

# **PERFORMANCE ANALYSIS OF LIQUID-BASED BATTERY THERMAL MANAGEMENT SYSTEM IN ELECTRIC VEHICLES**

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# **Performance Analysis of Liquid-based Battery Thermal Management System in Electric Vehicles**

by

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*Dedicated to my family members*

## **DECLARATION**

I declare that this written submission represents my ideas in my own words. I have adequately cited and referenced the original sources when including others' ideas and words. I further declare that I have adhered to all academic honesty and integrity principles and have not misrepresented, fabricated, or falsified any idea, data, fact, or source in my submission.

This thesis is composed of my original work and contains no material previously published or written by another person, except where due reference has been made in the text. I have clearly stated the contributions of others to jointly authored works included in this thesis.

I acknowledge that an electronic copy of my thesis must be lodged with the university library, subject to the policy and procedures of the Indian Institute of Technology Delhi.

Suyash Vikram

## Certificate

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This is to certify that the thesis titled **Performance Analysis of Liquid-based Battery Thermal Management System in Electric Vehicles** submitted by **Mr. Suyash Vikram** to the Indian Institute of Technology Delhi for the award of the degree of **'Doctor of Philosophy'** is a Bonafide record of the original research work done by him under my guidance and supervision at Department of Energy Science and Engineering, Indian Institute of Technology Delhi. The contents of this thesis, in full or in parts, have not been submitted to any other University or Institute for the award of any degree or diploma.

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## ABSTRACT

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In recent years, a shift from internal combustion engines to electric vehicles has been intensified due to increasing global environmental concerns. The lithium-ion battery is key to this transformation because of its several benefits, such as specific power output, higher energy density, and longer life span. However, the major concern is that its performance is highly sensitive to working temperatures, especially under dynamic driving conditions. Battery Thermal Management Systems (BTMS) are therefore essential in electric vehicle design to alleviate any thermal issues in the battery pack and maintain its consistent performance. BTMS has been classified into various categories based on the cooling medium utilized, namely Air Cooling, Liquid Cooling, Phase Change Material-based Cooling, etc. Furthermore, BTMS are typically classified as active and passive cooling systems. Active cooling systems necessitate an external energy source, specifically the energy necessary to operate fans or pumps in air or liquid cooling systems. Passive cooling solutions require no external energy sources, such as PCM or a heat pipe-based cooling system. Among the various cooling strategies available, liquid cooling-based BTMS are recognized for their exceptionally good heat transfer capabilities and compact configurations.

This thesis presents a comprehensive performance analysis of liquid cooling-based BTMS in electric vehicles through both numerical and experimental studies. A cold plate liquid cooling-based BTMS has been proposed, and its performance with water as a coolant has been analysed at different ambient temperatures for actual driving cycles. The present study employs a MATLAB/Simulink model for a liquid cooling-based BTMS in an electric vehicle. The battery pack is positioned above the cold plate. The coolant circulates in the cooling channels integrated

within the cold plate. The liquid coolant extracts heat from the battery pack, and the study examines changes in the average battery pack temperature along with the total energy consumed by the BTMS. The simulation model is designed to maintain the battery pack at a constant temperature of 25°C. Additionally, the influence of varying ambient temperatures on the efficacy of the liquid cooling system has been examined. Findings indicate that as the ambient temperature increases, the BTMS requires more time duration to lower the battery pack temperature, and overall energy usage also rises. The following chapter extends this analysis by evaluating the BTMS performance using three different coolants. To identify the most effective coolant and its ideal concentration, mixtures of water with ethylene glycol and propylene glycol at various ratios are tested. These additives are blended with water to enhance the coolant's thermal characteristics. In the case of a Water-Propylene glycol mixture, 25% propylene glycol concentration is advised; however, for a water-ethylene glycol mixture, 50% ethylene glycol concentration provides the optimal results.

Furthermore, in addition to BTMS in EVs, this thesis also focuses on the vehicle cabin thermal management. An integrated thermal management system, combining a BTMS with a vehicle cabin air conditioning system, is a viable approach to improving energy efficiency and reducing space requirements in electric vehicles. This study investigated the efficacy of an integrated system for EVs under an actual driving cycle. The simulations are conducted in MATLAB/Simulink, and the performance is analyzed at ambient temperatures and relative humidity levels. The model has been formulated in such a way as to regulate the cabin temperature between 22–24°C and the battery pack temperature within a safe range of 30–35°C. The results indicate that as ambient temperature rises, the duration required for the integrated system to attain the set cabin temperature increases, owing to increased heat exchange between the vehicle cabin and the surrounding environment at

higher ambient temperatures. At 25°C ambient temperature, the cabin air conditioning system requires 625 seconds to reach the required set point cabin temperature, whereas at 30°C and 35°C ambient temperature, the corresponding time durations are 2045 seconds and 2150 seconds. The BTMS, being more vital, gives an optimal performance and maintains the battery pack temperature in the range of 30–35 °C at different ambient conditions.

Finally, an experimental study has been carried out to analyse the efficacy of the immersion cooling technique for lithium-ion battery packs. Indirect liquid cooling systems, such as those utilizing a cold plate, have shown effective performance by maintaining the battery pack temperature within the specified range. With the increasing demand for fast charging in EVs, immersion cooling techniques for LiB are gaining popularity. Immersion cooling has superior heat transfer efficiency as it maintains direct contact between the coolant and the battery surfaces, eliminating the thermal resistance introduced by intermediate materials like a cold plate, etc. Also, the battery packs are submerged in coolant, directly ensuring even temperature distribution in the cells. This research seeks to assess cooling efficiency, thermal uniformity, and the effects of immersion cooling technique on lithium-ion battery performance. In this study, the battery pack is made using 9 cells in a 3x3 arrangement (3S3P), i.e., three cells in a row, each connected in a series, and each row is connected in a parallel connection. The study offers an in-depth analysis of the thermal characteristics of LiB cells submerged in transformer oil through the integration of thermocouples, data loggers, climate chambers, and a power supply. The results demonstrate a substantial reduction in the maximum temperature of the centre cell when the battery pack is entirely immersed in the transformer oil. The transformer oil has a greater specific heat than air, and immersion cooling also has a higher heat transfer coefficient. Therefore, the complete

immersion of the battery pack in the transformer oil enables more heat dissipation from the batteries.

In summary, this thesis delivers a detailed exploration of liquid and immersion cooling-based BTMS for EVs, using both simulation and experimental approaches. Furthermore, the integration of BTMS with cabin thermal management is shown to improve energy efficiency and system compactness, a crucial step toward optimizing EV design. The immersion cooling study, in particular, underscores the superior thermal regulation, making it a promising solution for high-demand applications like fast charging. Overall, the research contributes valuable knowledge toward developing robust, energy-efficient, and safe BTMS strategies for next-generation EVs.

Keywords: Lithium-ion battery; Immersion Cooling; Integrated thermal management system; Liquid cooling, Electric Vehicles

## सार

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हाल के वर्षों में आंतरिक दहन इंजन (ICE) से इलेक्ट्रिक वाहनों (EVs) की ओर संक्रमण में तेजी आई है, जिसका प्रमुख कारण बढ़ती वैश्विक पर्यावरणीय चिंताएँ हैं। इस परिवर्तन में लिथियम-आयन बैटरी की भूमिका अत्यंत महत्वपूर्ण है, क्योंकि इसमें उच्च ऊर्जा घनत्व, विशिष्ट पावर आउटपुट और लंबी जीवन अवधि जैसी अनेक विशेषताएँ होती हैं। हालांकि, एक प्रमुख चिंता यह है कि लिथियम-आयन बैटरियों का प्रदर्शन, सुरक्षा और दीर्घायु उनके कार्य तापमान पर अत्यधिक निर्भर करता है, विशेष रूप से गतिशील ड्राइविंग परिस्थितियों में। इसलिए, बैटरी थर्मल मैनेजमेंट सिस्टम (BTMS) इलेक्ट्रिक वाहनों के डिज़ाइन में आवश्यक हो जाते हैं, ताकि बैटरी पैक में किसी भी प्रकार की थर्मल समस्या को रोका जा सके और उसका स्थिर प्रदर्शन सुनिश्चित किया जा सके। BTMS को प्रयुक्त शीतलक माध्यम के आधार पर विभिन्न वर्गों में बाँटा गया है, जैसे वायु शीतलन (Air Cooling), तरल शीतलन (Liquid Cooling), फेज़ चेंज मटेरियल (PCM) आधारित शीतलन और हीट पाइप आधारित शीतलन। इसके अतिरिक्त, BTMS को सामान्यतः सक्रिय (Active) और निष्क्रिय (Passive) शीतलन प्रणालियों के रूप में वर्गीकृत किया जाता है। सक्रिय शीतलन प्रणालियों को बाहरी ऊर्जा स्रोत की आवश्यकता होती है, जैसे पंखे या पंप चलाने हेतु ऊर्जा, जो वायु या तरल शीतलन प्रणालियों में प्रयुक्त होती है। वहीं, निष्क्रिय शीतलन प्रणालियों को किसी बाहरी ऊर्जा स्रोत की आवश्यकता नहीं होती, जैसे PCM या हीट पाइप आधारित प्रणालियाँ। उपलब्ध विभिन्न शीतलन विधियों में, तरल शीतलन आधारित BTMS को उनके उत्कृष्ट ऊष्मा स्थानांतरण गुणों और कॉम्पैक्ट डिज़ाइन के कारण सबसे प्रभावशाली माना गया है।

यह शोधप्रबंध इलेक्ट्रिक वाहनों में तरल शीतलन आधारित BTMS का एक समग्र प्रदर्शन विश्लेषण प्रस्तुत करता है, जिसमें संख्यात्मक (Numerical) और प्रयोगात्मक (Experimental) दोनों प्रकार के अध्ययन

शामिल हैं। एक कोल्ड प्लेट आधारित तरल शीतलन BTMS प्रस्तावित किया गया है, और इसमें जल (Water) को शीतलक के रूप में उपयोग करते हुए विभिन्न परिवेश तापमानों पर तथा वास्तविक ड्राइविंग चक्रों के लिए इसका प्रदर्शन विश्लेषित किया गया है। इस अध्ययन में MATLAB/Simulink आधारित एक सिमुलेशन मॉडल का उपयोग किया गया है, जिसमें बैटरी पैक को कोल्ड प्लेट के ऊपर रखा गया है। कोल्ड प्लेट के अंदर बने शीतलन चैनलों से तरल शीतलक प्रवाहित होता है, जो बैटरी पैक से ऊष्मा को अवशोषित करता है। बैटरी पैक के तापमान में होने वाले परिवर्तन और BTMS द्वारा उपभोग की गई संचयी ऊर्जा की मात्रा का विश्लेषण किया गया है। सिमुलेशन मॉडल को इस प्रकार विन्यस्त किया गया है कि वह बैटरी पैक का तापमान 25°C पर बनाए रखे।

इसके अतिरिक्त, परिवेश तापमान का तरल शीतलन प्रणाली के प्रदर्शन पर क्या प्रभाव पड़ता है, इसका भी परीक्षण किया गया है। परिणामों से ज्ञात हुआ कि जैसे-जैसे परिवेश तापमान बढ़ता है, BTMS को बैटरी पैक को ठंडा करने में अधिक समय लगता है, और कुल ऊर्जा खपत भी बढ़ जाती है। अगले अध्याय में इस BTMS के तीन विभिन्न शीतलक द्रवों के साथ प्रदर्शन की तुलना की गई है। जल, जल-एथिलीन ग्लाइकोल मिश्रण और जल-प्रोपाइलीन ग्लाइकोल मिश्रण के विभिन्न सांद्रता स्तरों का उपयोग किया गया है, ताकि सर्वोत्तम शीतलक और उसकी उपयुक्त सांद्रता का निर्धारण किया जा सके। इन मिश्रणों में जल के साथ जोड़े गए योजक (Additives) उनके थर्मल गुणों को बेहतर बनाते हैं। जल-प्रोपाइलीन ग्लाइकोल मिश्रण के लिए 25% प्रोपाइलीन ग्लाइकोल की सांद्रता अनुशंसित की गई है, जबकि जल-एथिलीन ग्लाइकोल मिश्रण के लिए 50% एथिलीन ग्लाइकोल की सांद्रता सर्वोत्तम प्रदर्शन देती है, क्योंकि इससे BTMS की ऊर्जा खपत और बैटरी पैक में तापमान वितरण दोनों ही अनुकूल रहते हैं।

BTMS के अलावा, यह शोधप्रबंध इलेक्ट्रिक वाहनों के केबिन थर्मल प्रबंधन पर भी केंद्रित है। बैटरी थर्मल मैनेजमेंट सिस्टम और केबिन एयर कंडीशनिंग सिस्टम को एकीकृत करने वाली संयुक्त थर्मल प्रबंधन

प्रणाली (Integrated Thermal Management System - ITMS) को ऊर्जा दक्षता बढ़ाने और वाहन में स्थान की बचत के लिए एक व्यवहार्य विकल्प के रूप में देखा गया है। इस अध्ययन में, एकीकृत थर्मल प्रबंधन प्रणाली के प्रदर्शन को वास्तविक ड्राइविंग चक्र पर MATLAB/Simulink के माध्यम से विश्लेषित किया गया है। मॉडल को इस प्रकार तैयार किया गया है कि वह केबिन तापमान को 22–24°C के बीच तथा बैटरी पैक के तापमान को 30–35°C की सुरक्षित सीमा के भीतर बनाए रख सके। परिणाम बताते हैं कि जैसे-जैसे परिवेश तापमान बढ़ता है, वाहन केबिन को वांछित तापमान तक पहुँचाने में अधिक समय लगता है, क्योंकि परिवेश और केबिन के बीच अधिक ऊष्मा का आदान-प्रदान होता है। 25°C परिवेश तापमान पर केबिन एयर कंडीशनिंग सिस्टम को 625 सेकंड लगते हैं वांछित तापमान तक पहुँचने में; वहीं 30°C और 35°C पर यह समय क्रमशः 2045 सेकंड और 2150 सेकंड होता है। बैटरी थर्मल प्रबंधन प्रणाली, जो अधिक महत्वपूर्ण है, सभी परिवेश तापमानों पर 30–35°C के भीतर बैटरी पैक तापमान बनाए रखकर उत्तम प्रदर्शन देती है।

अंततः, लिथियम-आयन बैटरी पैक के लिए इमर्शन कूलिंग (Immersion Cooling) रणनीति का एक प्रयोगात्मक अध्ययन किया गया है। हालाँकि कोल्ड प्लेट जैसे अप्रत्यक्ष तरल शीतलन विधियाँ भी अच्छा प्रदर्शन देती हैं और बैटरी पैक को आवश्यक तापमान सीमा में बनाए रखती हैं, फिर भी इलेक्ट्रिक वाहनों में तीव्र चार्जिंग की बढ़ती माँग के चलते इमर्शन कूलिंग तकनीकें लोकप्रियता प्राप्त कर रही हैं। इमर्शन कूलिंग में शीतलक द्रव बैटरी की सतहों के सीधे संपर्क में होता है, जिससे कोल्ड प्लेट जैसे मध्यवर्ती अवरोधकों द्वारा उत्पन्न तापीय प्रतिरोध समाप्त हो जाता है। इसमें बैटरी पैक को शीतलक में पूरी तरह डुबो दिया जाता है, जिससे (Cells) में समान रूप से तापमान वितरण सुनिश्चित होता है। यह अध्ययन इमर्शन कूलिंग तकनीक की शीतलन दक्षता, तापीय एकरूपता और लिथियम-आयन बैटरी के प्रदर्शन पर इसके प्रभाव का मूल्यांकन करता है। इस प्रयोगात्मक अध्ययन में ट्रांसफॉर्मर ऑयल में डुबोए गए बैटरी

सेल्स की तापीय प्रवृत्ति का विश्लेषण थर्मोकपल, डेटा लॉगर, जलवायु कक्ष और विद्युत आपूर्ति की सहायता से किया गया है। परिणामों से यह सिद्ध होता है कि जब बैटरी पैक को पूरी तरह ट्रांसफॉर्मर ऑयल में डुबोया गया, तो केंद्र स्थित बैटरी सेल का अधिकतम तापमान काफी हद तक कम हो गया। ट्रांसफॉर्मर ऑयल की विशिष्ट ऊष्मा (Specific Heat) वायु की तुलना में अधिक होती है, और इमर्शन कूलिंग की ऊष्मा स्थानांतरण गुणांक (Heat Transfer Coefficient) भी अधिक होता है। इसलिए, ट्रांसफॉर्मर ऑयल में बैटरी पैक की पूरी डुबकी से बैटरियों से अधिक ऊष्मा का निष्कासन संभव हो पाता है।

संक्षेप में, यह शोध प्रबंध तरल और इमर्शन कूलिंग आधारित बैटरी थर्मल मैनेजमेंट सिस्टम (BTMS) के लिए एक विस्तृत अध्ययन प्रस्तुत करता है, जिसमें सिमुलेशन और प्रायोगिक दोनों दृष्टिकोणों का उपयोग किया गया है। साथ ही, BTMS का केबिन थर्मल मैनेजमेंट के साथ एकीकरण ऊर्जा दक्षता और सिस्टम की कॉम्पैक्टनेस को बढ़ाता है, जो इलेक्ट्रिक वाहन (EV) डिज़ाइन के अनुकूलन की दिशा में एक महत्वपूर्ण कदम है। विशेष रूप से, इमर्शन कूलिंग अध्ययन बेहतर तापीय नियंत्रण को रेखांकित करता है, जिससे यह फास्ट चार्जिंग जैसी उच्च मांग वाली अनुप्रयोगों के लिए एक आशाजनक समाधान बन जाता है। समग्र रूप से, यह शोध अगली पीढ़ी के EVs के लिए मज़बूत, ऊर्जा-कुशल और सुरक्षित BTMS रणनीतियों के विकास में महत्वपूर्ण ज्ञान का योगदान करता है।

कीवर्ड: लिथियम-आयन बैटरी; इमर्शन कूलिंग; एकीकृत थर्मल मैनेजमेंट सिस्टम; तरल शीतलन; विद्युत वाहन

## Contents

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CERTIFICATE.....	i
ACKNOWLEDGEMENT.....	iii
ABSTRACT.....	iv
List of Figures.....	xvii
List of Tables.....	xxiii
Nomenclature.....	xxiv
1 Introduction.....	27
1.1 Background.....	27
1.2 Lithium-Ion Battery.....	28
1.3 Heat Generation in Lithium-Ion Battery.....	30
1.4 Thermal Issues in Lithium-Ion Battery.....	31
1.4.1 Low Temperature Effect.....	32
1.4.2 High Temperature Effect.....	32
1.5 BTMS Classification.....	34
1.6 Organisation of Thesis.....	36

2	Literature review.....	40
2.1	Introduction.....	40
2.2	Air Cooling based BTMS.....	41
2.3	Liquid Cooling based BTMS.....	45
2.4	Phase Change Material based BTMS.....	50
2.5	Heat Pipe based BTMS.....	54
2.6	Hybrid Battery Thermal Management System.....	57
	2.6.1 Air-PCM based Hybrid BTMS.....	58
	2.6.2 Liquid-PCM based Hybrid BTMS.....	61
2.7	Conclusions from the Literature Review.....	68
2.8	Research Gaps.....	70
3	Performance analysis of Liquid-based BTMS for Electric Vehicles during discharge under drive cycles at various ambient temperatures	
3.1	Introduction.....	73
3.2	Numerical Modelling Interpretation.....	75
	3.2.1 Drive Cycle Model.....	77
	3.2.2 Electrothermal Model.....	80
	3.2.3 Boundary Conditions.....	84
3.3	Model Validations.....	85
3.4	Results and Discussions.....	87

3.5	Conclusions.....	93
4	Performance analysis of Liquid-based BTMS system for Electric Vehicles during discharge under drive cycles for different coolants	
4.1	Introduction.....	95
4.2	Coolant Details.....	97
4.3	Numerical Modelling Interpretation.....	99
4.3.1	Drive Cycle Model.....	100
4.3.2	Electrothermal Model.....	103
4.3.2.1	Battery Electro thermal model.....	103
4.3.2.2	Cold plate Heat Exchanger Model.....	106
4.3.2.3	Cooling Unit model.....	106
4.4	Boundary Conditions.....	107
4.5	Model Validation.....	109
4.6	Results and Discussions.....	111
4.7	Conclusion.....	123
5	Performance analysis of integrated battery and cabin thermal management system in Electric Vehicles	
5.1	Introduction.....	125
5.2	Methodology.....	126
5.3	Modelling Interpretation.....	131
5.3.1	The Driving Cycle Subsystem.....	131

5.3.2	The Comprehensive Integrated EV Thermal Management Subsystem.....	134
5.3.2.1	The Motor Pump Subsystem.....	134
5.3.2.2	The Radiator Subsystem.....	134
5.3.2.3	The Battery Subsystem.....	135
5.3.2.4	The Compressor Subsystem.....	137
5.3.2.5	The Condenser Subsystem.....	137
5.3.2.6	The Evaporator Subsystem.....	138
5.3.2.7	The Blower Subsystem.....	138
5.3.2.8	The Vehicle Cabin Subsystem.....	139
5.4	Validation.....	141
5.5	Results and discussion.....	143
5.6	Conclusions.....	158
6.	Experimental Study of Immersion Cooling Technique for Lithium-Ion Battery Pack	
6.1	Introduction.....	160
6.2	Experimental Set Up Details.....	161
6.3	Thermophysical Characterisation of the dielectric coolant.....	166
6.4	Uncertainty associated with the Experiment.....	169
6.5	Experimental Procedure.....	170
6.6	Results and Discussion.....	171

6.7 Conclusions.....	180
7. Conclusions and Future Scope.....	181
8. References.....	189
9. Appendices.....	203
10. Biodata.....	206
11. Publications.....	207

## List of figures

---

Figure 1.1. Showing Intercalation Mechanism in Lithium-Ion Battery.....	29
Figure 1.2. Analyzing the Influence of Temperature on the Performance and Safety of Lithium-Ion Batteries.....	30
Figure 1.3. Classification of BTMS.....	36
Figure 2.1. Schematic representation of a Air-based BTMS.....	41
Figure 2.2. Schematic showing an experimental setup for air-based BTMS for Aligned, Staggered, and Crossed battery packs .....	43
Figure 2.3. Schematic showing an Air Cooling-based BTMS .....	44
Figure 2.4. Schematic showing (a) Direct contact immersion, (b) Indirect contact cooling techniques for BTMS.....	45
Figure 2.5. Showing an experimental set-up for immersion cooling-based BTMS.....	47
Figure 2.6. Schematic of a mini channel-cooled cylinder-based liquid cooling .....	49
Figure 2.7. Schematic of PCM-based BTMS.....	50
Figure 2.8. Mechanisms of Thermal Regulation Using Phase Change Materials based .....	51
Figure 2.9. Schematic showing (a) BTMS with no PCM and Fins (b) With PCM (c) With both PCM and Fins.....	54
Figure 2.10. (a) Schematic showing the working of a heat pipe & (b) Basic Layout of Heat Pipe Based BTMS.....	55
Figure 2.11. Basic Layout of Air-PCM Hybrid BTMS.....	58
Figure 2.12. Schematic of Air PCM hybrid BTMS .....	61

Figure 2.13. Basic Layout of Liquid-PCM Hybrid BTMS.....	62
Figure 2.14. Schematic showing a delayed cooling strategy of Liquid PCM hybrid BTMS.....	66
Figure 2.15. Schematic showing a Liquid PCM hybrid BTMS.....	66
Figure 2.16. Showing a graphical representation of different BTMS techniques.....	67
Figure 3.1. Schematic of an Indirect contact-based liquid cooling system.....	75
Figure 3.2. Schematic showing MATLAB Simulink Model.....	76
Figure 3.3. Showing the working principle and methodology.....	77
Figure 3.4. (a): Speed Profile of Indian Drive Cycle, (b) Speed Profile of FTP-75 Drive Cycle.....	79
Figure 3.5. Schematic showing single RC Equivalent circuit model.....	83
Figure 3.6. Average Battery Temperature validation.....	87
Figure 3.7. Average battery pack temperature for the FTP-75 drive cycle for water as a coolant at various ambient temperatures.....	89
Figure 3.8. Average battery pack temperature for the IDC for water as a coolant at various ambient temperatures.....	90
Figure 3.9. Cumulative Energy Consumption by the battery cooling system for FTP-75 drive cycle for water as a coolant at various ambient temperatures.....	92
Figure 3.10. Cumulative Energy Consumption by the battery cooling system for IDC for water as a coolant at various ambient temperatures.....	93

Figure 4.1. Schematic Representation of an Indirect Contact Liquid Cooling Configuration for BTMS.....	97
Figure 4.2. Showing Methodology and Working Principle .....	100
Fig.4. 3. (a): Speed Profile of Indian Drive Cycle, (b): Speed Profile of FTP-75 Drive Cycle....	102
Figure 4.4. Showing a detailed electrothermal model .....	108
Figure 4.5. Schematic showing single RC Equivalent circuit model .....	109
Figure 4.6. Average battery temperature validation.....	111
Figure 4.7. Average battery pack temperature for FTP-75 drive cycle with Water-EG solution as a coolant at 40°C ambient temperature .....	113
Figure 4.8. Cumulative energy consumption by the BTMS for FTP-75 drive cycle for Water-EG solution as a coolant at 40°C ambient temperature.....	114
Figure 4.9. Average battery pack temperature of the battery pack for an IDC with Water-EG solution at 40°C ambient temperature .....	116
Figure 4.10. Cumulative Energy Consumption by the BTMS for IDC for Water-EG solution as a coolant at 40°C ambient temperature .....	117
Figure 4.11. Average battery pack temperature for FTP-75 drive cycle with Water-PG solution at 40 °C ambient temperature. ....	119
Figure 4.12. Cumulative Energy Consumption by the BTMS for FTP-75 drive cycle for Water-PG solution as a coolant at 40 °C ambient temperature .....	120

Figure 4.13. Average battery pack temperature for an IDC with Water-PG solution at 40°C ambient temperature .....	121
Figure 4.14. Cumulative Energy Consumption by the BTMS for the IDC for Water-PG solution as a coolant at 40 °C ambient temperatures .....	123
Figure 5.1. IIT Delhi Weather station for Continuous Measurement of Ambient Temperature and Relative Humidity.....	128
Figure 5.2. Optimal Operating Temperature Range for Lithium-Ion Batteries in Electric Vehicle Applications.....	129
Figure 5.3. Optimal Cabin Temperature Range for Thermal Comfort in Electric Vehicles.....	130
Figure 5.4. Showing MATLAB Simulink model .....	130
Figure 5.5. Speed profile for Indian Drive Cycle.....	133
Figure 5.6. Single RC equivalent circuit model.....	137
Figure 5.7. Showing Heat Transfer in Vehicle Cabin.....	139
Figure 5.8. Average battery temperature validation .....	142
Figure 5.9. Cabin Temperature and Average battery pack temperature at 25°C ambient temperature.....	144
Figure 5.10. Cabin temperature and Average battery pack temperature at 30°C ambient temperature .....	146

Figure 5.11. Cabin temperature and Average battery pack temperature at 35°C ambient temperature.....	147
Figure 5.12. Cabin temperature and average battery pack temperature at 40°C ambient temperature.....	149
Figure 5.13. Comparison of the time required to achieve the cabin set point temperature by the EV at various ambient temperatures.....	150
Figure 5.14. Maximum power demand by the integrated thermal management system at various ambient temperatures .....	151
Figure 5.15. Cabin temperature and average battery pack temperature at 60% RH.....	153
Figure 5.16. Cabin temperature and average battery pack temperature at 70% RH.....	154
Figure 5.17. Cabin temperature and average battery pack temperature at 80% RH.....	155
Figure 5.18. Cabin temperature and average battery pack temperature at 90% RH.....	155
Figure 5.19. Cabin temperature and average battery pack temperature at 100% RH .....	156
Figure 5.20. Maximum power demand by the integrated thermal management system at various relative humidity levels.....	157
Figure 6.1.(a). Showing the Battery Pack used in this study .....	163
Figure 6.1 (b). Showing the location of the Centre, Side, and Corner cells in the Battery Pack .....	164
Figure 6.2: - Showing Experimental Set-up for Immersion Cooling of LiB battery pack .....	164
Figure 6.3 (a): - Showing NI data logger .....	165

Figure 6.3 (b): - Showing thermocouple calibrator and K-type thermocouple .....	166
Figure 6.4: - Pictorial Image of a Differential Scanning Calorimeter (DSC).....	167
Figure 6.5: Pictorial Image of Thermal Conductivity Meter .....	168
Figure 6.6: - Showing Specific Heat vs Temperature plot of Dielectric Coolant .....	168
Figure 6.7. Showing Battery Temperature under Natural Air Convection .....	172
Figure 6.8. Showing Battery Temperature under Complete Immersion .....	174
Figure 6.9. Showing Battery Temperature under Partial Immersion (75% depth immersion).....	175
Figure 6.10. Showing Battery Temperature under Partial Immersion (50% depth immersion)..	176
Figure 6.11. Showing Battery Temperature under Partial Immersion (25% depth immersion)...	177
Figure 6.12. Demonstrating the maximum temperature variation in the battery pack under various cooling situations.....	179

## List of tables

---

Table 3.1. Various forces acting on the Vehicle.....	80
Table 3.2. Vehicle Parameter for the selected Electric Sedan.....	80
Table 3.3. Battery Pack Details and Cell Parameters.....	82
Table 4.1. Thermophysical properties of Water, Ethylene glycol, and propylene glycol at 20°C...99	
Table 5.1: Vehicle Parameters for the selected Electric Sedan in this study.....	133
Table 5.2 Technical Specifications of the Battery Pack used in this simulation.....	136
Table .5.3. Vehicle Cabin Subsystem Parameters.....	140
Table 6.1: Specification of DMEGC INR18650-26E Cell.....	162
Table 6.2. Specifications of the Battery Pack.....	163
Table 6.3. Specification of HP Transformer Oil .....	169
Table 6.4. Uncertainties Involved in the Experiment.....	170
Table 6.5. Test parameters for charging and discharging the battery pack.....	171

## Nomenclature

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### A. Acronyms

AC Air Conditioning

BTMS Battery thermal management system

EG Ethylene Glycol

ECM Equivalent Circuit Model

CCHS Channel Cooled Heat Sink

CFD Computational Fluid Dynamics

CF Copper Foam

CPCM Composite Phase Change Material

EG Ethylene Glycol

ECM Equivalent Circuit Model

ICE Internal Combustion Engine

IDC Indian Driving Cycle

LiB Lithium-Ion Battery

PCM Phase changing material

EV Electrical vehicle

SOC State of charge

## B. Symbols

$I$	Current (A)
$k_{bat}$	Thermal Conductivity of the battery material (W/m.K)
$h_{amb}$	Ambient convective heat transfer coefficient
$T$	Temperature ( $^{\circ}C$ )
$T_{ambient}$	Ambient Temperature ( $^{\circ}C$ )
$V$	Voltage(V)
$C_d$	Drag Coefficient
$F_{acc}$	Acceleration of Vehicles ( $m/sec^2$ )
$F_{ad}$	Aerodynamic Drag acting on the Vehicle (N)
$F_r$	Rolling Resistance on the Vehicle (N)
$F_g$	Uphill Resistance on the Vehicle (N)
$T_c$	Coolant Temperature
$h_{in}$	Convective heat transfer coefficient in the inside region
$Q_{overall}$	Overall Heat Exchange in the Cabin of the Vehicle
$U_{overall}$	Overall Heat Transfer Coefficient
$T_{batt}$	Battery Temperature ( $^{\circ}C$ )
$T_{cabin}$	Cabin Temperature( $^{\circ}C$ )
$k_b$	Thermal Conductivity of the vehicle cabin material
$R_{int}$	Internal Resistance