

# **BATTERY THERMAL MANAGEMENT SYSTEM IN ELECTRIC VEHICLES**

**ASHIMA VERMA**



**DEPARTMENT OF ENERGY SCIENCE AND ENGINEERING  
INDIAN INSTITUTE OF TECHNOLOGY DELHI  
APRIL, 2023**

# Battery Thermal Management System in Electric Vehicles

by

Ashima Verma

Department of Energy Science and Engineering

Submitted

in fulfillment of the requirements of the degree of

Doctor of Philosophy

to the



Indian Institute of Technology Delhi

April, 2023

**©Indian Institute of Technology Delhi (IITD), New Delhi, 2023**

---

## CERTIFICATE

---

This is to certify that the thesis entitled “**Battery Thermal Management System in Electric Vehicles**” being submitted by Ms. Ashima Verma to the Indian Institute of Technology Delhi in fulfillment of the requirements for the award of the degree of ‘Doctor of Philosophy’ is a record of the original bonafide research work carried out by her under our guidance and supervision at Department of Energy Science and Engineering, Indian Institute of Technology Delhi. The results contained in the thesis have not been submitted in part or full to any other University or Institute for the award of any degree or diploma.

**(Prof. Dibakar Rakshit)**

Associate Professor,

Department of Energy Science and  
Engineering,

Indian Institute of Technology  
Delhi,

Hauz Khas New Delhi - 110016

---

## ACKNOWLEDGEMENTS

---

I whole heartedly would like to thank my supervisor, Prof. Dibakar Rakshit for his suggestions, support and freedom provided to me for carrying out the desired research studies, over my course of PhD. It has been a learning experience for me, both on professional and personal fronts through the detailed interactions I have had with him over various activities during my PhD.

I thank my SRC members, Prof. K. A. Subramanian, Prof. Anil Verma and Prof. Rahul Goyal for their suggestions and support given to me from time to time during my Ph.D. I would also like to thank the Ministry of Human Resource Development, Government of India for providing the necessary support to facilitate the research.

I am thankful to my senior and fellow lab members -Dr. Sai Saran Yagnamurthy, Dr. Pranaynil Saikia, Ms. Sana Fatima Ali, Mr. Alok Ray, Mr. Tewodros Belay Ashagre, Mr. Sagar Vashisht, Mr. Rahul Verma, and others for helping me and upholding my moral high during tough times of my research work. I am also thankful to the lab staff and other student colleagues at IIT Delhi, for extending their support whenever necessary.

I express my heartfelt gratitude towards my parents, siblings, and husband for their encouragement and support, without which I couldn't have carried out this work.

Ashima Verma

---

## ABSTRACT

---

The ever-increasing global environmental concerns have paved the way for electric vehicles (EVs) to hold deep roots in the transport market. Lithium-ion (Li-ion) batteries are the most explored and central part of the EV. Li-ion batteries are preferred due to their high energy density, power density, service life, and low self-discharge rates. However, the dependence of the cell performance on the operating temperature has limited customer satisfaction due to issues of safety and longevity. In this regard, many vehicle manufacturers' prime focus is designing and developing an effective battery thermal management system (BTMS). A reliable, cheap, energy-efficient, and simple structure are some of the primary needs for an effective BTMS. BTMS has been categorized into two main categories, (i) Active cooling systems (ACSs) and (ii) Passive cooling systems (PCSs). The ACSs are further subdivided into two categories, (i) Air cooling systems and (ii) Liquid cooling systems. Many leading EV manufacturers have widely adopted air-cooled BTMS in their battery packs. However, the air-cooled BTMS is inefficient in hyper ambient conditions and involves bulky structures. Liquid-cooled BTMS is more effective than air-cooled BTMS, but leakage and non-uniform temperature distribution are troublesome when employed in the battery pack. Additionally, the ACSs consume energy for their operation, referred to as parasitic energy consumption. PCSs do not consume parasitic energy and, thus, are most explored by researchers.

This thesis explores liquid and phase change material (PCM) cooled battery packs through numerical and experimental studies. A novel PCM-fin structure that works well under high ambient and discharge rates has been proposed. The effect of PCM's mass and fin length directly influenced the thermal performance. The proposed model was a combination of PCM and fins. For

the seamless operation of Evs in a hot climate, this study examined a novel passive cooling system. This cooling system features two distinct types of heat extraction media: (i) PCM-based isothermal storage-based heat sink and (ii) fin-based augmented thermal transport-based heat sink. These two sub-components were investigated in mutually competitive and complementing scenarios to understand the relative contributions of each component in heat extraction and realize the maximum cooling potential achievable from a combined implementation. The extensive and intensive properties of the retrofit were clubbed together under a new non-dimensional index, which has been called variable system response (VSR). The results of the parametric study were used to propose a set of two correlations. Different combinations of the design variables achieved a cooling of 142.1 W.

Furthermore, comprehensive research on liquid cooling mini-channels was carried out to determine the best combination of geometric and thermos-fluidic parameters of the mini-channels. The volume average battery temperature at the end of the driving cycle for the beat case was 313.31 K. The study showcases the importance of less intense cooling, which results in low power consumption (0.85 W) by the ACS.

Finally, the thesis compares the popular battery types: (i) cylindrical and (ii) prismatic for the passive cooling system. The study reveals that a cylindrical battery stores more heat at low ambient temperature conditions when compared to a prismatic battery. Also, design attributes are different for the PCM cooling system in the two lithium-ion batteries owing to the shape factor. This study attempted to cap the maximum temperature within permissible limits through the PCM cooling system.

---

## सार

---

लगातार बढ़ती वैश्विक पर्यावरणीय चिंताओं ने इलेक्ट्रिक वाहनों (ईवी) के लिए परिवहन बाजार में गहरी जड़ें जमाने का मार्ग प्रशस्त किया है। लिथियम-आयन (ली-आयन) बैटरी ईवी का सबसे अधिक खोजा गया और केंद्रीय भाग है। ली-आयन बैटरी को उनके उच्च ऊर्जा घनत्व, शक्ति घनत्व, सेवा जीवन और कम स्व-निर्वहन दरों के कारण पसंद किया जाता है। हालांकि, ऑपरेटिंग तापमान पर बैटरी के प्रदर्शन की निर्भरता ने सुरक्षा और दीर्घायु के मुद्दों के कारण ग्राहकों की संतुष्टि को सीमित कर दिया है। इस संबंध में, कई वाहन निर्माताओं का मुख्य ध्यान प्रभावी बैटरी थर्मल प्रबंधन प्रणाली (बीटीएमएस) को डिजाइन और विकसित करना है। एक प्रभावी बीटीएमएस के लिए एक विश्वसनीय, सस्ता, ऊर्जा-कुशल और सरल संरचना कुछ प्राथमिक आवश्यकताएं हैं। बीटीएमएस को दो मुख्य श्रेणियों में वर्गीकृत किया गया है, (i) एक्टिव कूलिंग सिस्टम (एसीएस) और (ii) पैसिव कूलिंग सिस्टम (पीसीएस)। एसीएस को आगे दो श्रेणियों में विभाजित किया गया है, (i) वायु-शीतलित प्रणाली और (ii) तरल-शीतलित प्रणाली। कई अग्रणी ईवी निर्माताओं ने अपने बैटरी पैक में वायु-शीतलित बीटीएमएस को व्यापक रूप से अपनाया है। हालाँकि, वायु-शीतलित बीटीएमएस अत्यधिक परिवेशी परिस्थितियों में अक्षम है और इसमें भारी संरचनाएँ शामिल हैं। तरल-शीतलित बीटीएमएस वायु-शीतलित बीटीएमएस की तुलना में अधिक प्रभावी है, लेकिन बैटरी पैक में उपयोग किए जाने पर रिसाव और गैर-समान तापमान वितरण परेशानी भरा होता है। इसके अतिरिक्त, एसीएस अपने संचालन के लिए ऊर्जा की खपत करते हैं, जिसे परजीवी ऊर्जा खपत कहा जाता है। पीसीएस परजीवी ऊर्जा का उपभोग नहीं करते हैं और इस प्रकार, शोधकर्ताओं द्वारा सबसे अधिक खोजे जाते हैं।

यह शोध प्रबंध संख्यात्मक और प्रयोगात्मक अध्ययनों के माध्यम से तरल और चरण परिवर्तन सामग्री (पीसीएम) शीतलित बैटरी पैक की पड़ताल करती है। एक नई पीसीएम-फिन संरचना प्रस्तावित की गई है जो उच्च परिवेश और निर्वहन दरों के तहत अच्छी तरह से काम करती है। पीसीएम के द्रव्यमान और फिन की लंबाई के प्रभाव ने सीधे ऊष्मीय प्रदर्शन को प्रभावित किया। प्रस्तावित मॉडल पीसीएम और फिन्स का संयोजन था। एक गर्म जलवायु में ईवी के निर्बाध संचालन के लिए, इस अध्ययन ने एक नवीन पैसिव कूलिंग सिस्टम की जांच की। इस कूलिंग सिस्टम में दो अलग-अलग प्रकार के ताप निष्कर्षण माध्यम हैं: (i) पीसीएम-आधारित समतापी भंडारण-आधारित ताप सिंक और (ii) फिन-आधारित संवर्धित ऊष्मीय ट्रांसपोर्ट-आधारित ताप सिंक। ताप निष्कर्षण में प्रत्येक घटक के सापेक्ष योगदान को समझने और एक संयुक्त कार्यान्वयन से प्राप्त अधिकतम शीतलन क्षमता का एहसास करने के लिए इन दो उप-घटकों की पारस्परिक रूप से प्रतिस्पर्धी और पूरक परिदृश्यों में जांच की गई थी। रेट्रोफिट के व्यापक और गहन गुणों को एक नए गैर-आयामी सूचकांक के तहत एक साथ जोड़ा गया, जिसे वेरिबल सिस्टम रिस्पॉंस (वीएसआर) कहा गया है। पैरामीट्रिक अध्ययन के परिणामों का उपयोग दो सहसंबंधों के एक सेट को प्रस्तावित करने के लिए किया गया था। डिजाइन चर के विभिन्न संयोजनों ने 142.1 W का शीतलन हासिल किया।

इसके अलावा, मिनी-चैनलों के ज्यामितीय और ऊष्मीय-द्रवीय मापदंडों के सर्वोत्तम संयोजन को निर्धारित करने के लिए तरल शीतलन मिनी-चैनलों पर व्यापक शोध किया गया। श्रेष्ठ परिदृश्य के लिए ड्राइविंग चक्र के अंत में आयतन औसत बैटरी तापमान 313.31 K था। अध्ययन कम तीव्र शीतलन के महत्व को दर्शाता है, जिसके परिणामस्वरूप एसीएस द्वारा कम बिजली की खपत (0.85 W) होती है।

अंत में, शोध प्रबंध लोकप्रिय बैटरी प्रकारों: (i) बेलनाकार और (ii) प्रिज्मीय पैसिव कूलिंग सिस्टम के लिए की तुलना करती है। अध्ययन से पता चलता है कि प्रिज्मीय बैटरी की तुलना में एक बेलनाकार बैटरी कम परिवेश के तापमान की स्थिति में अधिक ताप संग्रहीत करती है। इसके अलावा, आकार कारक के कारण दोनों

लिथियम-आयन बैटरी में पीसीएम कूलिंग सिस्टम के लिए डिज़ाइन विशेषताएँ भिन्न हैं। इस अध्ययन ने पीसीएम शीतलन प्रणाली के माध्यम से अधिकतम तापमान को अनुमेय सीमा में रखने का प्रयास किया है।

## Contents

---

CERTIFICATE .....	i
ACKNOWLEDGEMENTS .....	ii
ABSTRACT .....	iii
संक्षेप .....	v
List of figures .....	xiii
List of tables .....	xx
Nomenclature .....	xxii
1 Introduction .....	1
1.1 Background .....	1
1.2 Battery .....	1
1.3 Li-ion battery .....	3
1.3.1 Discharging and charging of Li-ion battery .....	4
1.4 Electrification of transportation: Challenges and risks .....	5
1.5 Organization of the thesis .....	10
2 Literature review .....	13
2.1 Introduction .....	13
2.2 Air cooling system .....	14
2.2.1 Recent advances in Air Cooling Systems .....	16
2.3 Liquid Cooling System .....	20
2.3.1 Recent advances in the liquid cooling system .....	21

2.4	Passive cooling system .....	23
2.4.1	Recent advances in PCM cooling system.....	24
2.5	Comparison of the BTMS and challenges .....	29
2.6	Conclusions from the literature review .....	32
3	Unification of intensive and extensive properties of the Li-ion battery thermal management system .....	35
3.1	Introduction.....	35
3.2	Materials and method.....	37
3.2.1	Research methodology .....	37
3.3	Design of experiments .....	39
3.3.1	Non - dimensional input parameter formulation .....	39
3.3.2	Evaluation criteria of retrofit’s thermal performance .....	42
3.4	Numerical model.....	43
3.5	Mesh-timestep size independence check and model validation .....	51
3.5.1	Mesh-independence study .....	51
3.5.2	Timestep size independence study .....	52
3.5.3	Validation .....	53
3.6	Results and discussion .....	55
3.6.1	Battery pack without BTMS.....	55
3.6.2	Battery pack with BTMS .....	57
3.7	Effect of extensive properties .....	58
3.7.1	Volume average temperature.....	58
3.7.2	Active time .....	62
3.7.3	Temperature uniformity.....	67
3.7.4	Heat duty.....	68

3.8	Effect of intensive properties .....	70
3.8.1	Volume average temperature.....	70
3.8.2	Active time .....	74
3.8.3	Temperature uniformity.....	75
3.8.4	Heat duty.....	75
3.9	Correlation development for BTMS thermal performance estimation .....	76
3.10	Cross-validation of correlation .....	81
3.11	Conclusions.....	83
4	Thermal performance analysis of Li-ion batteries through inclined mini-channels .....	85
4.1	Introduction.....	85
4.2	Materials and Method .....	86
4.2.1	Research methodology .....	86
4.2.2	Design of experiments .....	87
4.2.3	Criteria for evaluation of thermal performance of the BTMS.....	90
4.3	Multi-criteria decision-making for optimal design selection.....	91
4.4	Numerical model of the BTMS.....	94
4.5	Model stability and validity assessment .....	102
4.5.1	Mesh and timestep size independence check .....	102
4.5.2	Model validation.....	105
4.6	Experimental validation.....	107
4.7	Results and discussion .....	112
4.7.1	Battery without BTMS under a real driving cycle .....	112
4.7.2	Effect of fluid inlet temperature on a retrofitted battery .....	114
4.7.3	Effects of mass flow rate, Re, and aspect ratio.....	117
4.7.4	Effect of inclination angle .....	121

4.7.5	Parasitic power consumption.....	124
4.8	Optimal design selection.....	127
4.9	Conclusions.....	128
5	Performance analysis of PCM-Fin heat sink under hostile conditions .....	129
5.1	Introduction.....	129
5.2	Materials and Method .....	129
5.2.1	Methodology.....	129
5.2.2	Numerical model .....	133
5.3	Mesh and Time-step size independence study.....	138
5.3.1	Meshing .....	138
5.3.2	Mesh independence study.....	139
5.3.3	Time-step size independence study .....	140
5.4	Validation.....	141
5.5	Results and discussion .....	143
5.5.1	Results for the battery pack without BTMS .....	143
5.6	TypeA design.....	144
5.7	TypeB design .....	151
5.7.1	Temperature variation in the battery pack .....	151
5.7.2	Effect of PCM thickness and fin length on the liquid fraction.....	156
5.7.3	Heat flux to the heat sink (PCM + fins) from the battery pack .....	158
5.7.4	Hot spot location.....	159
5.7.5	Performance analysis based on overall temperature coefficient and enhancement ratio 163	
5.8	Conclusions.....	165

6	A comparative analysis based on the BTMS and ambient between prismatic and cylindrical battery configuration.....	167
6.1	Introduction.....	167
6.2	Objective and problem statement.....	168
6.3	Design and Modelling.....	172
6.3.1	Mesh-independence Study.....	177
6.3.2	Validation .....	178
6.4	Results and discussion .....	181
6.4.1	Prismatic battery under 323 K ambient and 2C discharge rate .....	182
6.4.2	Prismatic Li-ion battery under 323 K ambient and 3C discharge rate .....	184
6.4.3	Cylindrical Li-ion battery at different C rates .....	186
6.5	Comparative study .....	188
6.5.1	Cylindrical and prismatic battery without BTMS .....	188
6.5.2	Cylindrical and prismatic battery with BTMS .....	190
6.6	Effectiveness of the PCM cooling system .....	203
6.7	Conclusions.....	204
7	Conclusions and scope for future work .....	205
	Publications.....	212
	References.....	214
	Appendices.....	233
A.1	Data for repeatability of the experiment .....	233
	Bio-data.....	273

---

## List of figures

---

Figure 1.1. Battery specific energy over time [6].	3
Figure 1.2. Lithium atom [7].	4
Figure 1.3. Charging/Discharging of Li-ion batteries [10].	5
Figure 1.4. Electrification of vehicles [11].	6
Figure 1.5. Li-ion battery safety window [33].	9
Figure 2.1. BTMS techniques.	14
Figure 2.2. (a) Passive air cooling system. (b) Active air cooling system [49].	16
Figure 2.3. (a) U-type air cooling channel [70]. (b) Z-type air cooling channel [71]. (c) T-type air cooling channel [72].	20
Figure 2.4. (a) Cold plate attached to battery monomer. (b) Cold plate in between batteries. (c) Cold plate at sides of the battery module.	21
Figure 2.5. Temperature characteristic of PCM cooling system [93].	24
Figure 2.6. Cylindrical battery module using PCM [100,101].	25
Figure 2.7. Circular Pin-fins with PCM (volume of fraction is 9 %) [125].	28
Figure 3.1. Flowchart for the parametric study.	38
Figure 3.2. Graphical plot showing the spread of input parameters across the search space.	41
Figure 3.3. DOE development.	42
Figure 3.4. Design of the battery pack with BTMS.	44
Figure 3.5. Meshing.	51
Figure 3.6. (a) Mesh independence study. (b) Time independence study.	52
Figure 3.7. Validation with the study done by Wu et al. (b) Validation with the study done by Javani et al.	55

Figure 3.8. Maximum and minimum temperature distribution for different heat generation rates. .....	56
Figure 3.9. Temperature contours for heat generation rates: (a) 35 W; (b) 11.2 W; (c) 4 W. ....	57
Figure 3.10. Volume average temperature for different DR.....	60
Figure 3.11. Temperature contour for PCM thickness 11.28 mm and fin length 45.13 mm (DR = 14396.2). ....	62
Figure 3.12. Heat rate to PCM and fins for DR: (a) 14396.2; (b) 62894; (c) 18858.66; (d) 48011.59. .....	64
Figure 3.13. Effect of PCM thickness and fin length on liquid mass fraction.....	66
Figure 3.14. Effect of fin length (constant PCM thickness) on liquid mass fraction. ....	67
Figure 3.15. Graphical plot highlighting the temperature uniformity for different cases.....	68
Figure 3.16. Graphical plot of heat duty for: (a) Fins; (b) PCM.....	70
Figure 3.17. Goodness of fit by ANSYS DX.....	72
Figure 3.18. (a) 3-D Response surface of temperature for DR = 13007. (b) Plot for temperature variation against DR for constant MR (1.14) and LR (3.89).....	73
Figure 3.19. Liquid mass fraction contours for MR = 0.8 and LR = 1.....	74
Figure 3.20. Temperature uniformity for MR = 0.8 and LR = 1. ....	75
Figure 3.21. Graphical plot of heat duty for MR = 0.8 and LR = 1.....	76
Figure 3.22. (a) Relationship between response and predictor for VSR greater than 0.55. (b) Relationship between response and predictor for VSR less than 0.55. (c) Parity plot for VSR less than 0.55 (d) Parity plot for VSR greater than 0.55.....	80
Figure 3.23. Parity plot for volume average temperature. ....	83
Figure 4.1. Temperature distribution in India on 15 April 2022 at 4:00 pm [167].....	87

Figure 4.2. Sample distribution of design variables through the LHS method.....	89
Figure 4.3. (a) Depiction of mini-channels arranged at different inclination angles on the cell surface. (b) single mini-channel.....	96
Figure 4.4. Realistic driving cycle adopted in the study [170]. .....	97
Figure 4.5. Meshed image of the CFD model.....	102
Figure 4.6. (a) Mesh independence study. (b) Time independence study. ....	105
(b).....	106
Figure 4.7. Validation: (a) Ref. [179] (flow through mini-channel). (b) Ref. [180] (battery model). .....	106
Figure 4.8. (a) Experimental setup. (b) Thermocouple location.....	109
Figure 4.9. Comparison between the experimental and numerical solutions: (a) 0.8C; (b) 0.5C. (c) Repeatability of the experiment at 0.8C discharge rate. ....	111
Figure 4.10. Plots for: (a) Volume average temperature with time; (b) total heat generation with time. ....	113
Figure 4.11. Temperature contours for battery without BTMS.....	113
Figure 4.12. (a) Plot showing the effect of fluid temperature on volume average temperature and temperature difference in the cell. (b) Plot showing DOEs with temperature difference less than 5 K. (c) Comparative temperature contours for fluid inlet temperature 312.9 K ( $i= 5^\circ$ ) and 298.1 K ( $i= 68.9^\circ$ ). ....	117
Figure 4.13. Effect of mass flow rate and fluid inlet temperature on volume average temperature. ....	117
Figure 4.14. Counter flow depiction in the mini-channels. ....	118

Figure 4.15. (a) Plot showing the effect of mass flow rate on pressure drop and volume average temperature. (b) Graphical plot showing effect of aspect ratio and Re on volume average temperature. (c) Comparative temperature contours for mini-channel aspect ratio 8.1 ( $i = 31.1^\circ$  and 1.1 ( $i = 67.1^\circ$ )). ..... 121

Figure 4.16. (a) Plot showing the effect of inclination angle on the pressure drop. (b) Plot showing the effect of inclination angle on volume average temperature and temperature difference. (c) Comparative temperature contours for inclination angle  $1.4^\circ$  and  $68.9^\circ$  for fluid inlet temperature 298 K..... 123

Figure 4.17. Variation of pumping power for input parameters: (a) inclination angle; (b) aspect ratio and fluid inlet velocity..... 126

Figure 4.18. Variation of work input against mass flow rate and fluid inlet temperature. .... 126

Figure 5.1. (a) TypeA design. (b) TypeB design. .... 131

Figure 5.2. Schematic of the numerical model. .... 133

Figure 5.3. Meshed image of battery module with 7 mm PCM thickness..... 139

Figure 5.4. (a) Mesh independence study. (b) Time step-size independence study. .... 141

Figure 5.5. Model Validation..... 142

Figure 5.6. Maximum and minimum temperature distribution for different heat generation rates. .... 143

Figure 5.7. (a) Maximum and minimum temperature distribution for  $200000 \text{ W/m}^3$  for all PCM thicknesses. (b) Temperature contours for battery pack without PCM at  $22800 \text{ W/m}^3$ . (c) Temperature contours for 7 mm PCM thickness at  $22800 \text{ W/m}^3$ . (d) Temperature contours for battery pack without PCM at  $63970 \text{ W/m}^3$ . (e) Temperature contours for 7 mm PCM thickness at

63970W/m <sup>3</sup> . (f) Temperature contours for battery pack without PCM at 200000 W/m <sup>3</sup> . (g) Temperature contours for 7 mm PCM thickness at 200000 W/m <sup>3</sup> .....	146
Figure 5.8. (a) Maximum and minimum temperature variation of the cells in the battery module for 7 mm PCM thickness and 200000 W/m <sup>3</sup> discharge rate. Temperature contours for 9 mm PCM thickness at 200000 W/m <sup>3</sup> : (b) without PCM; (c) with PCM.....	147
Figure: 5.9. (a) Temperature contours for 7 mm PCM thickness (all around) at 200000 W/m <sup>3</sup> . .....	149
Temperature contours comparison for 7 mm PCM thickness (all around) at 200000 W/m <sup>3</sup> : (b) cell 1; (c) cell 2. ....	149
Figure 5.10. Temperature contours: (a) without PCM; (b) with PCM; (c – f) Mass fraction contours for 12 mm PCM thickness at 200000 W/m <sup>3</sup> at different time intervals.....	150
Figure 5.11. Maximum and minimum temperature distribution for 200000 W/m <sup>3</sup> different PCM thickness for different fin length.....	154
Figure 5.12. (a) 7 mm PCM, 14 mm fin length. (b) 7 mm PCM, 30 mm fin length (200000 W/m <sup>3</sup> ). (c) 9 mm PCM, 14 mm fin length. (d) 9 mm PCM, 30 mm fin length (200000 W/m <sup>3</sup> ). (e) 12 mm PCM, 14 mm fin length. (f) 12 mm PCM, 30 mm fin length (200000 W/m <sup>3</sup> ). ....	156
Figure 5.14. Heat flux from the battery pack to the heat sink. ....	158
Figure 5.15. (a) Change in the location of maximum temperature point along the cell length and cell length for 200000 W/m <sup>3</sup> for battery module with 7 mm, 9 mm and 12 mm PCM. (b) location of the hotspot.....	161
Figure 5.16. (a) Change in the location of maximum temperature point along the cell length for different fin lengths for battery module with 7 mm thick PCM layer. (b) Change in the location of	

maximum temperature point along the cell height for different fin lengths for battery module with 7mm thick PCM layer.....	162
Figure 5.17. (a) The enhancement ratios of the PCM-fin system for 200000 W/m <sup>3</sup> heat generation rate for different PCM thicknesses. (b) Overall temperature coefficients along the horizontal points in the cell for different cases. ....	164
Figure 6.1 (a) Prismatic Lithium-ion battery. (b) Cylindrical Lithium-ion battery. ....	172
Figure 6.2. Meshed geometry of Prismatic battery and cylindrical Li-ion battery.....	177
Figure 6.3. Mesh Independence Study.....	178
Figure 6.4. 4 × 5 cylindrical battery pack. ....	179
Figure 6.5. Validation for: (a) cylindrical battery (without PCM cooling system); (b) cylindrical battery (with PCM cooling system); (c) prismatic battery (with and without PCM cooling system). ....	181
Figure 6.6. Battery without PCM at 323 K at 2C discharge rate. ....	183
Figure 6.7. Battery with PCM at 2C discharge rate at 1200 s. ....	184
Figure 6.8. Battery without PCM at 323 K at 3C discharge rate. ....	186
Figure 6.9. Cylindrical Li-ion battery under 4 C discharge rate. ....	187
Figure 6.10. Cylindrical battery transient trend of temperature for various discharge rates. ....	187
Figure 6.11. Graphical plot for prismatic and cylindrical battery at different C rate and ambient conditions.....	190
Figure 6.12. Graphical plot between maximum temperature and time for different cases.....	193
Figure 6.13. (a) Cylindrical battery with BTMS at 27 °C ambient. (b) Prismatic battery with BTMS at 27°C ambient.....	195

Figure 6.14. (a) Mass fraction contours: (a) prismatic battery at 27°C ambient; (b) cylindrical battery at 27°C ambient..... 196

Figure 6.15. (a) Temperature contour at 1200th second. (b) Mass fraction contour at 200th second for case 1 with PCM A, cylindrical battery. .... 197

Figure 6.16. (a) Cylindrical battery with BTMS at 35 °C. (b) Prismatic battery with BTMS at 35 °C. .... 198

Figure 6.17. Mass fraction contours: (a) prismatic battery at 35 °C ambient; (b) cylindrical battery at 35 °C ambient..... 199

Figure 6.18. (a) Cylindrical battery with BTMS at 45 °C. (b) Prismatic battery with BTMS at 45 °C. .... 201

Figure 6.19. Mass fraction contours: (a) prismatic battery at 45 °C ambient; (b) cylindrical battery at 45 °C ambient..... 202

Figure 6.20. Graph showing Li-ion battery under air and PCM cooling system at discharge condition of 3 A. .... 203

---

## List of tables

---

Table 1.1. Cell failure precursors.....	8
Table 2.1. Limitations of BTMS techniques.....	31
Table 3.1. Details of the PCM layer. ....	40
Table 3.2. Input parameters values. ....	41
Table 3.3. Heat generation rate. ....	44
Table 3.4. Structural details. ....	44
Table 3.5. Battery specifications.....	45
Table 3.6. Thermophysical properties of retrofits. ....	46
Table 3.7. Boundary conditions.....	47
Table 3.8. Maximum temperature for different DR.....	60
Table 3.9. Minimum temperature for different DR. ....	61
Table 3.10. Candidate utopian points. ....	73
Table 3.11. Cross-validation of the developed correlation. ....	82
Table 4.1. Input parameters. ....	87
Table 4.2. Material specifications.....	94
Table 4.3. Retrofitted battery structural details. ....	95
Table 4.4. Key parameters of the hybrid bus.....	97
Table 4.5. Boundary conditions.....	98
Table 4.6. NTGK Model parameters. ....	100
Table 4.7. Mesh quality. ....	103
Table 5.1. Thermophysical properties of the PCM.....	130
Table 5.2. Dimensions of PCM and Fins.....	132

Table 5.3. Titles for different cases for TypeB configuration. ....	132
Table 5.4. Battery Specifications. ....	134
Table 5.5. Boundary conditions. ....	135
Table 5.6. Heat generation rate. ....	135
Table 5.7. Validation. ....	142
Table 5.8. Average temperature of the critical cases. ....	156
Table 6.1. Heat generation rate for prismatic Li-ion battery .....	171
Table 6.2 Heat generation rate for cylindrical Li-ion battery .....	171
Table 6.3 Battery properties for prismatic Li-ion battery. ....	173
Table 6.4. Battery properties for cylindrical Li-ion battery. ....	173
Table 6.5. Boundary conditions. ....	174
Table 6.6. PCM thermophysical Properties .....	183
Table 6.7. Maximum Temperature in the prismatic and cylindrical battery for different ambient without BTMS at 3C and 5C discharge rate. ....	189
Table 6.8. Thermophysical properties of PCMs. ....	192
Table 6.9 Maximum temperature for all the cases with PCM. ....	193

---

## Nomenclature

---

### A. Acronyms

BTMS : Battery thermal management system

ACS : Active cooling system

PCS : Passive cooling system

HCS : Hybrid cooling system

PCM : Phase change material

Re : Reynolds number

EV : Electrical vehicle

SOC : State of charge

SOH : State of health

DOE : Design of experiment

MR : mass ratio

DR : thermal diffusivity ratio

LR : length ratio

VSR : variable system response index

### B. Nomenclature

$mass_{Fin}$  : mass of the fins (kg)

$mass_{battery\ pack}$  : mass of the battery pack (kg)

$mass_{PCM}$  : mass of the PCM plates (kg)

$C_P$  : specific heat at constant pressure (J/kg-K)

$R_{conv}$  : convective resistance (K/W)

$R_{cond}$  : conductive resistance (K/W)

$h_t$  : convective heat transfer coefficient (W/m<sup>2</sup>-K)

$h_{rad}$  : radiative heat transfer coefficient (W/m<sup>2</sup>-K)

$A_{mushy}$  : mushy zone parameter

$P$  : pressure (N/m<sup>2</sup>)

$S$  : momentum source term (kg/m<sup>3</sup>-s)

$\vec{S}_h$  : volumetric heat source term (J/K-m<sup>3</sup>)

$k$  : Thermal conductivity (W/m-K)

$\vec{V}$  : velocity of fluid (m/s)

$h_{ref}$  : reference enthalpy (J/kg)

$h$  : heat transfer coefficient (W/m<sup>2</sup>-K)

$L$  : latent heat (J/kg)

$\gamma$  : liquid fraction

$U$  : open circuit potential (volts)

$V$  : cell potential (volts)

$v$  : fluid inlet velocity (m/s)

$i$  : mini-channel inclination angle (degree)

$x$  : mini-channel aspect ratio

$t_i$  : fluid inlet temperature (K)

$t_a$  : ambient temperature (K)

$t_{initial}$  : initial temperature (K)

$m$  : mass flow rate (kg/s)

$D_p$  : hydraulic diameter (m)

$\mu$  : dynamic viscosity (kg/m-s)

$\rho$  : density (kg/m<sup>3</sup>)

$W_P$  : pumping power (W)

$W_c$  : refrigeration work (W)

$\Delta P$  : pressure drop (Pa)

$Q$  : volumetric flow rate (m<sup>3</sup>/s)

$f$  : friction factor

$T_{solidus}$  : PCM's freezing temperature (K)

$T_{liquidus}$  : PCM's melting temperature (K)

$T_{max,local}$  : maximum local temperature (K)

$T_{ref}$  : reference temperature (K)

$T_{max-gen}$  : maximum temperature of all the cases (K)

$V_{nom}$  : Nominal voltage

$V_{max}$  : Maximum voltage

$V_{min}$  : Minimum voltage

$C_{nom}$  : Nominal capacity

### **C. Greek Symbols**

$\rho$  : density (kg/m<sup>3</sup>)

$\gamma$  : liquid fraction

$\theta$  : Overall temperature coefficient

$\varepsilon$  : Enhancement ratio

$\varnothing_k$  : direction vector