of voltage was clearly different when changing materials in almost every case and was also affected by the structure of the battery pack when it is deformed, punctured. The use of insulating materials in cases 1 and 2 showed no significant voltage differences outside the battery pack. However, in cases 3 and 4, the presence of external leakage sources caused high voltage differences between external points, leading to leakage currents in these cases. Therefore, a solution to reduce leakage current was proposed. Placing a high-conductivity material between the two external electrodes of the battery pack in case 3 was observed to significantly reduce the leakage current. This finding indicated that structural modifications to the battery pack can mitigate leakage currents and combining two types of materials can further enhance leakage reduction.

In summary, the shell materials have caused significant changes in electrical leakage. Electrical conductivity is a crucial parameter in this study, and altering the material leads to changes in electrical conductivity. Additionally, the condition of the battery pack greatly influences the results, as any issue that alters the electrical conductivity can cause significant changes in voltage and current. Using insulating materials is more effective in cases 1 and 2 but poses greater risks in cases 3 and 4. Combining two types of materials is considered to passively reduce leakage in hazardous scenarios. It is concluded that changes in material and electrical conductivity can affect electrical behavior, and a specific battery pack structure can be designed to prevent the most common accidents.

Nomenclature

FEM Finite element method

Acknowledgments

The authors gratefully acknowledge the support from National Energy Technology Center (ENTEC) Thailand, King Mongkut's Institute of Technology Ladkrabang and Tokyo Institute of Technology.

References

[1] Zhao J, Feng X, Tran MK, Fowler M, Ouyang M, Burke AF. Battery safety: Fault diagnosis from laboratory to real world. J Power Sources. 2024;598:234111.
[2] International Energy Agency. Global EV Outlook 2024. Paris: IEA; 2024.
[3] Kjosevski S, Kostikj A, Kochov A. Risks and safety issues related to use of electric and hybrid vehicles. In: Sci Proc XIV International Congress "Machines. Technologies. Materials". 2017;Vol II:169–172.
[4] Noorzad N, Gürleyük SS. Effects of electrical current passing through the human body and safety requirements. 6th International Students Scientific Congress. 2022.
[5] Lin Z, Chen H, Li J, Zhang Y. Research on electric shock prevention and first aid for electric vehicles. J Automot Saf Energy. 2020;11(3):257–264.
[6] International Electrotechnical Commission (IEC). Effects of current on human beings and livestock – Part 1: General aspects (IEC Standard No. 60479-1). Geneva: IEC; 2005.
[7] Chompo PV, Laoonual Y, Wongwises S. Lessons from the electric vehicle crashworthiness leading to battery fire. Energies. 2021;14:4802.
[8] Linse C, Kuhn R. Advances in battery technologies for electric vehicles. In: Design of high-voltage battery packs for electric vehicles. 2015;245–263.
[9] Hummel RE. Electrical conduction in metals and alloys. In: Electronic Properties of Materials. 2011;79–114.
[10] Sauerheber R, Heinz B. Temperature effects on conductivity of seawater and physiologic saline: Mechanism and significance. Chemical Sciences Journal. 2015;6(4):109.