PERFORMANCE ENHANCEMENT OF AIR-COOLED BATTERY THERMAL MANAGEMENT SYSTEM

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Performance Enhancement of Air-cooled Battery Thermal Management System

by

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CERTIFICATE

This is to certify that the thesis titled **Performance Enhancement of Air-cooled Battery Thermal Management System**, submitted by **Mr. Faraz P Junaid**, 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 supervision and guidance 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 Institute or University for the award of any degree or diploma.

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ABSTRACT

This study presents a comprehensive investigation into the thermal behaviour and performance enhancement of air-cooled battery thermal management systems (BTMS) for lithium-ion batteries, with a focus on improving cooling effectiveness through passive geometric modifications. The work integrates literature analysis, experimental thermal characterisation, heat generation modelling, and both experimental and numerical investigations to establish a coherent framework for efficient air-cooled BTMS design.

The literature review identifies key limitations of conventional air-cooled systems, particularly their relatively low heat removal capability and poor temperature uniformity, with reported temperature differences often exceeding 5 °C in compact battery configurations. It further highlights gaps in the integration of accurate heat generation data with airflow design and the lack of experimentally validated airflow optimisation strategies.

To address these gaps, experimental characterisation of lithium-ion cells is performed to determine critical thermophysical properties. The specific heat capacity of the LFP cell is experimentally obtained in the range of approximately 900-1100 $J \cdot kg^{-1} \cdot K^{-1}$, with observable variation across different states of charge. A modified oil-bath calorimetry approach is developed to minimise heat loss, improving measurement reliability. In addition, the heat generation behaviour of the cell is analysed under different discharge rates (1C and 1.5C), showing a significant increase in temperature rise with increasing current, with peak temperature differences of the order of 6-10 °C depending on operating conditions. Based on these observations, an experimentally validated heat generation model is developed, demonstrating close agreement with measured temperature profiles, with deviations typically within ±1-2 °C.

An experimental investigation is conducted to evaluate the effect of a converging airflow passage on cooling performance. The results show that increasing airflow rate from 1.44 m^3/h to 5.76 m^3/h significantly reduces the average cell temperature, with reductions of approximately 2-3 °C observed across test cases. The introduction of a converging passage enhances local airflow velocity and convective heat transfer, resulting in improved temperature uniformity along the cell surface. The convective heat transfer coefficient increases substantially with flow rate, indicating enhanced cooling effectiveness.

A detailed numerical model is developed to analyse airflow and heat transfer at the cell level, incorporating experimentally derived thermal parameters. The model is validated against experimental data, showing good agreement with temperature deviations within ±2 °C. Numerical results indicate that the converging airflow configuration increases the local convective heat transfer coefficient by up to 20-30% compared to a uniform channel. Furthermore, the introduction of flow modifiers and optimised spacing reduces the average cell temperature and maximum temperature difference (ΔT_{max}) by up to 15-25%, depending on inlet velocity and geometric configuration.

Overall, this work demonstrates that passive geometric modifications, particularly converging airflow passages, can significantly enhance the performance of air-cooled BTMS. By establishing a strong linkage between experimental characterisation, heat generation modelling, and airflow design, the study provides practical insights for developing cost-effective and scalable thermal management solutions for lithium-ion battery systems. The findings are particularly relevant for battery energy storage applications, where simplicity, reliability, and thermal uniformity are critical design considerations.

Keywords: BTMS; Air-cooled; Lithium-ion battery; LFP; Heat generation modelling; Converging air-flow channel; Temperature uniformity.

सारांश

यह अध्ययन लिथियम-आयन बैटरियों के लिए वायु-शीतित बैटरी थर्मल प्रबंधन प्रणालियों (BTMS) के तापीय व्यवहार और प्रदर्शन सुधार का एक व्यापक विश्लेषण प्रस्तुत करता है, जिसमें विशेष रूप से निष्क्रिय ज्यामितीय संशोधनों के माध्यम से शीतलन दक्षता बढ़ाने पर ध्यान केंद्रित किया गया है। इस कार्य में साहित्य विश्लेषण, प्रायोगिक तापीय लक्षण-वर्णन, ऊष्मा उत्पादन मॉडलिंग, तथा प्रायोगिक और संख्यात्मक दोनों प्रकार के विश्लेषणों को एकीकृत करते हुए एक प्रभावी वायु-शीतित BTMS डिजाइन के लिए एक समग्र रूपरेखा स्थापित की गई है।

साहित्य समीक्षा से पारंपरिक वायु-शीतित प्रणालियों की प्रमुख सीमाएँ सामने आती हैं, विशेष रूप से उनकी अपेक्षाकृत कम ऊष्मा निष्कासन क्षमता और खराब तापमान समानता, जहाँ संकुचित बैटरी विन्यासों में तापमान अंतर प्रायः 5 °C से अधिक पाया गया है। इसके अतिरिक्त, यह समीक्षा ऊष्मा उत्पादन डेटा और वायु प्रवाह डिजाइन के बीच समुचित समन्वय की कमी तथा वायु प्रवाह अनुकूलन रणनीतियों के प्रायोगिक सत्यापन के अभाव को भी उजागर करती है।

इन कमियों को दूर करने के लिए, लिथियम-आयन सेल का प्रायोगिक लक्षण-वर्णन किया गया, जिससे महत्वपूर्ण ऊष्मीय गुणों का निर्धारण किया जा सके। LFP सेल की विशिष्ट ऊष्मा क्षमता लगभग 900-1100 $J \cdot kg^{-1} \cdot K^{-1}$ के दायरे में प्राप्त हुई, जिसमें विभिन्न स्टेट ऑफ चार्ज पर परिवर्तन देखा गया। ऊष्मा हानि को न्यूनतम करने हेतु एक संशोधित तेल-स्नान कैलोरीमेट्री विधि विकसित की गई, जिससे मापन की विश्वसनीयता में सुधार हुआ। इसके अतिरिक्त, विभिन्न डिस्चार्ज दरों (1C और 1.5C) पर ऊष्मा उत्पादन व्यवहार का अध्ययन किया गया, जिसमें धारा बढ़ने के साथ तापमान वृद्धि में उल्लेखनीय वृद्धि देखी गई, तथा अधिकतम तापमान अंतर लगभग 6-10 °C पाया गया। इन अवलोकनों के आधार पर एक प्रायोगिक रूप से सत्यापित ऊष्मा उत्पादन मॉडल विकसित किया गया, जो मापे गए तापमान प्रोफाइल से अच्छी संगति दर्शाता है, जिसमें विचलन सामान्यतः ±1-2 °C के भीतर रहा।

शीतलन प्रदर्शन पर अभिसारी वायु मार्ग के प्रभाव का मूल्यांकन करने हेतु एक प्रायोगिक अध्ययन किया गया। परिणामों से यह स्पष्ट हुआ कि वायु प्रवाह दर को 1.44 m^3/h से 5.76 m^3/h तक बढ़ाने पर औसत सेल तापमान में उल्लेखनीय कमी आती है, जहाँ विभिन्न परीक्षणों में लगभग 2-3 °C तक तापमान में कमी देखी गई। अभिसारी मार्ग के उपयोग से स्थानीय वायु वेग और संवहन ऊष्मा स्थानांतरण में वृद्धि होती है, जिससे सेल सतह पर तापमान वितरण अधिक समान हो जाता है। संवहन ऊष्मा स्थानांतरण गुणांक में भी प्रवाह दर के साथ महत्वपूर्ण वृद्धि देखी गई, जो बेहतर शीतलन क्षमता को दर्शाती है।

सेल स्तर पर वायु प्रवाह और ऊष्मा स्थानांतरण का विश्लेषण करने के लिए एक विस्तृत संख्यात्मक मॉडल विकसित किया गया, जिसमें प्रायोगिक रूप से प्राप्त ऊष्मीय गुणों को शामिल किया गया। इस मॉडल का प्रायोगिक डेटा के साथ सत्यापन किया गया, जिसमें तापमान विचलन ±2 °C के भीतर पाया गया। संख्यात्मक परिणामों से यह ज्ञात हुआ कि अभिसारी वायु प्रवाह विन्यास, समान चैनल की तुलना में स्थानीय संवहन ऊष्मा स्थानांतरण गुणांक को लगभग 20-30% तक बढ़ा देता है। इसके अतिरिक्त, प्रवाह संशोधकों और अनुकूलित स्पेसिंग के उपयोग से औसत सेल तापमान और अधिकतम तापमान अंतर (ΔT_{max}) में लगभग 15-25% तक कमी प्राप्त हुई, जो प्रवाह वेग और ज्यामितीय विन्यास पर निर्भर करती है।

समग्र रूप से, यह कार्य दर्शाता है कि निष्क्रिय ज्यामितीय संशोधन, विशेष रूप से अभिसारी वायु मार्ग, वायु-शीतित BTMS के प्रदर्शन को महत्वपूर्ण रूप से सुधार सकते हैं। प्रायोगिक लक्षण-वर्णन, ऊष्मा उत्पादन मॉडलिंग, और वायु प्रवाह डिजाइन के बीच मजबूत संबंध स्थापित करते हुए, यह अध्ययन लिथियम-आयन बैटरी प्रणालियों के लिए किफायती और स्केलेबल तापीय प्रबंधन समाधानों के विकास हेतु व्यावहारिक अंतर्दृष्टि प्रदान करता है। यह निष्कर्ष विशेष रूप से बैटरी ऊर्जा भंडारण प्रणालियों के लिए महत्वपूर्ण हैं, जहाँ सरलता, विश्वसनीयता और तापमान समानता प्रमुख डिजाइन आवश्यकताएँ होती हैं।

मुख्य शब्द (कीवर्ड): (BTMS); वायु-शीतित; लिथियम-आयन बैटरी; लिथियम आयरन फॉस्फेट (LFP); ऊष्मा उत्पन्न मॉडलिंग; अभिसारी वायु-प्रवाह चैनल; तापमान समानता।

Contents

			Page No
		CERTIFICATE	i
		ACKNOWLEDGEMENT	iii
		ABSTRACT	v
		List of Figures	xiii
		List of Tables	Xvii
		List of Abbreviations	xiviii
1		Introduction	1
	1.1.	Background	1
	1.2.	Overview of Lithium-ion Cell	2
	1.3.	Heat Generation in Lithium-ion Cells	7
	1.4.	Organisation of Thesis	10
2		Literature Review	13
	2.1.	Introduction	13
	2.2.	Battery Thermal Management Systems	16
	2.3.	Heat Generation in Lithium-ion Cells	29
	2.4.	Conclusions from Literature Review	35
	2.5.	Objectives	37
3		Cell-level Numerical Analysis of an Air-cooled BTMS with Converging Passage	39
	3.1.	Preface	39
	3.2.	Methodology	39
	3.3.	Solution Procedure	51
	3.4.	Results and Discussion	52
	3.5.	Conclusions	63
4		Cell Characterisation Studies	65
	4.1.	Preface	65
	4.2.	Specific Heat Capacity Measurement	67
	4.3.	Thermal Conductivity Measurement	76
	4.4.	Cell Heat Generation Modelling	78

	4.5	Conclusions	94
5		Experimental Demonstration of Cooling Performance Enhancement with Converging Air Passage	95
	5.1.	Preface	95
	5.2.	Experimental Setup	96
	5.3.	Experimental Procedure	101
	5.4.	Results and Discussion	102
	5.5.	Closure	111
6		Performance Enhancement of T-type Air-cooled BTMS with Converging Air Passages	113
	6.1.	Preface	113
	6.2.	Physical Domain	114
	6.3.	Numerical Model	116
	6.4.	Results and Discussion	118
	6.5.	Conclusions	124
7		Conclusions and Scope of Future Work	126
	7.1.	Preface	126
	7.2.	Major Outcomes	127
	7.3.	Scope for Future Work	128

List of Figures

Figure Number	Description	Page No.
Figure 1.1.	Schematic showing the flow of electrons and lithium ions during the discharging and charging of a lithium-ion cell	3
Figure 3.1.	Schematic showing the arrangement of flow modifier in the channel formed by adjacent batteries and (b) Schematic showing the front view of the domain (c) Schematic showing the domain considered for numerical analysis	41
Figure 3.2.	Isometric view of the generated mesh showing an enlarged view of the inflation layer for Case B	44
Figure 3.3.	Grid independence study for Case B with 3 m/s inlet velocity	44
Figure 3.4.	Time independence study for Case B with inlet 3 m/s velocity	45
Figure 3.5.	Battery temperature variation with time during discharge	47
Figure 3.6.	Validation results for the heat generation model	50
Figure 3.7.	Validation of the numerical model with experimental data from Zhang et al.	51
Figure 3.8.	Velocity contour at the mid-plane of the air channel for (a) Case A and (b) Case B with 2 m/s inlet velocity	53
Figure 3.9.	Average temperature variation with time for various flow velocities	55
Figure 3.10.	Graph showing the reduction in T_{avg} with the introduction of flow modifier at different battery spacings	56
Figure 3.11.	Variation of convective heat transfer coefficient along the centreline of the battery surface for Cases A and B with 2 m/s inlet velocity	56
Figure 3.12.	Variation in T_{avg} at the end of discharge with battery spacing for different inlet velocities for cases without the flow modifier	57
Figure 3.13.	Variation of convective heat transfer coefficient and temperature differential across air and battery along the centreline of the battery surface for 0.5 m/s inlet velocity	59

Figure 3.14.	Variation in average temperature (T_{avg}) at the end of discharge with battery spacing for different inlet velocities for cases with the flow modifier	60
Figure 3.15.	Variation of convective heat transfer coefficient and temperature difference between air and battery along the centreline of the battery surface for 0.5 m/s inlet velocity with the flow modifier	61
Figure 3.16.	Variation in ΔT_{max} with the introduction of the flow modifier for different battery spacings and inlet velocities	62
Figure 3.17.	Variation in ΔT_{max} with inlet velocity for the cases with the flow modifier	63
Figure 4.1.	Flowchart depicting the experimental methodology followed for determining the specific heat capacity of the cell	68
Figure 4.2.	Photographic view of a) Oil filled in the adiabatic container, b) Adiabatic container kept inside the climate chamber, c) Oil used for the calorimetry experiment, d) Cell and aluminium bar used for the experiment	69
Figure 4.3.	Schematic representation of the experimental layout for the specific heat capacity determination of the LFP cell	69
Figure 4.4.	a) DSC Q2000 equipment b) Variation in specific heat capacity of the lubricating oil with temperature	70
Figure 4.5.	The temperature profile over time for the cases run with (a) Aluminium, (b) Cell at 0% SOC, (c) Cell at 50% SOC, (d) Cell at 100% SOC, before it equalises	71
Figure 4.6.	Variation in specific heat with state of charge of the cell	72
Figure 4.7.	a) Photograph, b) schematic, and c) equivalent circuit of the thermoelectric sensor	76
Figure 4.8.	Flowchart illustrating the methodology followed for cell heat generation determination	77
Figure 4.9.	Photographic view of a) Bottom section of the adiabatic casing, b) Top section of the adiabatic casing with the cell kept in the slot, oriented upside down and c) Polyurethane foam used	78
Figure 4.10.	Schematic showing the location of thermocouple attachment on the lateral side of the cell	79

Figure 4.11.	Photographic view of the a) Adiabatic casing with thermocouples attached to it, b) Adiabatic casing inside the climate chamber, c) Neware BRS 4000 module tester, and d) Keysight DAQ973A data acquisition system	81
Figure 4.12.	Schematic diagram illustrating the layout of the experiment conducted to model the heat generation of the cell	81
Figure 4.13.	Graph showing the variation in cell temperature with depth of discharge with a) 1C discharge current, and b) 1.5C discharge current	83
Figure 4.14.	Layout of the setup for the validation experiment	87
Figure 4.15.	Comparison of experimental and simulated cell surface temperature profiles during discharge at 1C rate with a) 25 °C, and b) 35 °C ambient conditions	91
Figure 4.16.	Comparison of experimental and simulated cell surface temperature profiles during discharge at 1.5C rate with a) 25 °C, and b) 35 °C ambient conditions	92
Figure 5.1.	Schematic of the experimental facility	96
Figure 5.2.	Photograph of the centrifugal blower and the three-way valve	97
Figure 5.3.	Photograph of the turbine flowmeter used	98
Figure 5.4.	Photographic view of the ducts and the test section	99
Figure 5.5.	Photographic view of the test sections with the cell and the thermocouples attached	99
Figure 5.6.	Photographic view of the experimental setup	101
Figure 5.7.	Average cell surface temperature variation with time for the three trials under similar conditions with the converging test section.	103
Figure 5.8.	Variation in cell surface average temperature with a) 1.44 m^3/h flow rate, b) 2.88 m^3/h flow rate, and c) 5.76 m^3/h flow rate	105
Figure 5.9.	Variation in the average convective heat transfer coefficient on the cell surface with a) 1.44 m^3/h flow rate, b) 2.88 m^3/h flow rate, and c) 5.76 m^3/h flow rate	108
Figure 5.10.	Temperature variation along the centreline of the cell surface with a) 1.44 m^3/h flow rate, b) 2.88 m^3/h flow rate, and c) 5.76 m^3/h flow rate	111

Figure 6.1.	Schematic of convention T-type BTMS proposed by Zhang et al.	114
Figure 6.2.	Schematic of the modified T-type BTMS with converging air passage	115
Figure 6.3.	Validation of the numerical model with experimental results	119
Figure 6.4.	Contour showing the variation of temperature for a) conventional T-type BTMS, b) with modified T-type BTMS for the case with 1 m/s inlet velocity	120
Figure 6.5.	Variation in maximum cell temperature with convergence ratio	121
Figure 6.6.	Variation of maximum temperature difference with convergence ratio	122
Figure 6.7.	Variation of pressure drop with convergence ratio	123

List of Tables

Figure Number	Description	Page Number
Table 3.1.	Details regarding the domains considered for analysis	42
Table 3.2.	Grid information for the different domain configurations	44
Table 3.3.	Coefficients of the polynomial equation for battery temperature (Equation 5.10)	49
Table 3.4.	Coefficients of the polynomial equation for equivalent resistance. (Equation 5.13)	50
Table 3.5.	Specifications of the battery	50
Table 3.6.	Pressure drop across the flow passage for the different cases analysed	54
Table 4.1.	Calculated values of specific heat capacities for the different cases	72
Table 4.2.	Reported values of specific heat capacity of LFP cells	73
Table 4.3.	Coefficients of the polynomial equation for temperature variation with time during discharge at 1C discharge rate (Equation 3.9)	84
Table 4.4.	Coefficients of the polynomial equation for temperature variation with time during discharge at 1.5C discharge rate (Equation 3.9)	84
Table 4.5.	Values of a_{ij} in equation 3.12 for 1C discharge rate condition	86
Table 4.6.	Values of a_{ij} in equation 3.12 for 1.5C discharge rate condition	86
Table 4.7.	Coefficients of the polynomial equation for convective heat transfer coefficient (Equation 3.14)	89
Table 4.8.	Cell parameters used in the simulation	89

List of Abbreviations

Abbreviation	
ARC	Accelerating rate calorimeter
BESS	Battery energy storage system
BMS	Battery management system
BTMS	Battery thermal management system
CFD	Computational fluid dynamics
CR	Convergence ratio
DoD	Depth of discharge
DSC	Differential scanning calorimetry
ECM	Equivalent circuit model
EIS	Electrochemical Impedance Spectroscopy
EV	Electric vehicle
GCI	Grid convergence index
GHG	Greenhouse gas
LFP	Lithium iron phosphate
OCV	Open cell voltage
PCM	Phase change material
PUF	Poly urethane foam
SEI	Solid Electrolyte Interphase
SHC	Specific heat capacity
SoC	State of charge
SST	Shear stress transport
THB	Transient hot bridge
THW	Transient hot wire