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THERMAL MANAGEMENT OF BATTERY SYSTEMS IN ELECTRIC VEHICLE AND SMART GRID APPLICATION

BY

MOHAMMAD REZWAN KHAN

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AALBORG UNIVERSITY
DENMARK

THERMAL MANAGEMENT OF BATTERY SYSTEMS IN ELECTRIC VEHICLE AND SMART GRID APPLICATION

by

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AALBORG UNIVERSITY
DENMARK

Dissertation submitted

.

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Dedication

To my beloved mother …

Who inspires me by her countless sacrifice,

unrequited love and unconditional support

that shapes up my life.

CV

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Educational Qualifications

Degree	Year	University	Title
Doctor of Philosophy	2013-2016	Aalborg University (AAU), Denmark	Thermal Management of Battery Systems in Electric Vehicle and Smart Grid Application
Master of Science	2008-2010	Università di Bologna (UNIBO), Italy.	Materials and Sensors Systems for Environmental Technologies (Erasmus Mundus)
Bachelor of Science	2003-2008	Bangladesh University of Engineering & Technology (BUET), Bangladesh.	Electrical & Electronic Engineering

Awards/Honour

- Received the research grant from the Strategic Research Council of Denmark for PhD study from 2013-2016.
- Research assistantship sponsored by Flemish Institute for Technological Research (VITO) and Free University of Brussels (VUB) for 2011-13.
- Received the Erasmus Mundus scholarship provided by the European Union for Polytechnic University of Valencia (UPV) and University of Bologna (UNIBO) for the academic year 2008-2010.
- Technical scholarship, Dean List, Merit and Compensatory scholarship: The scholarships were given by Bangladesh government and Bangladesh University of Engineering & Technology (BUET) from 2003-2008.

Outreach and Organizational Experience

- Co-chairman of the plenary session Modelling and Control of Energy Systems I in the 55th International Conference on Simulation and Modelling, Aalborg, Denmark, 2014.
- Youth Goodwill Ambassador of Denmark (YGWA, ygadenmark.org) -- Branding Denmark, International talent recruitment, Social Coordination (2014-2016).
- Volunteered as an International Buddy at Aalborg University to act as a contact person and helps a foreign student in the first days, weeks or months at Aalborg University. (2014-2016).
- Representative for the Erasmus Mundus alumni program, which is led by the European Union, at the Polytechnic University of Madrid during (2010-11).

ENGLISH SUMMARY

Last few years' governments are tightening the carbon emission regulations. Moreover, the availability of different financial assistances is available to cut the market share of the fossil fuel vehicles. Conversely, to fill up the gap of the required demand, higher penetration of electrical vehicles is foreseen. The future battery manufacturers strive to meet the ever growing requirement of consumer's demand using the battery as a primary power source of these cars. So naturally, the growing popularity of battery electric and hybrid vehicles have catapulted the car industry in the recent years. The products include for instance: hybrids, plug-in hybrids, battery and fuel-cell-battery electric vehicles (EV) and so forth. Undeniably, the battery is one of the most significant parts in all of those. Furthermore, stationary storage is another aspect of an emerging field. It represents next generation smart grids, for instance, photovoltaic (PV) with battery users. Additionally, the stakeholders in the energy sector are anticipating higher market share of the battery system as different battery powered system is penetrating into the consumer market. Currently, there is a revolution going on the power-system domain. The dumb grids are turning into a smart grid that contains computer intelligence and networking abilities to accommodate dispersed renewable generations (e.g. solar, wind power, geothermal, wave energy and so forth). The battery takes a primary role both as stationary and transportable source of energy in these cases. The phenomenon demonstrates economic and environmental benefits. It changes the fundamental structure of the paradigm of the status quo of the energy system with battery. So battery driven applications have been taken onto the centre stage in the current world.

However, while the expanding battery market is alluring, the performance, safety, and security of the EV more specifically battery related thermal management – particularly is a barrier to mass deployment. This represents a non-trivial challenge for the battery suppliers, EV manufacturers, and smart grid developers. The industry is under intense pressure to enhance the performance of the battery. The industry is seeking for a suitable indicator to select the optimum battery showing the accurate efficiency level. It helps to bring products with an optimum efficiency. Furthermore, it assists them to produce tailored product with appropriate efficiency to meet the consumer demand. Moreover, the battery system users can benefit from the better pricing of the system that can provide the desired amount of efficiency. So there may be successful battery product with a higher level of adoption.Ultimately, it helps industrial battery users for example automakers to achieve a higher level of profitability.

The performance degradation of large battery packs is influenced significantly by the thermal conditions, i.e. the temperature gradients over the pack. One of the main focus of this PhD project is to develop an advanced simulation model framework. It is a multiphysics model to solve the challenge. It couples' fluid flow and heat transfer both in cell and pack level which is accompanied by the precision experimental data as

measured using isothermal calorimetric techniques. The model is used to study the local temperature distribution in the battery cell and pack with cooling fluid air. The predicted temperature distributions are found to foresee cell thermal behaviour and performance parameters. The aim is to illustrate heat removal problems resulting from non-uniform cell-to-cell performance variations.

The principal outcome of the PhD research is to deliver experimental and modelling framework targeted for both EV and next-generation smart grid application developer. The results of the research assist in providing a correct datasheet for a battery cell. It is a result of an experimental framework that is comprised of systematic performance assessment methodology. The method is generic, so it applies to all Li-ion battery cell with necessary adaptation. The research aspires to answer whether the ultimate optimal battery selection from different options is achievable or not. To accomplish the goal, both experimentation and modelling approach are employed—each one represents distinct benefits with relative advantages. This is largely possible as an advanced multiphysics modelling method is used. It is complemented by meticulous measurements using the unique isothermal calorimetric technique. Using the developed methodology, it enables to determine how the current input affects the heat flux generation inside a battery cell and how it is possible to find the key performance indicator (KPI) efficiency. That is a key question because, through precise heat generation measurement, determination of the real loss level inside the battery is possible. Consequently, using the electrical power input of the battery and the heat flux generation (represents the precise measurement of the loss incurred inside the battery cell) the exact efficiency is found. Particularly, the expertise on the isothermal calorimeter is the significant enabler to determine the performance indicators (efficiency and heat generation). This fact positions the research in a unique place in the competitive battery system testing field. Using the results, a full battery performance database is possible to build using different battery cells in various ageing and operational level.

Additionally, in the research, the physics-based three-dimensional thermal models are developed. The models are required to describe the thermodynamic behaviour of the cell. In turn, this can help to understand the correlation between the heat generation of the battery, and to determine the best operating limits of the cells. So apparently, the purpose of the presented study defines the physics-dependent effective thermal behaviours of both single battery cell as well as for battery cells in a pack structure (similar specification is stipulated for both cell and pack research). The result is demonstrated for a selected and specific electrochemical lithium titanate oxide (LTO) commercial battery.

Methodology and lessons learned on BTMS modelling and experimentation are documented to convey the result to the thermal management designer communities. The framework of the research sets the foundation for the thermal system of battery systems. The designed framework is applicable for diverse applications. Consequently, it offers assistance to support in evolving a robust BTMS.

DANSK RESUME

De senere år har regeringer rundt om i verden indført stadigt strammere regler for udledning af kuldioxid. Der ud over indføres forskellige økonomiske incitamenter for at reducere andelen af køretøjer drevet af fossile brændstoffer. For at dække dette stigende behov forudses en stigende andel af elektriske biler og batterier vil spille en væsentlig rolle som energikilde i disse biler. Den voksende popularitet af batteri og hybridbiler har drevet bilindustrien i de seneste år. Produkterne omfatter hybridbiler, plug-in hybrider, batteribiler og brændselscelle-batteri hybrider. Batteribilen er uden tvivl en af de væsentligste af disse. Ydermere, stationær energilagring er et andet fremtidigt anvendelsesområde for batterier. Det udgør næste generation smart grids for eksempel solceller med batterilager. Interessenter i energisektoren retter deres opmærksomhed mod batterisystemer i takt med de introduceres på markedet. På nuværende tidspunkt revolutioneres energiforsyningen. Forsyningsnettet omstilles til et smart grid der indeholder intelligens og internet tilslutning for at muliggøre tilslutning af vedvarende energikilder (sol, vind, geotermi, bølgeenergi og så videre). Batteriet opfylder en nøglerolle både som stationær og mobil energikilde i disse sammenhænge. Denne udvikling medfører økonomiske og miljømæssige fordele, der grundlæggende ændrer den tidligere status quo. Batteridrevne applicationer er taget en central plads på scenen i nutidens samfund.

På trods af at det voksende batterimarket er dragende så er ydelse, sikkerhed af batterielektriske biler – mere specifikt den termiske management – en barriere for storskala udrulning. Det udgør en ikke triviel udfordring for batterileverandører, producenter af elbiler and smart grid udviklere. Der er stort pres på branchen for at forbedre batteriernes ydelse. Industrien leder efter en passende indikator til at udvælge det optimale batteri der giver et præcist billede af batteriets ydelse. Det vil hjælpe til at udvikle produkter med optimal effektivitet. Ydermere, det hjælper til at udvikle forbruger tilpassede løsninger med passende effektivitet. Der ud over vil brugerne af batterisystemer nyde godt af en lavere prissætning af et system som kan levere den ønskede effektivitet. Ultimativt vil det hjælpe industrielle batteribrugere som for eksempel bilproducenter til at opnå højere profitibiliet.

Degraderingen af store batteripakkers ydelse påvirkes væsentligt af de termiske forhold, det vil sige temperatur-gradienter over pakken. Et af de primære fokuspunkter i dette PhD projekt er udvikling af et avanceret simuleringsværktøj. Det er en multifysisk model, som kobler fluid strømning og varmetransport både på celle- og pakkeniveau. Dette suppleres af præcise eksperimentelle data målt med et isotermt kalorimeter. Modellen anvendes til at undersøge den lokale temperaturfordeling i battericellen og pakken med luft som kølemedie. De beregnede temperatur fordelinger er vist at kunne forudse den termiske opførsel og ydelse af batteriet. Målet er at vise problemer relateret til køling resulterende fra forskelle i ydelse med individuelle celler.

Det væsentligste resultat af PhD forskningen er et eksperimentelt og numerisk grundlæg målrettet mod udviklere af både elbiler og næste generation af smart grids. Resultatet af PhD projektet medvirker til at tilvejebringe et retvisende datablad for battericeller. Det er resultatet af et eksperimentelt grundlag der udgøres af en metode til systematiske bestemmelse af ydelsen. Metoden er generisk så den kan tilpasses anvendelse på alle lithium-ion battericeller. Forskningen forsøger at belyse om en optimal udvælgelse af batteritype er opnåeligt eller ej. For at opnå målet anvendes både eksperimentelle undersøgelser og modellering – hver især har de to metoder deres fordele og ulemper. Dette er langt hen ad vejen muligt fordi der anvendes en avanceret multifysisks modelleringsmetode. Det komplimenteres med grundige målinger med en enestående isotermisk kalorimeter teknik. Ved at anvende den udviklede teknik er det muligt at forudsige hvordan strømstyrken påvirker varmeproduktion inden i batteriet og det er muligt at finde en key performance indicator (KPI) effektivitet. Dette er et afgørende skridt fordi den reelle varmeproduktion i batteriet kan findes ved hjælp af præcise målinger. Som resultat kan den præcise effektivitet findes ud fra den elektriske strøm og varmeproduktionen, som repræsenterer det interne tab i batteriet. Specielt ekspertisen omkring det isotermiske kalorimeter udgør en betydelig faktor i forhold til bestemmelse af key performance indikatorer (effektivitet og varmeproduktion). Dette forhold positionerer forskningen unikt i det konkurrenceprægede område omkring test af batterisystemer. Ved af anvende resultaterne kan der opbygges en komplet database med batteriydelse for forskellige battericeller i forskellige stadier af levetid og driftforhold.

Der ud over er der udviklet en fysisk-baseret tredimensionel termisk model. Modellen anvendes til at beskrive den termiske opførsel af battericellen. Dette kan bruges til at forstå koblingen mellem varmeproduktion i cellen og den termiske opførsel og der med forudsige de driftsmæssige grænser for cellen. Den udviklede model og procedure kan anvendes til at forudsige den fysikafhængige resulterende termiske opførsel af såvel enkeltceller som hele batteripakker med den samme grundlæggende beskrivelse. Resultatet er eftervist for et specifikt kommercielt tilgængeligt lithium titanate oxide (LTO) batteri.

Metoder og erfaringer med modellering og eksperimenter relateret til termisk management systemer er dokumenteret for at formidle resultaterne til udviklere inden for branchen. Resultaterne fra forskningen er med til at udbygge fundamentet for termiske management af batterisystemer. Den udviklede metode kan udnyttes inden for forskellige anvendelser og som resultat medvirke til udvikling af robuste batterisystemer.

ACKNOWLEDGEMENTS

This PhD dissertation is based on the research that I have performed at the Department of Energy Technology (ET), Aalborg University (AAU), funded by the Danish Strategic Research Council (Danish Innovation Foundation), Denmark under the project "*Advanced Lifetime Predictions of Battery Energy Storage (ALPBES)*".

As I have grown older, I have realised whatever good has happened in my life has more to do with the blessings, inspiration and help of others than my action. Taking the opportunity, I would like to express my sincere gratitude to all those who spent time, energy, and effort in support of the project. During last three years, I meet numerous people who contributed to the research.By this way, the research has been benefitted from their scientific knowledge, friendship and guidance. Therefore, I wish to offer my sincere gratitude to all of them without whom this PhD project would hardly reach its goal. Because if it were not for them, I am not sure I would have made it through. Whatever I have accomplished during my time here, which admittedly is not much, it is largely because of them. Moreover, frankly, the most precious thing, that I am taking away from this sweet little city Aalborg, is not a degree nor professional training, but the friendships I have had the honour and privilege of sharing with the fantastic people. Those include the old university mates and new found (and newborn) friends, sports partners, language learning folks, lab mates of different ages and nationalities. It is a credit to them that they were able to bring out the best in me, and for that, I'll always be grateful to them. It truly has been a blast.

Many thanks are due to many of my colleagues at ET who always, in different capacities, provided me with insights and supports, I have never felt alone being inside the group that is made up of individuals from different nationalities and cultures. A true international ambience in its best!

Thanks to all the colleagues with whom I have shared my office during the whole PhD life. I would like to thank all of those lovely roommates. Those have always been ready to help whenever I asked.

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My research group has actively contributed to my research. I am grateful for their support either in reviewing articles or providing me with useful feedback during my presentation in front of them. I benefit greatly from their guidance, criticism and constructive comments during my research period.

I thank my supervisor, Søren Knudsen Kær, for his exceptionally thoughtful and inquisitive advice and guidance. I feel without those I would have been de-focused of the research goal, so there was a chance of eventual fail. He inspires me to rethink options more deeply and thoroughly. I have a great pleasure to pursue the PhD under him.

Last, but not least, I must acknowledge the contribution of my family members (Hridi, Nusrat, Israt, Reaz), friends and relatives from my home country. Several years ago I left my home country in the search for a better opportunity than anyone in my family had had because they made it possible for me. Both in Europe and at home, they have been the driving force behind my work. My teachers, relatives and friends played a big part too. Moreover, though I may have never thanked them individually, I will always owe a debt of gratitude towards them. They have been supporting for the entire period of the PhD. Their love and cooperation always inspired me to move ahead. Without their support, I could not complete my work in Aalborg University, Denmark. They encouraged me every day by the phone or video call conversation from Bangladesh. I am inspired by their sacrifices. Their blessings are the driving forces for moving forward for the future.

Special thanks to my mother who was always ready to talk with me when I need it most.

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Google Scholar: https://scholar.google.dk/citations?user=DDIYODgAAAAJ&hl=en

Published and Accepted papers and articles

Publications in Journal

[1] F. Deng, Z. Chen, **M. R. Khan**, and R. Zhu, "*Fault Detection and Localization Method for Modular Multilevel Converters*" **IEEE Transactions on Power Electronics**, 15 August 2014.

[2] **M. R. Khan**, G. Mulder, and J. Van Mierlo, "*An online framework for state of charge determination of battery systems using combined system identification approach*," **Journal of Power Sources**, vol. 246, pp. 629-641, Jan 15 2014.

[3] M. Swierczynski, D. I. Stroe, **M. R. Khan**, S. K. Kær, and R. Teodorescu, "*Investigation of Multidimensional Electrothermal Impedance Spectroscopy Measurement on Lithium Ion Battery Cell*," **ECS Transactions**, vol. 70, pp. 305-310, December 3, 2015 2015.

Publications in Conference/Symposium proceedings[1]

[4] **M. R. Khan** and S. K. Kær, "*Investigation of Battery Heat Generation and Key Performance Indicator Efficiency using Isothermal Calorimeter* " in The 13th IEEE Vehicle Power and Propulsion Conference (**VPPC16**), Hangzhou.China, 2016.

[5] **M. R. Khan** and S. K. Kær, "*Three Dimensional Thermal Modeling of Li-Ion Battery Pack based on Multiphysics and Calorimetric Measurement*," in The 13th IEEE Vehicle Power and Propulsion Conference (**VPPC16**), Hangzhou, China, 2016.

[6] **M. R. Khan** and S. K. Kær, "*Multiphysics Based Thermal Modeling of a Pouch Lithium-Ion Battery Cell for the Development of Pack Level Thermal Management System*," in Eleventh International Conference on Ecological Vehicles and Renewable Energies (**EVER16**) Grimaldi Forum, Monaco, 2016.

[7] **M. R. Khan**, M. J. Swierczynski, and S. K. Kær, "Determination of the Behavior and Performance of Commercial Li-Ion Pouch Cells by the means of Isothermal Calorimeter," in Eleventh International Conference on Ecological Vehicles and Renewable Energies (**EVER16**), Grimaldi Forum, Monaco, 2016.

[1] Publication [4-7] has an opportunity to be included as an automatic entry for resubmission to the special section of the IEEE Transactions on Vehicular Technology.

[8] **M. R. Khan**, G. Mulder, J. Van Mierlo, and S. K. Kær, "*The Integration and Control of Multifunctional Stationary PV-Battery Systems in Smart Distribution Grid*," in **EU PVSEC** The 28th European Photovoltaic Solar Energy Conference and Exhibition Paris, France, 2013, pp. 3841 - 3851.

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[10] **M. R. Khan**, J. V. Barreras, A. I. Stan, M. Swierczynski, S. J. Andreasen, and S. K. Kær, "*Behavior Patterns, Origin of Problems and Solutions Regarding Hysteresis Phenomena in Complex Battery Systems*," in Hysteresis: Types, Applications and Behavior Patterns in Complex Systems, J. C. Dias, Ed., First ed: **Nova Science Publishers** 2014, pp. 215-226.

Publications in the popular magazines

[11] **M. R. Khan**, S. J. Andreasen, and S. K. Kær. (2014, 01.08.2014), "*Novel Battery Thermal Management System for Greater Lifetime Ratifying Current Quality and Safety*" *Standard*. **Battery Connections**. 6-10.

Publications in conference as a poster

[12] **M. R. Khan** and S. K. Kær, "*Modeling Thermal Effects of Battery Cells Inside Electric Vehicle Battery Packs*," in 2015 **COMSOL** Conference, Grenoble, France, 2015.

Submitted articles

[S1] **M. R. Khan,** M. Swierczynski and S. K. Kær, " *Towards an Ultimate Battery Thermal Management System: A Review*," Submitted to **Batteries**.

CHAPTER 1. INTRODUCTION

Now a days, battery powered devices are penetrating as an essential part of modern living. Those come in different forms and applications spanning from various household to industrial apparatuses, equipments, vehicles and so forth. Moreover, these modern battery driven devices are getting more powerful day by day. However, it means due to this higher power requirement of a particular application; high power demands are being placed simultaneously on the battery. A fitting example is during electric vehicle quick acceleration operation. This acceleration requires more power from the batteries than normal operation. Due to the high power discharging (applicable also for charging) operation, the temperature is increased in the battery cell. Moreover, charging at low temperatures (sub-zero temperatures) may cause plating of lithium on the anode [1, 2]. This leads to irreversible capacity loss [3-6]. Furthermore, there is a greater chance of possible internal short circuit [7-13]. The desired operating temperature of common type lithium-ion batteries is approx. 25-45°C [14-17]. At this temperature, its lifetime is maximised. To ensure the temperature level at an optimum level, the battery must be employed with the proper battery thermal management system (BTMS). Figure 1 shows a generic structure of BTMS [18-20]:

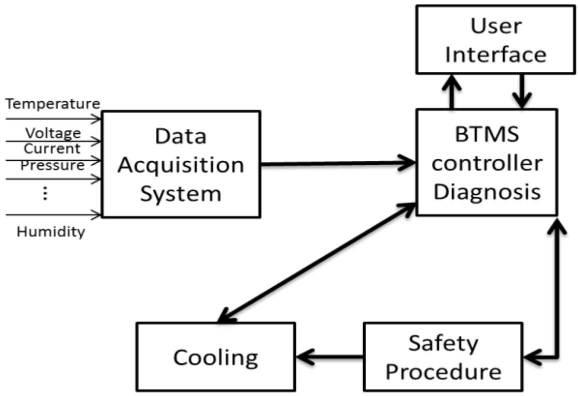

Figure 1 The structure of battery thermal management systems [21].

A BTMS is made up of cooling, heating and insulation components. The intensity, direction of cooling and heating will depend on the particular application requirement [21-29]. The cooling function has to be activated when the battery system is exposed to the high rate of charge and discharge.Therefore, BTMS is an important and integral part of battery management system (BMS).

Figure 2 illustrates basic battery thermal management system topology.

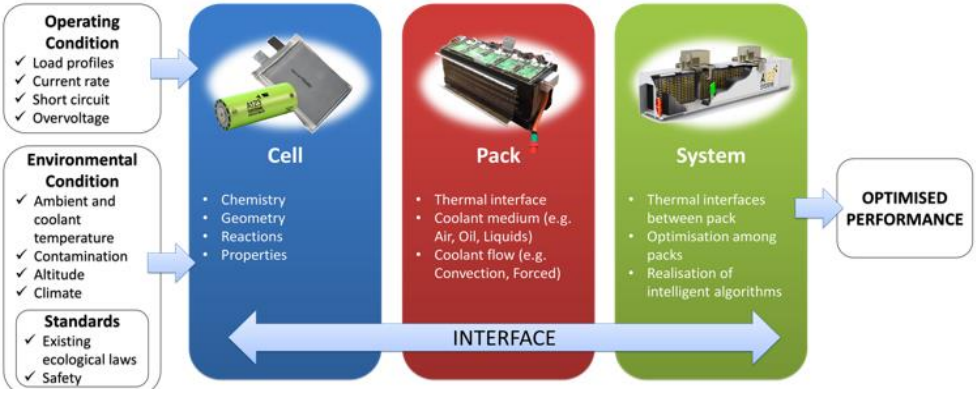

Figure 2 Battery Thermal Management System Topology [21].

For maximum performance of battery driven devices for instance in electric vehicles (EV), optimum temperature control of the battery is essential. In battery-driven powertrains, heat and temperature control (forced/natural heating/cooling) can play a more significant role than that of gasoline or diesel engines. Without a combustion engine, the vehicle does not have a substantial amount of abundant energy supply. Therefore, an increasing focus is on thermal management as it largely contributes to the battery's performance as well as the overall efficiency of the vehicle. So it is crucial that the battery operate in a most efficient way to optimise the performance of the system.

The battery cell is an electrochemical device. It associates with the reactions of the electrochemical process when it is charged or discharged. Those reactions are mostly connected with exothermic conditions (heat is generated across the surface of the battery). The level of reaction rate depends on the associated amount of current flow, the electrochemical reaction, and the electrochemical transport of the ions and molecules in both the electrode and electrolyte [30-34]. Nevertheless, as the temperature is one of the major factors in battery cell ageing, non-uniformity of the temperature distribution may lead to imbalanced ageing.Ultimately, it may lead to the degradation and imbalance of cell performance [32, 35-38]. To avoid such undesirable behaviours, improvements need to be made at both the cell level and pack level. At the cell level, material properties and physical properties can be improved [15, 39-42], whereas at the pack level, improvements in cooling architecture can be incorporated [16, 41, 43-47].

Persistent exposure of battery cells to high temperatures can lead to thermal runaway [13, 48-50]. High temperatures are caused by exposure to sources of heat or battery overload (i.e. excessive charge or discharge power levels) and high ambient temperatures. The consequences of this risk can be fatal and catastrophic. A suitable example is a catastrophe that followed by Boeing® aeroplane battery thermal management system failure. A Boeing 787 passenger flight from Japan Airlines caught fire in its lithium-ion batteries while on the ground in 2013. So, many of the flights are grounded for a year and more across the whole world (source: Wikipedia). This means loss of revenue, as well as the reputation of Boeing, was severely tarnished due to the accident. Figure 3 shows the condition of the battery after the failure.

Figure 3 Catastrophe due to bad thermal management (Source: Wikipedia).

The other influencing factor is to check the cost and feasibility of BTMS so that the manufacturer remains sustainable in the long run. So, the battery manufacturers, EV manufacturers and smart grid developers are striving to meet the BTMS demand at a low cost. By this way, they can reach to their customers with a higher level of penetration ultimately causing profit maximisation [26, 51-53].

The research is focused on the study of battery thermal behaviour using appropriate experimentation and modelling technique. It introduces a battery efficiency parameter determined from measurement in an isothermal calorimeter-- it is suggested as a "*key performance indicator* (KPI)" to be incorporated into modern battery datasheet. To achieve this, newly established electro-thermal testing procedures (experimental framework) is designed and implemented. The demonstration is accomplished with high power and high energy lithium ion battery. This experimental research achieves the heat generation determination and efficiency determination target using novel isothermal calorimetric approach. Moreover, for addressing battery thermal related issues, the study is associated with the development of robust modelling methods complemented by this experimental framework. It is developed for evaluating the performance in targeting all stages of the life cycle of the battery (Beginning of Life

(BoL), End of Life (EoL) and so on) and all levels of the system (Cell - pack -system level).

It is found that the results can guarantee an exemplary result using coordinated approach (experimental and modelling approach) for covering of all relevant thermal behaviours for the particular optimal operation of the battery system. To achieve this purpose, there are several specific objectives that are obtained during the research period:

- Deliver an overview/background of thermal management on the lithium-ion battery cell (Objective, Challenges, Methods, State-of-art)
- Perform theoretical and experimental analysis of the thermal phenomena inside battery cell and pack
- Perform multiphysics analysis of the thermal transport at cell level by providing physical geometric and thermal properties (using finite element method (FEM) based computational fluid dynamics (CFD) techniques).
- Perform simulation analysis of the thermal aspects of both cell and pack level by obtaining temperature evolution. The pack level behaviour is deduced.
- Make a decision framework tool based on techno-economic criteria for the battery thermal management system for smart grid and electric vehicle operation.

1.1. THESIS ORGANIZATION

To investigate the battery’s thermal behaviour and performance, experimental framework and modelling framework have been developed.The experimental part is made up of cell level isothermal calorimetric experiments. Consequently, this cell level experimental results are used as the input for both cell and pack level modelling framework.

Figure 4 illustrates the organisation of the research.

THERMAL MANAGEMENT OF BATTERY PACKS IN ELECTRIC VEHICLE AND SMART GRID APPLICATION

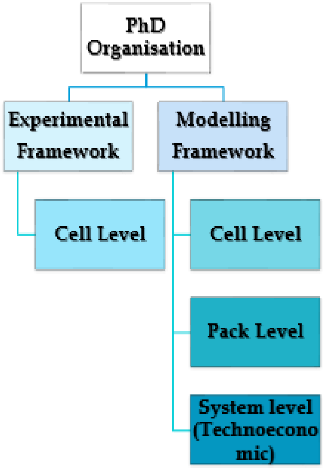

Figure 4 Research organisation

The main body of the thesis consists of four chapters that associate with five papers.

EXPERIMENTAL FRAMEWORK

To demonstrate the thermal experimentation of a lithium battery cell, chapter 2 is written. It has to be read with the general summary as presented in the chapter as well as two papers and Corrigendum.

Those are:

PapI M. R. Khan, M. J. Swierczynski, and S. K. Kær, "Determination of the behaviour and performance of commercial Li-Ion pouch cells using isothermal calorimeter," in *2016 Eleventh International Conference on Ecological Vehicles and Renewable Energies (EVER)*, 2016, pp. 1-8.

PapII M. R. Khan and S. K. Kær, "Investigation of Battery Heat Generation and Key Performance Indicator Efficiency using Isothermal Calorimeter " in *The 13th IEEE Vehicle Power and Propulsion Conference (VPPC)*, Hangzhou.China, 2016.

PapII has to be read with Corrigendum section.

The combination of modern measuring instrument and the developed novel methodology is unique in the global perspective for the determination of heat generation and efficiency, since it was not reported previously in the literature.

MODELLING FRAMEWORK

It contains three chapters (chapter 3, chapter 4 and chapter 5) with three associated papers with three levels of battery system (cell, pack and system level). An accurate model of the thermal dynamics of the battery system is essential for the process of monitoring, estimation of states, diagnosis and control of the battery system as a whole.

The models are developed with necessary simplifications using the experimental calorimetric data, laboratory measurement and literature data set to suit the battery under investigation. It is used to predict its thermal behaviour in both the spatial and temporal domains. The modelling process is most conveniently being executed using Comsol Multiphysics® environment because of the problem characteristics since it demands the capability of multiphysics simulation coupling.

The following papers are associated with the research.

Multi-physics based Cell level modelling framework

PapIII M. R. Khan and S. K. Kær, "Multiphysics based thermal modelling of a pouch lithium-ion battery cell for the development of the pack level thermal management system," in *2016 Eleventh International Conference on Ecological Vehicles and Renewable Energies (EVER)*, 2016, pp. 1-9.

Multi-physics based Pack level modelling framework

PapIV M. R. Khan and S. K. Kær, "Three-Dimensional Thermal Modeling of Li-Ion Battery Pack based on Multiphysics and Calorimetric Measurement," in *The 13th IEEE Vehicle Power and Propulsion Conference (VPPC)*, Hangzhou, China, 2016.

System level Techno-economic optimisation model

The modelling investigation is linked with the constructing of a cutting-edge simulation model for a feasibility study. It is associated with finding the feasibility of employing a battery thermal management system (BTMS) in electric vehicle and smart grid application. The techno-economic analysis is made to assess the feasibility among different BTMS options.

The motivation behind the model is to establish the decision criteria of employing a BTMS. It is used therefore to explore the feasibility of applying air, liquid and refrigerant cooling as cooling media.

PapV M. R. Khan, M. P. Nielsen, and S. K. Kær, "Feasibility Study and Techno-economic Optimization Model for Battery Thermal Management System," in *Proceedings of the 55th Conference on Simulation and Modelling (SIMS 55), Modelling, Simulation and Optimization*, Aalborg, Denmark, 2014, pp. 16-27.

General discussions and future work of the whole PhD is p resented in Chapter 6.

In summary, the thesis is made up of following components:

- Title page
- Abstract
- Acknowledgements
- CV
- Table of Contents
- Introduction (Chapter 1)
- Cell level Experimental Framework (Chapter 2)
- Cell level Modelling Framework (Chapter 3)
- Pack Level Modelling Framework (Chapter 4)
- Techno-Economic Model of BTMS for Smart Grid and EV application (Chapter 5)
- Discussion and Future work (Chapter 6)
- Conclusion (Chapter 7)

CHAPTER 2. CELL LEVEL EXPERIMENTAL FRAMEWORK

The thermal behaviour and performance of a battery cell are brought into investigation through experimentation. To evaluate the performance of the battery cell, different calorimetric experiments are conducted. Moreover, relevant thermal battery performance parameters are recorded to assess critical performance indicator efficiency termed as "*Key Performance Indicator (KPI)*".

2.1. MOTIVATION

Li-ion batteries generate heat depending on the applied current magnitude. The amount of heat generation depends on the electrical and thermal condition of the battery for instance charged and discharge condition [54-58]. Variations in temperature profiles between the different types have to be detected for understanding thermal phenomena. To investigate the thermal behavior of a battery cell properly, obtaining accurate heat generation data from battery modules is also crucial [23, 59]. In this work, it is accomplished through calorimetric experiments at the cell level.

Currently, battery manufacturer and the application builder have no clear idea on battery efficiency parameter i.e. the suggested KPI. The fact applies to both supplier of the datasheet (battery manufacturer) and user of the datasheet (EV and smart grid manufacturer and so on). So they are unaware of the usefulness of KPI for the battery which can be measured conveniently using isothermal calorimeter. The key performance indicator measurements of the particular battery cell at the given operating condition can be repeated for a set of battery candidates for a particular application. The result can be compared to the battery cells to identify the right battery cell that addresses the optimal efficiency parameter. This unawareness may cause the problem like failed product or catastrophic events for example product recall [23, 59].

2.2. EMPLOYED TOOLS

Sophisticated and exclusive research facilities using the new technology development is essential to answering complex challenges associated with the battery thermal management research. Intransigent scientific questions of the battery system can be solved using the most modern experimental equipment. The recent exciting equipment for instance: large scale isothermal calorimeter is one of many startling types of equipment that is available today. This can be used to answer the burning question of the determination of key performance indicator efficiency of a battery cell [23, 59].

For finding the thermal parameters within the research framework, a laboratory facility with exceptional state of the art laboratory equipment is developed. Different fitting experimental tests are designed, accomplished and demonstrated to find KPI of the battery cell. The tests uncover the determination of the battery cell indicators at the different operating conditions [23, 59].

The procedure for determining the core framework is presented schematically in Figure 5.

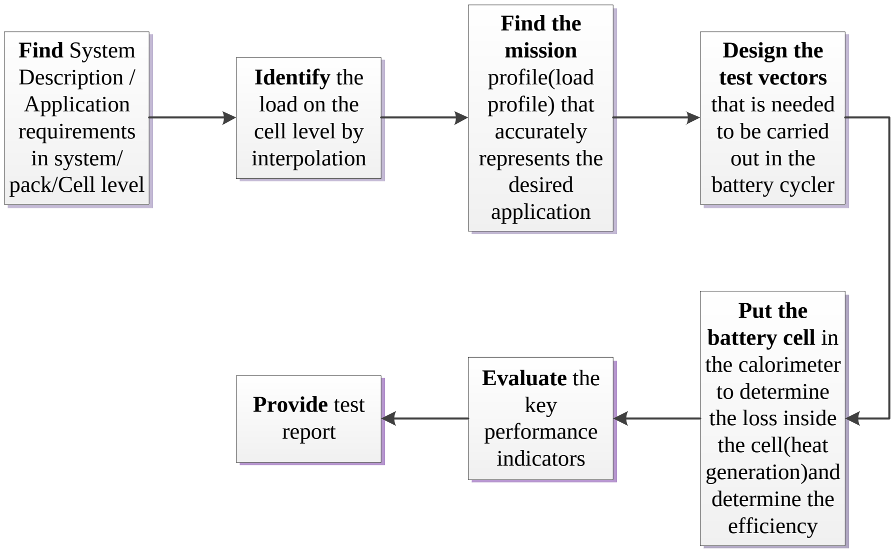

Figure 5 The flow diagram of the key performance indicator measurement using the experimental framework.

For measuring the different parametres of the battery system, different state of the art measuring devices are employed. Those include for instance: isothermal calorimeter (for instantaneous heat flux measurement), contact thermocouples (temperature), current and voltage sensors (for electrical state measurement). The principle is to measure them simultaneously in a calorimeter chamber. Those are handled in an inert atmosphere. Due to this, external and ambient based influencing factors are avoided. Moreover, these make the achieved results comparable. To accomplish this, the experimental framework is taking advantage of a range of modern experimental instruments for example isothermal calorimeters and battery cyclers (Refer to Figure 6).

The battery cell is exposed different test vectors as developed through battery cycler device [23, 59].

Figure 6 Experimental Framework Measurement Tools. [Left]Netzsch® Isothermal Calorimeter [middle]Digatron® Battery tester, [Right] Maccor® Battery Cycler.

2.3. RESULTS

The contribution of the experimental framework contains a set of indicators, graphs that are representative of battery operating condition. It represents the battery performance characteristics of the battery system. The framework provides fixed quantified performance indicators [23, 59].

REFER TO **PAPI** AND **PAPII**

[1] M. R. Khan, M. J. Swierczynski, and S. K. Kær, "Determination of the behavior and performance of commercial Li-Ion pouch cells by means of isothermal calorimeter," in *2016 Eleventh International Conference on Ecological Vehicles and Renewable Energies (EVER)*, 2016, pp. 1-8.

[2] M. R. Khan and S. K. Kær, "Investigation of Battery Heat Generation and Key Performance Indicator Efficiency using Isothermal Calorimeter " in *The 13th IEEE Vehicle Power and Propulsion Conference (VPPC), Hangzhou.China, 2016*.(Read with Corrigendum)

CHAPTER 3. CELL LEVEL MODELLING FRAMEWORK

The cell level modelling framework is a multiphysics solution of battery cell thermal problem. It represents a three-dimensional unit cell model. The model is developed to simulate the thermal performance phenomenas of a battery cell with the particular operating profile (the battery cell is exposed to cooling). More specifically, it is simulated to predict the cell level battery temperature distribution. The experimental data of the battery acquired from isothermal calorimeter is fed into a multiphysics model. The model can emulate the battery cell thermal behaviour with a detailed resolution. Definitely, it can show detailed effect regarding temperature gradient inside the cell and corresponding cooling performance [22].

The objective of the modelling research is to develop an advanced electro-thermal cell simulation model that uses conjugate heat transfer tool (coupled heat transfer tool and computational fluid dynamics (CFD)). The model is employed to study temperature evolution of a unit cell. It is used consequently to explore the local temperature distribution with air as cooling fluid. The framework is established based on modern simulation lab. It is equipped with a range of new simulation tools i.e. cutting edge simulation software with *Comsol® Multiphysics, Matlab,* etc. The simulation is carried out using high-performance workstation computers.

3.1. MOTIVATION AND CHALLENGE

The thermal performance model for Li-ion batteries under real operational conditions is a key challenge for battery system development. This is particularly important for the reliable integration of the battery. The problem is applicable not only for the battery-driven vehicle but also for stationary applications used in the smart grid. The determination and correct prediction of thermal performance of a battery cell is not a trivial task. This requires a detailed understanding of the battery cell composition, underlying mechanism, measurement with the highest level of precision to replicate the process, understanding of the parameters which influence the performance, as well an excellent knowledge of the relationships between variables and the corresponding performance [22, 60].

Experimental test data originated from the cell level calorimetric experiment are analysed to find the amount of heat generation. Naturally, the follow-up is to evaluate the effect of the cooling of the cell. The intended goal is to determine battery cell’s thermal behaviour (heating of battery and cooling interaction) using a model based study [22].

The tricky part with the battery cell production industry is that accurate data for instance: the physical composition rarely is disclosed. The fact makes physics-based model and its evaluation extremely challenging for an external party (e.g. researcher in academia). Unsurprisingly, modelling the thermal dynamics of the battery system is not trivial due to the multidisciplinary science and engineering requirements. An extra difficulty comes from the spatiotemporal and high nonlinear nature of the underlying process in both battery cell and packs setting.

Therefore, the model development is associated with a precision thermal measurement. The common desire is to study how cooling systems affect the outcome of interest i.e. temperature distribution of battery inside a cell or in a pack. Such numerical tools for the battery thermal modelling can be too complex. They require high computation burden stemming from coupled physics simulation. Moreover, specific tests are needed to be designed to parameterise the model. Those help to verify, parameterise and validate the developed model.

3.2. MODELLING APPROACH: STATE OF THE ART

There is numerous state of the art models as proposed by previous research. However, several of these thermal models are based on electrochemical modelling and corresponding measurement [22, 23, 59, 61-66].Relatively little or no attention has been paid to the multiphysics modelling complemented by the most advanced level calorimetric measurement.An accurate thermal model is a requirement for an effective BTMS. Battery modelling is valuable to investigate numerous thermal and cooling limitations. Through this, it assists to find the required specifications and configurations of BTMS for performance assessment. The thermal models of lithium-ion battery cells are developed in different physical dimensions lumped (0D), one-dimensional (1D), two-dimensional (2D) and three-dimensional (3D) levels.The choice depends on the purpose of the model, for example, they can include ageing and the failure mechanisms [13, 67-69]. An example of such motivation may be the localisation of internal short circuits [7, 70, 71] and thermal runaway [11, 13, 14, 34, 45, 48-50, 72-80]. Both commercially available and custom-built calorimeters are used for battery heat generation rates [6, 30, 81-87].The following Table 1, Table 2, able 3 and Table 4 contain a summary of the characteristics of the selected state of the models.

Table 1 Selected lumped and one-dimensional model used for BTMS development.

	Reference	Description
0d, 1d	S. Kandler and C. Y. Wang[88] [71]	-The thermal behaviour of a 6 Ah Li-ion battery cell is determined. – Estimated the total heat generation, state-of- charge (SoC), power, current, solid concentration and percent of total heat generation. – 1D electrochemical model is built. It is made for a hybrid vehicle and analysed the effects of solid state diffusion on high rate discharge and dynamic behaviour of current. The control variable was changing lithium concentration in either electrode or electrolyte. – The model did not consider the cell behaviour at very high discharge rates.
	Al-Hallaj [13]	– A simple one-dimensional thermal mathematical model was built. Lumped parameters are used to simulate temperature profiles inside cylindrical Li-ion cells
	Forgez et al.[89]	– A thermal model of a cylindrical $LiFePO_4$ /graphite lithium-ion battery is utilised. Lumped parameters are used to estimate the temperature response for bulk approximation.
	Smith and Wang [71]	– A complex one-dimensional thermal mathematical model with lumped parameters.

Table 2 Important two-dimensional models used for BTMS development

	Reference	Description
2d	Chen and Evans [90]	– Investigate the effect of various cell components for instance: Stack size and cooling conditions. – The performance of Li-polymer electrolyte batteries under different discharge rates was assessed. – The procedure to maintain operating temperature by designing proper cell stacks. It includes choosing appropriate cooling and insulating systems from heat transfer point of view.
	Inui et al. [91]	– The transient response of the temperature distribution was shown. – The cylindrical and prismatic Li-ion battery was shown during a discharge cycle – Battery with the laminated cross section has a remarkable effect on the suppression of the temperature rise. – There was a comparison with the battery with square cross section
	Wu et al. [92]	– Transient heat-transfer model to simulate the temperature distribution.

Table 3 Three-dimensional method found in literature used for BTMS development

	Reference	Description
3d	Inui et al. [10]	– The transient response of the temperature distribution is shown. – It was shown for both cylindrical and prismatic Li-ion battery during a discharge cycle. – Battery with the laminated cross section has a remarkable effect on the suppression of the temperature rise in comparison with the battery with square cross section
	Chen et al. [49]	– A detailed three-dimensional thermal model to examine the thermal behaviour of Li-ion batteries. – In the model, the layer-structured core region, the contact layer and the battery case are all taken into account. – The location-dependent convection and the radiation included in the model.
	Kim et al. [75]	– A three-dimensional thermal abuse model is built for Li-ion cells. – They Considered the effect of electrode configuration and current distribution.
	Chen et al. [93]	– The layered structure of the cell stacks, the case of a battery pack, and the gap between elements were considered; – A detailed three-dimensional thermal model in a similar form. – A battery pack is developed.
	Lee et al. [94]	– A three-dimensional thermal model for EV battery pack, – The cell to cell difference in not considered in their work

Table 4 Other significant literature of models for BTMS development.

	Reference	Description
Others	Maleki and Shamsuri [68]	– Evaluated numerically the thermal performance of a notebook computer Li-ion battery pack – The various operating conditions (charge and discharge) are addressed. – During the charge event, the battery temperature rise is dominated by the power dissipation from the control electronics. – During discharge event, the battery temperature rise is dominated by the heat dissipation from the li-ion cells.
	Fang et al.[95]	– Used an electrochemical-thermal-coupled model. – It is used to predict the performance of a Li-ion cell for its individual electrodes at various operating temperatures. – There is a validation of the model against the experimental data for constant current and pulsing conditions, characteristic of hybrid electric vehicle (HEV) applications. – The prediction of individual electrode potential compared with three-electrode cell experimental data.
	Forgeza et al.[89]	– A lumped- parameter thermal model of a cylindrical $LIFePO_4$/graphite li-ion battery is developed

		– Current pulses of different magnitudes are applied to the battery to determine heat transfer coefficients and heat capacity experimentally. – Steady-state temperature measurements are used to estimate the battery thermal resistance – The simulation exhibits the internal temperature directly from the measured current and voltage of the battery
	Smith et al. [8]	– A coupled electro-thermal model of a commercial 18650 size li-ion cell. – Cell electrical and thermal responses are modelled using equivalent electrical and thermal circuits – The cell model is extended to a module with 16 cells in parallel. The results from the cell model are integrated into a module-level model. – The module-level model is validated with experiment. – They utilised a parametric study to evaluate the battery thermal safety margin.
	D. Bernardi, E. Pawlikowski and J. Newman [58, 96]	– A general energy balance for battery systems are presented at charging and discharging cycles are calculated. Equations for thermal heat mixing terms were generated – LiAl/FeS cell is used for validation. – The research is based on different parameters such as concentrations, the state of charge (SoC) and efficiency. – Effects of step current, voltage responses on terminal current, voltage and temperature distributions are studied. – A charging performance at a constant current and a constant voltage are simulated and analysed. – The result showed the effects of the heat of mixing, phase change, heat capacity change, electrical work and heat transfer with the surroundings. -
	S.L. Hallaj, H. Maleki, J.S. Hong and J.R. Selman [17]	– The thermal model is built to measure the temperature at different operating discharge conditions with different current rates. – A Sony US18650 cell is used for validation. The thermal design of lithium ion cell is exposed. – The model is used to investigate thermal runaway conditions. – The influence of cooling rate and cell aspect ratio (L/D) on thermal runaway issues are seen. – Higher cooling rates (h=100 $Wm^{-2}k^{-1}$) is responsible for higher non-uniformity of temperature distribution inside the cell. – Inside the cell, lower cooling rates safeguards uniform temperature distribution.
	Jong-Sung Hong, H. Maleki, S. Al Hallaj, L Redey and J. R. Selman [97, 98]	– An electrochemical calorimetric setup is used to measure voltage and area-specific impedance with different discharge capacity and discharge rates, cell temperature distribution with time, heat dissipation rate with time, total reversible heat generated with changing temperature experimentally.
	Catherino et al. [76]	– Performed a model to attempt studying the thermal runaway effect in lead-acid batteries.
	Gu and Wang [69], [99]	– A micro-macroscopic electro-chemical model is proposed. Those are coupled with the thermal model to

		predict both the cell electrochemically and thermal behaviours inside a cell. – The model is used to identify the mechanisms responsible for thermal runaway and the thermal behaviour of Li-ion battery cell.
	Hatchard et al. [100], Spotnitz et al. [11], Guo et al. [73]	– The thermal abuse models are used for considering the safety problems. – The thermal abuse terms are coupled with other heat generation terms. – The heat generation value comes from chemical reactions. – The models are used to predict behaviours such as thermal runaway under abuse conditions
	Johnson [101] Onda [65] Weinert [102]	– The batteries generate much more heat during rapid charge and discharge cycles at high current levels, such as during quick acceleration. The improvement of battery-powered vehicles needs large-scale battery; however, with the size increasing and large packages forming, severe thermal stability problems will depose. The safety risks such as overheating, combustion, and explosive increase of heat energy contained within the battery or pack.

3.3. METHOD

The model is developed with necessary simplifications using the experimental calorimetric data, laboratory measurement and literature data set to suit the battery under investigation. It is used to predict its thermal behaviour in the spatial and temporal domains. The heat capacities of the components of the cells with the measured values and other values published in the literature is utilised for the modelling purpose [103, 104]. Alternatively, the heat capacities can be both estimated by data as measured with a calorimeter [22].

In the research, in transient study interpolation function of Comsol Multiphysics is used to define heat generation as a function of time. The method allows incorporating complex heat rate with heterogeneous material properties in battery systems. Moreover, it utilises the multiphysics material libraries. Using the corresponding values from the material library helps to avoid difficulties of individual characterisations. Additionally, use of multiphysics software contributes to avoiding the challenges that may arise when assembling complex multipart geometries with different boundary condition. Nevertheless, there are situations in which assembling or defining the individual parts of highly complex parts inside the battery can be non-trivial. Naturally, several iterations of the modelling process are to be simulated to ensure the model convergence.

A generic electro-thermal modelling flow diagram is presented as a schematic in Figure 7 .

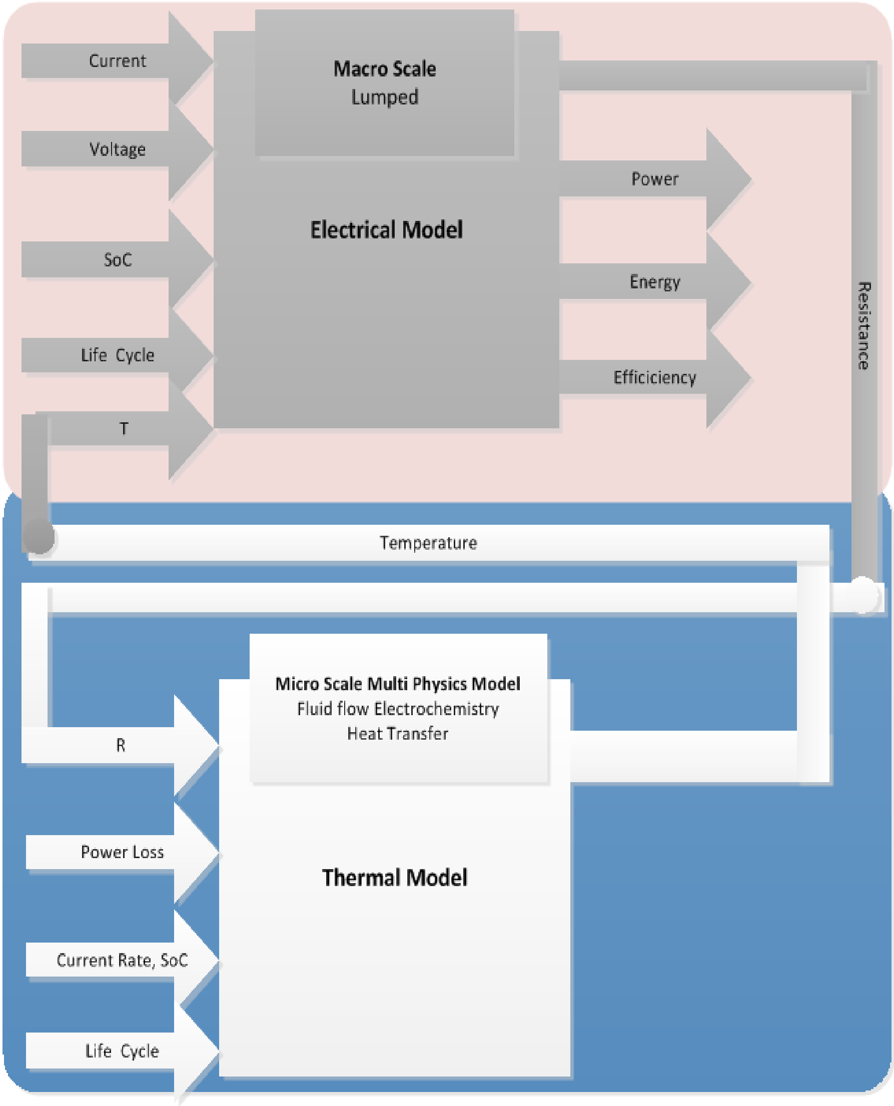

Figure 7 Block diagram showing the coupling of electrical and thermal model.

Additionally Figure 8 represents the complete flow diagram of the cell level modelling framework that has been used in the research:

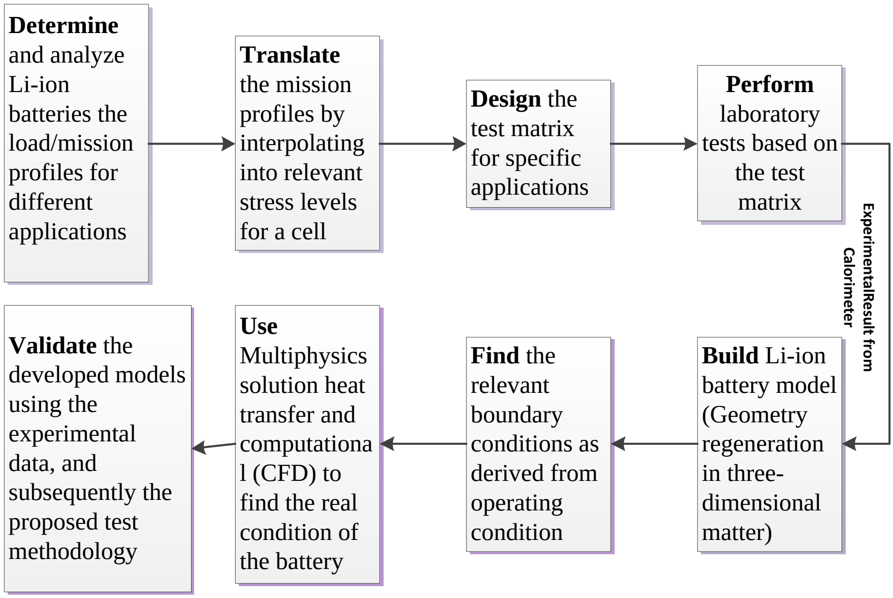

Figure 8 Block diagram of cell level modelling.

3.4. MODELLING EQUATIONS

At the heart of computational thermal modelling are the mathematical equations. Those include a set of governing classical equations of physics (e.g. fluid flow, heat transfer, and the underlying couplings of the physics). Those describe the physical processes for instance electrochemistry taking place inside a battery cell. The mathematical expressions are in the form of partial differential equations. Using modern techniques and advanced software allows these equations to be solved numerically over the domain of battery cell. For instance, one of these processes could be the transfer of heat from a battery to its surroundings (cells and accessories, etc.). These equations govern the physics of the process. It is made to include external influences taking place like forced convection of the carrier fluid. So, those are accomplished with a set of relevant inputs such as fluid velocity, initial battery surface temperature, and ambient temperature.

3.5. RESULTS

A realistic, well-performing cell model is made. The validation of the model is done on the experimental and theoretical basis. The result of the cell model is used to inspire the pack model. An advantage is a flat cell as found in pouch cell is heat rejection. So obviously it is more efficient than the cylindrical cells. However, the dimensions of the battery are specific for the flat cells, since cylindrical cells would occupy more space due to their geometry. The pouch cells can be packed thanks to their prismatic shape very efficiently. This means that the cooling structure is limiting the most efficient packing of the cells. The evident benefit of employing a thermal model is that different temperature levels can be estimated without temperature-sensors to reach the goal.

3.6. COMPARATIVE PERFORMANCE AMONG THE MODELS

There are different ways to model the thermal performance and gradient of the battery. The most popular method is physical modelling based on electrochemical approach. The system designer or modeller has to choose from the availability of the different types of the model. The research does not suggest that the presented multiphysics model is better than the electrochemical counterpart. However, it can boast of the fact that it is more straightforward and intuitive.

The data used in the research is from a particular point of operation of the battery cell in time.So, it means no ageing level is considered. The result is not applicable for aged cells because ageing and cycle life study is out of the scope of the research. However, since aged cell differs from a new cell, there is a need of re-parametrise the thermal model.Additionally it is needed to adapt the voltage level that an aged cell can reach. The usefulness of the research is that the research can be extended up to an aged cell using the same frameworks as developed with necessary modification and adaptation. Thus, the validity of the findings and the legitimacy of the study frameworks is established at this moment.

In order to conceptually compare the models' performance two distinct electrochemical models have been chosen. Those are Porous Electrode Model [57], Multi-Scale Multi-Dimension (MSMD) Model [105] and the developed unit cell model.The comparisons are presented in tabular form in Table 5.

Table 5 Comparison of Unit cell thermal model with the state of the art models.

Model	Porous Electrode Model [57]	Multi-Scale Multi-Dimension (MSMD) Model [105]	Unit cell thermal model [22]
Scope	Electrochemical	Electrochemical and thermal	Conjugate transfer (Heat Transfer and CFD)
Methods	Considers charge transfer kinetics at reaction sites through species , Charge, and energy conservation that captures lithium diffusion dynamics and charge transfer kinetics	Introduced separate computational domains for corresponding length scale physics Used Geometry decoupling between the domains.	Macroscopic model. Usage of coupling of Heat Transfer (HT) and computational fluid dynamics (CFD) to represent the thermal and cooling phenomena inside the battery cell.
Demonstrated battery cells	Lithium/Polymer cell sandwich, consisting of lithium-foil The anode, solid polymer electrolyte, and a composite cathode.	Spirally wound structures of lithium-ion batteries	Lithium Titanate Oxide
Special Characteristics	Predicts current/voltage response of a battery	Selectively resolve higher spatial resolution for smaller characteristic length scale physics	Designed for illustrating better spatiotemporal temperature distribution of a battery cell over a wide range of operating condition.
Advantages	Provides design guide for thermodynamics, kinetics, and transport across electrodes	Spiral wound cells with more tabs would be preferable to manage cell internal heat and electron current transport	Use of isothermal calorimeter experiments to parameterize the three-dimensional battery cell, thermal model. Uses hierarchical structure.So it is extended up to pack.
Disadvantages	Difficult to resolve heat and electron current transport in large cell systems	It is more complex and made only for specific type of battery chemistry.	It is not suitable for local heat. Additionally, it has no electrochemical justification so electrochemical phenomena are not possible to be found
Application Areas	Mostly used in basic electrochemical sources	To understand effects of tab configurations and the double sides electrodes structure	Intended for most battery chemistries with minimal adaptation

3.7. APPLICATIONS

Aimed at EV, PV and battery manufacturer, the framework can serve a broad range of application demands, for instance: different battery designs with specified operating conditions. The framework is opening a new field of battery thermal management research because it can be used in high-performance battery thermal system.

Refer to PapIII

M. R. Khan and S. K. Kær, "Multiphysics based thermal modeling of a pouch lithium-ion battery cell for the development of pack level thermal management system," in *2016 Eleventh International Conference on Ecological Vehicles and Renewable Energies (EVER)*, 2016, pp. 1-9.

CHAPTER 4. PACK LEVEL MODELLING FRAMEWORK

The research is accomplished by developing an advanced electro-thermal pack simulation model. Multiphysics simulation is employed (heat transfer and fluid dynamics (CFD) tool). The model is designed to investigate temperature evolution inside the pack while cooling fluid (air) is flowing. The model is simulated subsequently to illustrate the local temperature distribution in the battery pack [60]. The pack level modelling framework is intended at EV, PV and battery manufacturer.

4.1. MOTIVATION AND UNDERLYING CHALLENGE

The battery pack thermal model using numerical methods is extremely useful. It helps to understand how various design variables affects the thermal behaviour of the battery pack. Additionally, it contributes to determining how the temperature distribution affects the performance of the battery cell inside an entire pack. One of the significant advances in the last several years in the scientific field has been the availability and use of computational software tools for solving simultaneously the classical equations of multi-physics governing fluid flow, heat transfer equations (using appropriate commercial software). In this research, exploitation of high-performance workstation computer is employed. It considers the physical design and utilises modern software tools with multicore processor and higher memory.

The thermal performance model of Li-ion battery pack under operational condition (showing the thermal gradients of the battery) is a key challenge in battery system development in general. The determination and correct prediction of thermal performance of a battery pack are not minor tasks. A number of challenges are needed to be overcome to make a successful model as presented in Section 3.1.

4.2. EXPERIMENTAL DATA

To determine the amount of heat generation of cells inside the pack, experimental test data originated from the cell level calorimetric experiment is used. Indeed, it is used to gauge the consequence of the cooling of cells inside a battery pack. The intended target is to determine battery pack's thermal behaviour using a model based study.

4.3. METHOD

The cell level modelling methodology (refer to Section 3.3) is extended in particular pack geometry. It is used to forecast the temperature distribution in the spatial and temporal domains. The equations of the cell level modelling (Section 3.4) are used. It is extended for pack level modelling with necessary modification and adaptation. The

most important input is pack configuration (Number of cells in a row, Number of cells in a column and so on.). The appropriate boundary conditions are employed for pack level.
Figure 9 shows the complete flow diagram of the cell level modelling framework:

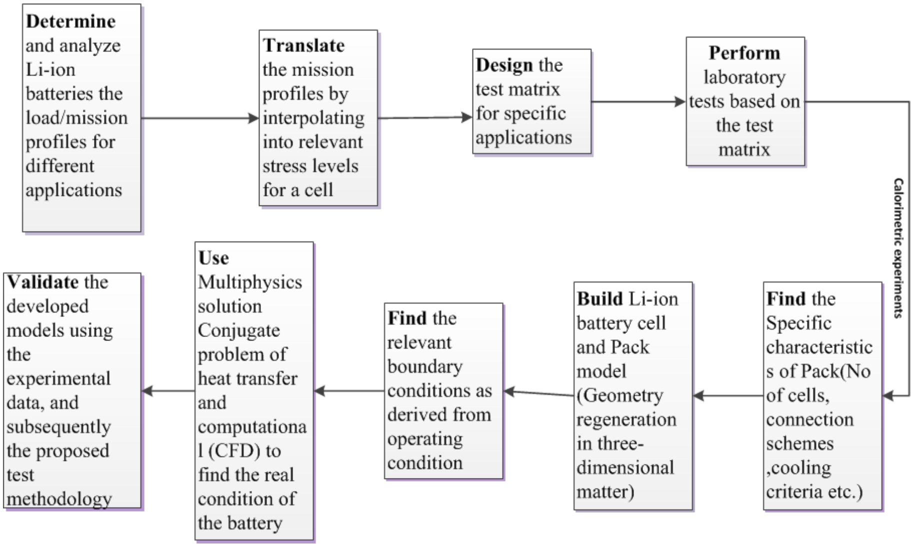

Figure 9 Research diagram of pack level modelling.

4.4. RESULTS

A three-dimensional study has been shown concerning the thermal performance of battery module of eight large pouch cells. It shows the time-dependent and steady-state behaviour of the battery cells with cooling inside the pack. It has been conducted regarding the thermal behaviour of battery modules made of large pouch cells, and the particular study has been addressed regarding the thermal response during the discharge and charged states at different temperature levels. The framework can serve a broad range of these application demands as well as others for instance: different battery designs with specified operating conditions. The effect of temperature change on the underlying operation of a set of battery cells in a pack setting is found. The results of this research become successful at showing hot-spots that represent critical stages in battery thermal management design. It certainly can play a vital role at the different stage of battery system development.

The important characteristic of the developed model is that it is pragmatic. It requires the least analyst attention. The evaluation is the realistic simulation showed that the developed approach makes a significant improvement in showing temperature gradients.Additionally, the method is generic, intuitive and straightforward. It can relate this to appropriate cooling mechanisms. Simulation results illustrate the distribution of temperature levels on the surface of battery cells inside a pack.

From a general thermal research point of view, the developed method is comprehensible and wide-ranging. Furthermore, it can handle a wide variety of thermal problems of both the battery cell and the pack level. The result of the framework can be used in monitoring, determining and controlling the thermal responses both the battery cell and the batteries inside a pack. A suitable example includes controlling the best flow rate. Those are extremely necessary for the energy storage systems' designed for various applications.

Moreover, it should be noted that the modelling approach, based on lumped model or single or two-dimensional model, cannot address the physics governing the thermal mechanisms correctly. Because the simulation uses the generic assumption of the lower dimension of the battery systems that may prove inadequate to exhibit the true nature of cooling inside pack level modelling.

It is designed to define the geometry-dependent effective thermal behaviours of battery cells in a pack structure. Moreover, it can also be a matter of interest to compare different cells for instance from other chemistry cells (e.g. Lithium Nickel Manganese Cobalt Oxide cell).

4.5. COMPARATIVE PERFORMANCE BETWEEN THE PACK MODELS

The comparison of the state of the art pack models is comparable to cell model as presented in Table 5.

CHAPTER 5. TECHNO-ECONOMIC MODEL OF BTMS FOR SMART GRID AND EV APPLICATION

The modelling research is associated with the development of an advanced simulation model for a feasibility study of employing a battery thermal management system (BTMS). The intended applications are for smart grid (photovoltaic system with battery) and electric vehicles. It is based on a techno-economic analysis. The model is to set the decision criteria of employing a BTMS. It is used consequently to explore the feasibility of acquiring BTMS with different cooling fluids: Air, liquid and refrigerant cooling. The method, which is used to determine the feasibility analysis, is called "*The decision tool framework* (DTF)". It is the primary enabler for studying further the sensitivity of the main dependent factors of BTMS feasibility. Those include lifetime and application requirements. DTF is designed to provide a standard feasibility assessment for BTMS and related accessories. It is targeted specifically for BTMS manufacturer, designer, and battery application developer.

Diverse options of different BTMS is achievable for evaluation of EV and PV applications. The results provide the higher sense of understanding the feasibility of employing particular kind of BTMS.Using the results, the required specification and configuration of a BTMS is found.

5.1. MOTIVATION AND CHALLENGE

"The feasibility study of a BTMS associates with the assessment and scientific reasoning of deploying a particular BTMS among different options. The primary target is to select the optimal one among different possible alternative configurations. Naturally, there are many variables within the design process of BTMS for the particular application. The noticeable variables include battery pack configuration, battery materials, mechanism of coolant flow, etc. So, some simplification is needed to be taken account.

Since the target is to select the optimum one, optimisation process plays an especially important role in choosing BTMS. This is evident that there is a high dependence on the design variables. The target is to find the associated trade-off in BTMS acquisition process for maximum benefit. Typically, this optimal BTMS is not readily determined from the individual technical study. Since to be feasible BTMS must be economically suitable, it is needed to be complemented by the financial aspects. By doing this, it ensures the result is acceptable for relevant stakeholders.

The optimisation procedure is apparently applied to find the satisfactory designs. The target is that the given requirements and constraints are met. The design of BTMS finally attained with an assessment of both technical and economic study is made for an optimal one, not just an acceptable one. Optimisation of the system can be carried out regarding the design spaces. In those circumstances, this modelling helps in obtaining and comparing alternative BTMS designs. It is accomplished by predicting the techno-economic performance of each possible configuration. Ultimately it leads to an optimal design" [26].

5.2. METHOD

"Two particular application (electric vehicle (EV) and photovoltaic (PV) application) is used for the case study that contains real-life profiles. The BTMS design problem is simplified through idealisations and approximations. It assists to make the problem manageable for achieving a reliable solution. The maximum temperature increase due to the current profile is needed to be the input of the model for a given battery chemistry with a given configuration and type. The mathematical modelling of BTMS involves modelling of the various components and subsystems that associate the thermal elements of the battery thermal system and corresponding components. This is followed by a coupling of all these batteries and the relevant accessories' models. This is done to obtain the final, combined model for the BTMS. When a particular design is found to satisfy the application requirement, it is deemed as an acceptable result. The next procedure is to execute the economy based lifetime model. The ultimate goal is to find the best optimum configuration" [26]. The full analysis schematics is shown in Figure 10.

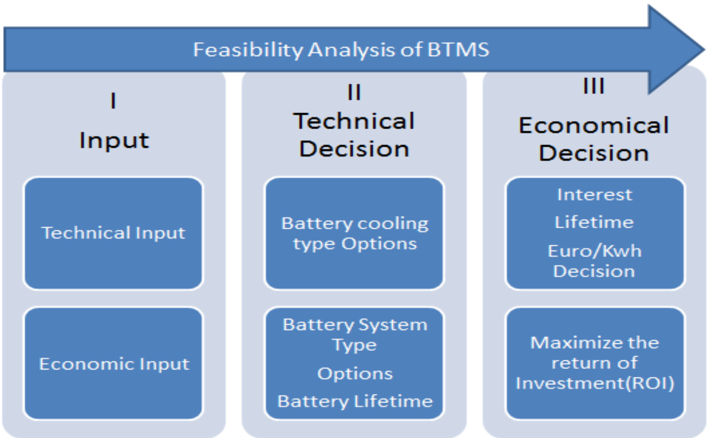

Figure 10 Block diagram of techno-economic analysis for BTMS [26].

"The optimum criteria that the chosen system satisfies the maximum return on investment (ROI). The purpose is to give a range of different pack configurations with the corresponding thermal requirement. It is done to compare the related impacts and to find the best optimal specification and configuration. Moreover, it is to be noted that function of the battery is set to a battery system that can deliver the amount of energy storage capacity and power needed for the d EV and PV application. Different scenarios are simulated". The techno-economic performance is evaluated using the model. As a flowchart, the techno-economic approach is shown in Figure 11 [26].

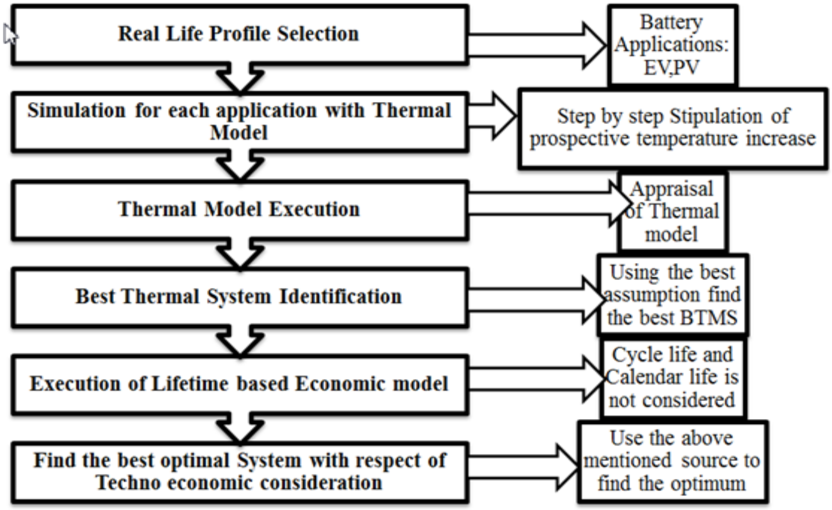

Figure 11 BTMS techno-economic analysis Flowchart [26].

5.3. RESULTS AND USEFULNESS OF THE RESULT

"Evaluation of the feasibility of the design problem is found. By undertaking this, the analysis can introduce considerable flexibility in the BTMS design. Additionally, the feasibility target is possible to achieve. The results of the techno-economic analysis provide the related stakeholders with enough information. It enables to consider a particular design BTMS among different options. It corresponds a significant step in the practical life for deploying a battery system. It is based on the results of the simulation with real life parameters. It encompasses the choice to carry on or halt the procurement of the BTMS for desired application. It enables the stakeholder to examine the problem in the context of broader business strategy. Aimed at different stakeholders, the framework can assist with wide-ranging application demands, for instance: different battery designs with specified operating conditions. The result is adequate for the evaluation of the various BTMS designs to choose the optimal one" [26].

5.4. Future Work

The techno-economic analyses generalise the problem. So, the results obtained from the analytical effect can be compared in future to the experimental investigation. It is possible to use with essential modifications to adapt to other similar systems. It helps to relate the circumstances covering both technical and economic scope. At that moment, once experimental analysis data from a prototype are available, a direct comparison between the analysed data and the results of the techno-economic result can be compared.

5.5. CONCLUSION

The research presents a complete feasibility analysis of battery systems with essential thermal management requirements. Technical parameters as battery lifetime and application requirement have been taken into account. The procedure assists in determining the feasibility of BTMS design.

REFER TO **PAPV**

M. R. Khan, M. P. Nielsen, and S. K. Kær, "Feasibility Study and Techno-economic Optimization Model for Battery Thermal Management System," in *Proceedings of the 55th Conference on Simulation and Modelling (SIMS 55), Modelling, Simulation and Optimization*, Aalborg,Denmark, 2014, pp. 16-27.

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CHAPTER 6. DISCUSSION AND FUTURE WORK

The overall target of the research is to improve the understanding of the thermal behaviour of the battery system. To accomplish the goal, the experimentation and modelling result is shown. The research associates the demonstration and validation based on a commercial 13Ah LTO battery cell. It has been addressed with a view of general versatility. So, only one type of battery is tested for comparability. The aim is to ace the process so that the experimental and modelling framework is enhanced for achieving the best result that can be extended up to a particular type of battery cell.

The framework presented in the research is not intended to set stringent requirements for either modelling or experimentation, rather, it presents itself as a useful paradigm to the modeller, battery tester and concerned stakeholder. So, it provides the maximum level of flexibility of the testing and modelling for battery thermal management system (BTMS) development.

The study is intended for use in BTMS industry for electric vehicle and smart grid application perspective. The results can also be employed for other applications including electric generating stations, substations, telecommunications installations, large industrial and commercial facilities, large uninterruptible power supply (UPS) installations.

6.1. CONTRIBUTION

Obviously, the battery thermal management system is a yield of continuous research. In this research, some steps have been taken to model the thermal dynamics of a battery cell with the help of necessary experimentation. To study battery behaviour under the proposed experimental framework, a comprehensive experimentation system is designed, developed and demonstrated. Using this framework each cell's internal thermal states under controlled situations can be measured. Also, to obtain the realistic thermal condition of both cell and pack, the modelling framework has been developed which signify a complete structure for engineering based thermal management.

Based on this understanding of thermal behaviour using the experimental and thermal framework, temperature-control approaches can be further developed. The result of the model can be utilised for monitoring, determining and controlling the thermal responses of the batteries in a pack setting. A suitable example is controlling best flow rate and the battery cells placement. Since the 3D approach appears necessary when other more complex geometric configurations have to be taken, so the presented research claims it is a future proof solution. The developed model compliments the BTMS design methodology.

This study, in fact, gives many suggestions and directions that future studies can take advantage. Those can benefit by employing the methods as suggested by the research both battery cell, pack or system level. Similarly, conceptualisation of thermal management modelling and experimental perspective and probable cooling strategies is presented which is very useful at the different stage of battery operation e.g. design stage. The results are extended up to techno-economic study for the feasibility of battery system.

The research result has a number of potential applications in industries especially in electric vehicle and photovoltaic cases. Since a generic approach is used and presented in the current research, so, it is possible to take account of different types of battery irrespective cell chemistry and sizes. The strength of the current research lies in the fact that it has experimental validation. Heat generation of a battery cell as measured by the isothermal calorimetric represents the most precise measurement level that is possible to achieve to date. The frameworks are developed to demonstrate one excellent paradigm option for both EV and smart grid industries.

Additionally, the modelling framework is built on numerical modelling methods complemented by the experimental calorimetric methods. The modelling research is focused on getting the spatial and temporal resolution of the battery both cell and pack systems. Using the framework, it is easy to understand the thermal phenomena inside the battery. By doing this, it makes the basis for future thermal analysis of battery cell using calorimetric experiments. So the research enables to identify, develop and establish the calorimetric based multiphysics modelling.

The research is targeted for a wide-ranging list of design considerations of BTMS. It represents engineering approach of a generic battery cell, pack and system to demonstrate its flexibility. The method applies to all common cell types, implying that the results from the model and experimentation can be considered indicative for generic batteries. Moreover, the influence of various design variables effects is possible to observe the thermal behaviour of the battery pack. Thus as a whole, all these provide critical information for the battery pack design specially in thermal aspect. It is by the concerned entity's decision as to what level of the proposed framework and what extent it is needed to be implemented. The battery system tester (e.g. application manufacturers) may use the framework for battery chemistries other than LTO battery that is presented in the research. In the case, they have to adapt to certain conditions for the particular application for battery cell under test. Additionally, they have to adjust to the framework's usefulness level depending on several factors for example battery characteristics, physical requirements, electrical requirements, environmental requirements, safety requirements, storage characteristics, venting system, employed thermal management and so on since many of these influence application implementation objective(s).

Thermal modelling predictions aided by modern calorimetric measurements are used to compare alternative reliable thermal design approaches. The computational modelling framework as presented in the research is the preferred choice because it can carry out rapidly numerous 'what-if' studies (e.g. what will happen (effect) if the battery's cooling velocity (cause) is changed etc.) during design. The research assists in assessing progress toward the most reliable and efficient BTMS goals. The aim of these predictions can provide a contribution to safety and maintenance. Consequently, it can reduce warranty costs, and the optimum configuration and specification can be achieved from the alternative of other BTMSs.

Exploitation of these modelling benefits industries by:

- ✓ predicting failure of thermal condition before it happens
- ✓ minimising the amount of physical prototyping
- ✓ improving quality and performance of the BTMS
- ✓ identifying optimal properties and process conditions for desired application
- ✓ generating knowledge of the thermal evolution process
- ✓ getting cutting edge BTMS to market earlier
- ✓ reducing overall development costs of an individual application

Both the modelling and experimentation serve as a paradigm of most common type of battery chemistries. Moreover, the research enables to evaluate and select the various proposals. This can assist to reach a decision for a particular battery selection for an application based on a systematic perception. It can take a long coherence to solve a complex and central question in the field of battery thermal modelling and experimentation.

Using the result, it enables stakeholders to design a future generation of battery thermal management system. The BTMS manufacturers, who could bring cost efficient yet longer lasting BTMS to market as early as possible, are a strong candidate to dominate the future BTMS business consequently harnessing a lion share of profit in the world battery market.

6.2. SHORTCOMINGS

Limitations are discussed here from the perspective of methodology and scope of the research. The shortcomings of the study and directions for future research are intertwined. So many of the solutions regarding shortcomings are placed on future work section (refer to Section 6.3).

The validity of the presented framework can be further examined in other battery cells applying on different ageing levels. More specifically, it is made for finding the temperature distribution when the temperature is on given operating ranges (25°C - 45°C). Since the model is not tuned for extensive temperature limits. For instance, higher temperature is possible (more than 50°C). Besides the model is not parameterised for those phenomena for thermal runaway temperature occurs (around 180°C or more). In the case of failure to show proper caution, the result of the model may provide the results that may not be representative of reality.

Another point is crucial to state and establish the validity of findings of the thermal management research. These include a few focused case studies with the scope, at a particular point in time, are sufficient to ensure the validity of the findings. This is an important issue since this study integrates multiple scales (cell-pack and system) and various levels (multiphysics and techno-economic modelling) of analysis. Similar limitations apply for generalising the findings from the cell to pack level. The techno-economic study is subject to verification by future research works through the proper pilot investigation.

A significant additional limitation that may affect the validity of the research is that the considered different thermal parameters are stemming from various scientific literature and multiphysics material library.A different aspect of the improvement is through an individual level post-mortem analysis of a battery cell that can provide necessary parameter needed for the model. Though the investigation study has proven that those are not extremely necessary to get consistently respectable results out of the model. It should be noted that the generic research framework is to be updated with the specific requirements.

However, future studies with emerging battery types (e.g. Zinc-air) may have different characteristics than this study uses. So, in that case, the frameworks may need a major revision.

6.3. FUTURE WORK

Regarding the developed procedure, the presented modelling seems quite capable; but, a means of further investigations is required to establish its suitability by testing and modelling scores of batteries. However, the research, with a wide selection of batteries, would be ideal; but, the research structure with contemporary systems and resources may be impractical within a short project like a PhD project.

In future, a modeller may require using the frameworks in different interesting areas. A suitable example is quick charge phenomena (charging with high current rate), or one may like to use the framework in the aged cell. The parameter list for the model is needed to be updated depending on the particular requirements. The charging and discharging voltage limits are necessary to be adjusted while accomplishing the experiments. The final results from such an analysis have to be cross-checked using appropriate tests.

There are different other ways to test and measure the heat flux or determine the efficiency than isothermal calorimeter (for instance: adiabatic and differential scanning calorimeter). The results attained with those can be compared to find the best method to calculate the key performance indicator.

To improve the techno-economic model, a better lifetime model is essential. Since the life-length of the battery in the vehicle significantly affects the (per km or year) the impact of the lifetime model is enormous.The possible replacements cost is a factor of assessing in greater detail. It is necessary that it be updated regularly using the latest cost and lifetime information. Besides case-specific driving cycles, coupled with a known chemistry and a certain life-length of the battery system could fully determine the actual impact of the battery system. In this research only indications of the most influential components are considered. Future improvements can, therefore, include collecting case-specific data for modelling one known battery configuration. Ideally, integrating cell, pack and system level would drive the result to improve as much as possible, minimising manual effort.

The results of the computational fluid dynamics model presented are possible to be validated with the experimental correlations of the Nusselt number. Those can be observed in the case of the air flow through an experimental study of a suitable prototype. The comparison of the computation values can outline the level of performances of the produced CFD model.

Adding the electrochemical transportation impact to the assessment would further improve the results. Besides a comparative study with the electrochemical modelling with the current study can accurately benchmark the presented modelling framework performance.

6.3.1. FUTURE WORK HIGHLIGHTS

- Include transportation (e.g. Tesla, Nissan EVs) types and geographical application behaviour (EU, the US driving cycle) details.
- Compare the similar batteries with similar characteristics that stems from a different manufacturer. Those can originate from the various geographic location. The framework is used to find the variability of the manufacturing process.
- Include the assessment of a particular cell chemistry and pack production path.
- Include addition of electrochemical modelling parameters and compare the result.
- Evaluate in detail the cooling system needed for individual scientific cases like extreme conditions in various cooling conditions and its consequences.

CHAPTER 7. CONCLUSIONS

The lessons learned from battery thermal management research is presented. The presented analysis offers a unique and profound knowledge of the battery systems at different levels (cell, pack and system level). The knowledge gap between the pack level and cell level is covered by the various framework schemes. The offered frameworks can be included in the diagnostic framework for the (good, bad or failed) battery. It helps to uncover the cause for substandard operation.

The innovative balanced modelling and experimental framework made the research unique among another state of the art studies. This is accomplished through the utilisation of the systematic approaches for evaluating both technical (multiphysics modelling for cell and pack level) and economic performance (Techno-economic study for battery systems). Moreover, it presents the proof-of-concept of the usage of the calorimetric measurements to address the cell level experimentation.The result of the cell level testing is used in modelling cell and pack. This is possible only because of the development of novel experimentation and modelling frameworks that complement each other.

In the experimental framework, the research presents an electro-thermal testing platform to test large commercial cells safely and efficiently. It is used to build and to profile a battery cell. The research establishes its potential for positive changes in battery driven thermal experimentation domain. To achieve this feat, it has been developed experiment frameworks to measure the important thermal parameters. It contributes to getting efficiency (presented as key performance indicator (KPI)), heat generation at different current rates and temperatures in the diverse operating condition of charge and discharge. Moreover, the experimental framework of the battery cell can be extended for lifetime profiling. The impact is enormous. Using the established experimental framework, the extensive full lifetime modelling can be attained. The results guide to an additional profound comprehension of the efficiency and heat generation of the battery cell.

An applied simulation cell level model is made simultaneously. The result of the model enables to meet a broad range of research requirements for BTMS studies. Unit cell thermal modelling framework is proposed, designed and simulated. To achieve this, thermo-physical characteristics of battery cells are studied in detail.In a three-dimensional manner, the primary results of this investigation are presented for viewing hot-spots of the battery cell. The results show there is a rise of the temperature gradient once the applied load (current) is increased. Through the evaluation of the performance using the developed model based on the calorimetric measurement, it may guide to the complete and convincing decision for optimal BTMS.

The pack level modelling investigation has successfully spotted the influences of the cell-to-cell temperature gradients within the pack. It enables to demonstrate the effect of heat generation. Ultimately it permits to follow the temperature gradient among the battery cells inside the pack. Furthermore, it delivers the significant endorsement of the familiar fact that the proper dissipation measures(e.g. air flow with sufficient velocity) can offer an appropriate thermal management strategy inside a battery pack. The temperature gradient within a particular cell rises with the larger current. This temperature gradient influences the cell to produce additional current, which instigates the warmer segments to increase further in temperature of the adjacent cells inside the pack. Consequently, the positive current temperature feedback can be contradicted by the suitable cooling mechanism. The modelling of the pack is to be regarded as a building unit or block for a battery system inside the desired application.

Therefore, the research result features seamlessly crafted model for both the battery cell and pack level. Thermal modelling tools are able to capture the physical phenomena affecting the behaviour of a battery cell and pack. This development will have a significant impact on the design and optimisation process of battery thermal system. Application requirements, operating conditions as well as battery geometry in a three-dimensional manner are integrated into the framework design.

A comprehensive feasibility analysis is presented of a battery system using techno-economic study. The technique takes into account of primary parameters that effect the performance i.e. battery lifetime and application requirement. Additionally, the technique can be used to determine the feasibility of the presence of any accessories. Those may be introduced over time in order to enhance lifetime for desired battery application. The offered investigation assists as policymaking support for battery researchers, practitioners by studying costs and performance of the battery.All of these have a paramount influence before buying or acquiring a required BTMS.

The results of the research will lead to a more profound understanding of specific battery cell's thermal performance for a particular application. The involvement of the EV and smart grid application is made the research more appealing for the current energy status quo. The experimental and modelling framework is designed to serve both the industry and the academia. The study contributes to the choice of the best battery and safe operation of Li-ion batteries for EV and smart grid applications by finding the optimum battery cell. Using the developed methodology, the effectiveness of the frameworks can be extended up to the more demanding application for instance military and space applications. So the research can be possibly considered invaluable for the expected impact evaluation for the battery industry in general. Moreover, the developed results can regularly be updated with the use of extensive testing and fitting multiphysics modelling.

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APPENDICES

Appendix A. Battery: 13 Amp Hour Lithium-Titanate Battery Cell

Performance Characteristics	**Nominal Values**
Nominal Voltage	2.26 V
Nominal capacity (26 amps [2 C rate] at 25˚C, CCCV charge)	13.4 Ah
Typical high rate capacity (120 amps [9.2 C rate] at 25°C, CCCV charge)	12.7 Ah
Typical energy (26 amps [2 C rate] at 25°C, CCCV charge)	29.7 Wh
Pulse power (130 Amp [10 C rate], 10 sec pulse, 50% SOC at 25°C) (Discharge/Charge)	260 W / 312 W
Pulse power (FreedomCar, 10 sec pulse, 50% SOC at 25°C) (Discharge/Charge)	644 W / 1,166 W
Energy density	146 Wh/l
Power density (Power at 25°C for ten secs is calculated using FreedomCar discharge formulas.)	3,180 W/l
Specific energy	74 Wh/kg
Specific power (Power at 25°C for ten secs is calculated using FreedomCar discharge formulas.)	1,611 W/kg
Internal charge impedance (10 sec DC pulse 50% SOC, at 25°C)	1.4 mΩ
Internal discharge impedance (10 sec DC pulse 50% SOC, at 25°C)	1.5 mΩ
Max continuous charge	130 A
Max continuous discharge	130 A
Pulse charge/discharge rate (10 sec pulse)	260 A max
Internal impedance (1 hertz AC, 10% SOC 25°C)	2.0 mΩ

Life Characteristics	
Cycle life at 2C charge & 2C discharge, 100% DOD, 25°C	>16,000 to 80% initial capacity
Cycle life at 2C charge & 2C discharge, 100% DOD, 55°C	> 4,000 to 80% initial capacity
Calendar life at 25°C	>25 years

Temperature Limits	
Operating and storage temperature range (Optimal storage temperature is 25°C.)	-40°C to +55°C cell temperature

Voltage Limits (In battery systems, the battery management system must enforce the voltage limits at the individual cell level)	
Discharge cut-off voltage at -40°C to +30°C	1.5 V
Discharge cut-off voltage at +30°C to +55°C	1.8 V
Charge cut off voltage at +20°C to +55°C	2.8 V
Charge cut-off voltage at -40°C to +20°C	2.9 V

Cell Dimensions (Cell terminal heights are not included in the stated cell dimensions.)	
Width (W) x Height (H) x Thickness (T; compressed)	204 mm x 129 mm x 7.7 mm
Weight	400 g

Design Standards	
Transportation specifications	UN 3090, UN 3480 compliant

Appendix B. Nomenclature

DOD	Depth Of Discharge (%)
BEV	Battery Electric Vehicle
HEV	Hybrid Electric Vehicle
HPPC	Hybrid Pulse Power Characterisation Test
LTO	Lithium Titanate Oxide
OCV	Open Circuit Voltage
RT	Room Temperature
Soc	State Of Charge (%)
Ah	Ampere Hour
BMS	Battery Management System
BTMS	Battery Thermal Management System
EV	Electric Vehicle
PV	Photovoltaic
Bol	Beginning of Life
Eol	End of Life
FEM	Finite Element Method
LTO	Lithium Titanate Oxide
BTMS	Battery Thermal Management System
HEV	Hybrid Electric Vehicles
PHEV	Plug-In Hybrid Electric Vehicles
PCM	Phase Change Materials
UPS	Uninterruptible Power Supply
ROI	Return of Investment
DTF	Decision Tool Framework

SUMMARY

Last few years' governments are tightening the carbon emission regulations. Moreover, the availability of different financial assistances is available to cut the market share of the fossil fuel vehicles. Conversely, to fill up the gap of the required demand, higher penetration of electrical vehicles is foreseen. The future battery manufacturers strive to meet the ever growing requirement of consumer's demand using the battery as a primary power source of these cars. So naturally, the growing popularity of battery electric and hybrid vehicles have catapulted the car industry in the recent years. The products include for instance: hybrids, plug-in hybrids, battery and fuel-cell-battery electric vehicles (EV) and so forth. Undeniably, the battery is one of the most significant parts in all of those. Furthermore, stationary storage is another aspect of an emerging field. It represents next generation smart grids, for instance, photovoltaic (PV) with battery users. Additionally, the stakeholders in the energy sector are anticipating higher market share of the battery system as different battery powered system is penetrating into the consumer market. Currently, there is a revolution going on the power-system domain. The dumb grids are turning into a smart grid that contains computer intelligence and networking abilities to accommodate dispersed renewable generations (e.g. solar, wind power, geothermal, wave energy and so forth). The battery takes a primary role both as stationary and transportable source of energy in these cases. The phenomenon demonstrates economic and environmental benefits. It changes the fundamental structure of the paradigm of the status quo of the energy system with battery. So battery driven applications have been taken onto the centre stage in the current world. However, while the expanding battery market is alluring, the performance, safety, and security of the EV more specifically battery related thermal management – particularly is a barrier to mass deployment. This represents a non-trivial challenge for the battery suppliers, EV manufacturers, and smart grid developers. The industry is under intense pressure to enhance the performance of the battery. The industry is seeking for a suitable indicator to select the optimum battery showing the accurate efficiency level. It helps to bring products with an optimum efficiency. Furthermore, it assists them to produce tailored product with appropriate efficiency to meet the consumer demand. Moreover, the battery system users can benefit from the better pricing of the system that can provide the desired amount of efficiency. So there may be successful battery product with a higher level of adoption.Ultimately, it helps industrial battery users for example automakers to achieve a higher level of profitability.

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