Computational Fluid Dynamics-based Design Optimisation of an Immersion Cooling Battery Thermal Management System

Ali Almshahy[1,2*], Z. Khatir[1,@], K.J. Kubiak[1,$] and M. Al Qubeissi[3]

[1] School of Mechanical Engineering, Faculty of Engineering and Physical Sciences,
University of Leeds, LS2 9JT, Leeds, UK.
[*]fsvl1319@leeds.ac.uk, [@]Z.Khatir@leeds.ac.uk, [$]K.Kubiak@leeds.ac.uk
[2] Inspection and Asset Integrity Department, Zubair Field Operating Division,
Basra Oil Company (BOC), Ministry of Oil, Basra 240, Iraq.
[2]alebadi899@gmail.com
[3] Department of Mechanical Engineering, College of Engineering & Technology,
University of Doha for Science and Technology, P. O. Box 24449, Doha, Qatar.
[3]mansour.alqubeissi@udst.edu.qa

Abstract

Effective design of battery thermal management system (BTMS) is essential to avoid system complexity, extra costs, and catastrophic battery failure. BTMS plays a significant role in prolonging the life span and ensuring the safety of lithium-ion batteries (LIB) in electric vehicles (EVs) and hybrid electric vehicles (HEVs). Accordingly, direct, also referred as immersion cooling is a potential solution which achieves a high heat transfer rate due to direct contact between the coolant and battery cells. In this work, an optimisation framework for LIB-based BMTS designs is investigated using biodiesel as a coolant by means of a combined computational fluid dynamic (CFD) with a surrogate modelling approach. Palm biodiesel is used as a dielectric coolant, proven to preserve LIBs within the temperature range 20 – 40 ℃, and prevent thermal runaway. The design of the BTMS is formulated in terms of two geometric and one operating design variables: inlet width, battery gap and coolant flow rate. Support Vector Regression (SVR)-based surrogate modelling approach using a Design of Experiment (DOE), and a permutation genetic algorithm is used to establish optimal process parameters.

Keywords: *Li-ion battery thermal management system, Hybrid electric vehicle, Immersive cooling, CFD, Optimisation, Surrogate modelling.*

1 Introduction

Development of LIBs has considerably increased due to applications evolving in the automotive industry, electricity generation using renewable energy, and consumer electronics. In these sectors, progress into reducing greenhouse gases emissions (GHG) and achieving net-zero carbon emissions has been accelerated by international drive to fulfil this goal by 2050 [1]. With that in mind, some factors may need improving, such as operating temperature, temperature uniformity, safety, lifespan, cost, power density, and recyclability [2]. Efficient battery thermal management systems (BTMSs) are vital to enhance temperature homogeneity, lifespan, optimise power capacity, and minimise the potential of thermal runaway [3]. The primary aim of these systems is to manage thermal dissipation and eliminate the heat from the battery pack, hence regulating the maximum temperature and temperature variation among the cells within an acceptable range. There are many cooling strategies for BTMSs: air cooling, indirect cooling, and phase change materials (PCM) [4], [5], [6]. Currently, many of BTMSs shift from passive cooling by using air to liquid cold plate method, referred to as indirect cooling [7], [8]. Whereby, liquid cooling systems have the potential to remove large amounts of heat compared to air cooling, due to their superior specific heat and convective heat transfer coefficient (HTC). However, this added functionality can lead to extra costs, complexity, and increased system weight.

Direct contact, referred to as immersion cooling has a significant attraction for the automotive industry and electronic devices [9]. The current study presents an optimisation framework for LIB-based BMTS designs using biodiesel as coolant. It has been proven by Al Qubessi *at al.* [10] that biodiesel fuel, notably palm, is useful to operate LIB cells at their full potential and maintain their lifespan. Biodiesel fuel in Diesel/battery powered HEVs can lightweight vehicle owing to its low density compared to 3m Novec (commonly used coolant in immersion BTMS) and reuse as heated and ready for combustion. A CFD-based surrogate modelling approach is implemented. BTMS is considered in terms of two geometric design variables: battery space h_b, inlet and outlet width W of the structure, and one operating condition as inlet flow rate Q_{in}. The objective of the optimisation problem is to maximise the temperature difference and minimize the maximum temperature, hence improvement in power capacity and thermal performance. A Design of Experiment (DOE) technique is combined with support vector regression (SVR) and different kernel functions.

2 Methodology

A 3D transient modelling study is conducted to simulate Lithium-ion batteries with their enclosure utilising Ansys-Fluent 2024/R2, while Design modeller V2024/R2 is used for the system design. An 8Ah commercial Li-ion battery prismatic is embedded within four cells in series and two in parallel (4s2p) module configuration. An enclosure approach is incorporated to partially immerse the LIBs module. Rectangular inlet and outlet with baffles guide the coolant around the battery cells. This ensures coolant is in direct contact with the cells surface, thus reducing thermal resistance and increasing thermal homogeneity. Figure 1 shows the battery module and the enclosure configuration.

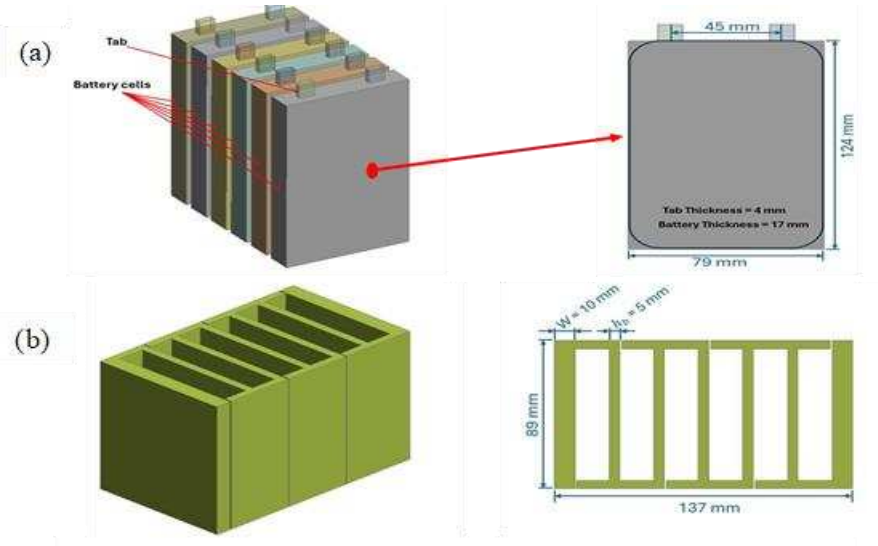

Figure 1. (a) Schematic of battery and (b) Module enclosure.

A grid independence analysis is completed, and it is found that 0.8M cells ensure proper convergence and accuracy in terms of battery temperature and pressure drop.

The numerical model is validated against the experimental work of Sheng *et al.* [11] by simulating transient thermal airflow of a single battery cell without BTMS. The maximum temperature profile of a prismatic battery single cell (8 Ah $LiFeO_4$) at 5C discharge rate is shown in Figure 2. Results agree with the experimental data demonstrating the numerical modelling approach to be reliable. Note that the maximum temperature exceeded 40 ℃ which might lead to a significant risk. An efficient BTMS is thus necessary to optimise such a thermal state for safety.

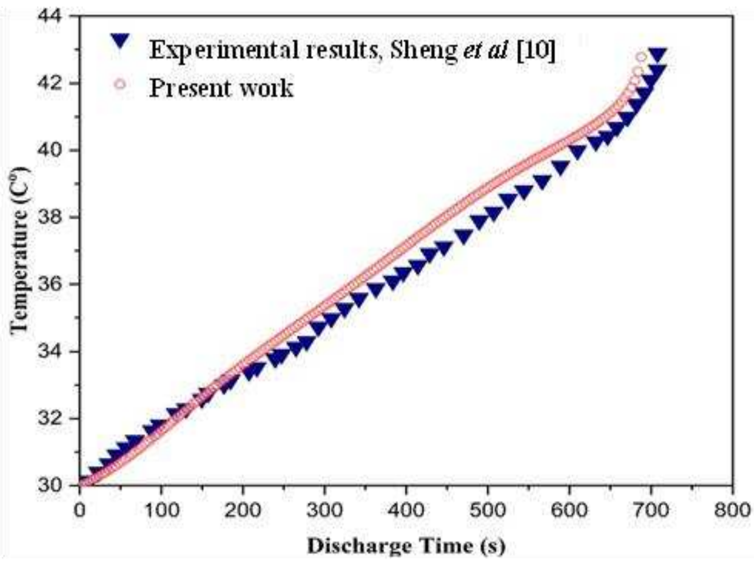

Figure 2. Numerical validation: Comparison with experimental results at 5C-rate [10].

3 Results

In this section, the effect of battery spacing, width inlet and outlet and inlet velocity is analysed using biodiesel coolant. Benchmark data without BTMS is conducted to analyse the thermal performance of battery module by using biodiesel as coolant. The palm coolant inlet and initial temperature is set at 27 ℃. The maximum temperature of Li-ion battery without BTMS is determined at three various discharging rates (5C, 7C, and 9C-rate) to generate the temperature and voltage profiles against time.

Figure 3 shows the battery module temperature profiles, and proves the battery module partially immersed in dielectric coolant to have superior cooling performance compared to without BTMS. The maximum temperature is reduced by 14.12 % and heat generation aligns well with the literature [12], [13], [14].

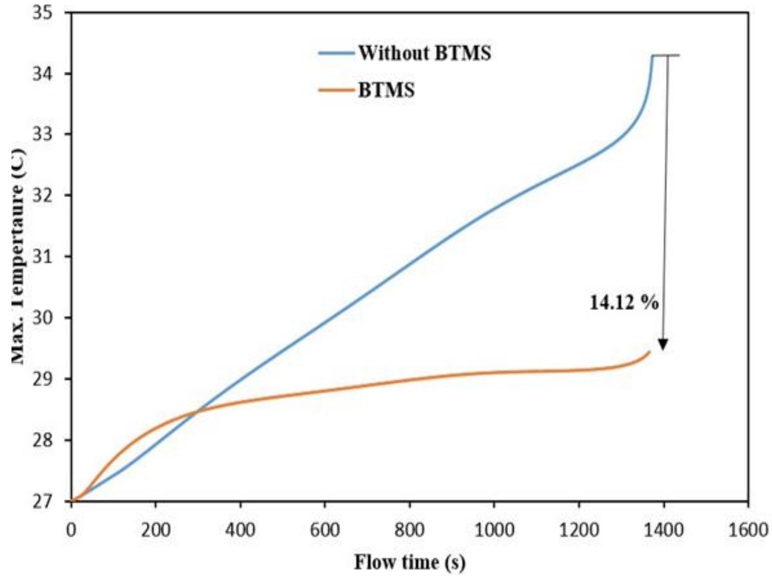

Figure 3. Li-ion battery with and without BTMS, 5C-rates

A radial basis function (RBF) and sigmoid-based functions are implemented to generate two metamodels for

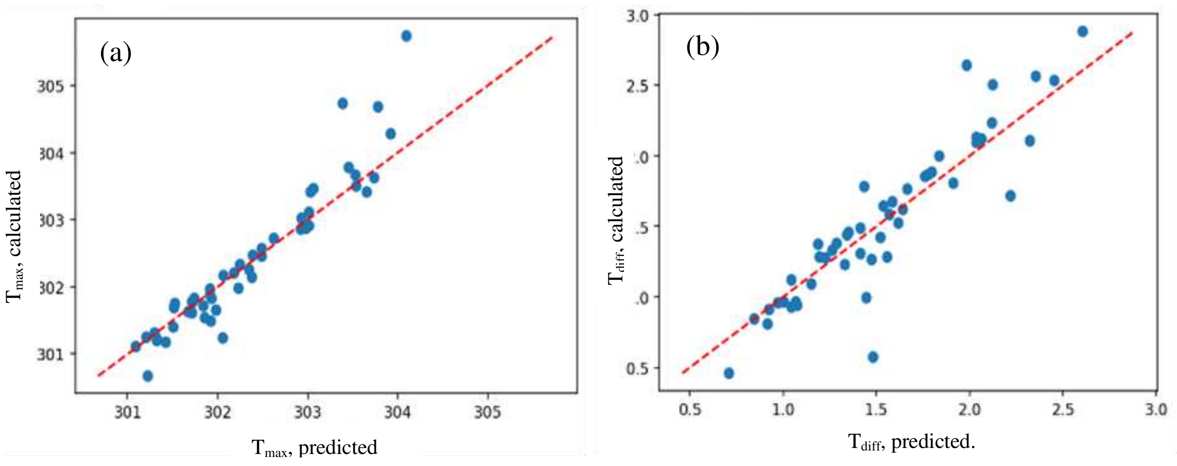

Figure 4. SVR-based metamodels predictions: (a) Maximum temperature, (b) Temperature difference.

both T_{max} and T_{diff} respectively using a Leave-One-Out Cross Validation (LOOCV) approach. Table 1 summarises the metamodeling process and indicates a mean square error (MSE) of 1.43% and 9.78% between the CFD calculated and predicted values for T_{max} and T_{diff} respectively. This demonstrates both metamodels accurately predict T_{max} and T_{diff}, and it is also evidenced in Figure 4.

Table 1. LOOCV for machine learning model

ML Model	Kernel	% MSE
T_{max}	RBF	1.43
T_{diff}	Sigmoid	9.78

4 Conclusion

A CFD-based multi-objective optimisation (MOO) of a BTMS has been achieved using biodiesel coolant. A 50-DOE points via Latin hypercube sampling (LHS) are combined with an SVR-ML approach. An RBF and sigmoid surrogate modelling-based functions are found to be effective for such complex thermal fluid flow systems. Work is in progress to explore a wide range of BMTS designs and build a Pareto front to enable designers to explore appropriate compromises between designs with optimum temperature responses.

References

[1] C. Roe *et al.*, "Immersion cooling for lithium-ion batteries – A review," Mar. 30, 2022, *Elsevier B.V.* doi: 10.1016/j.jpowsour.2022.231094.
[2] E. Fan *et al.*, "Sustainable Recycling Technology for Li-Ion Batteries and Beyond: Challenges and Future Prospects," Jul. 22, 2020, *American Chemical Society*. doi: 10.1021/acs.chemrev.9b00535.
[3] H. Fayaz *et al.*, "Optimization of Thermal and Structural Design in Lithium-Ion Batteries to Obtain Energy Efficient Battery Thermal Management System (BTMS): A Critical Review," Jan. 01, 2022, *Springer Science and Business Media B.V.* doi: 10.1007/s11831-021-09571-0.
[3] H. Fayaz et al., "Optimization of Thermal and Structural Design in Lithium-Ion Batteries to Obtain Energy Efficient Battery Thermal Management System (BTMS): A Critical Review," Jan. 01, 2022, Springer Science and Business Media B.V. doi: 10.1007/s11831-021-09571-0.
[4] Y. Liu and J. Zhang, "Self-adapting J-type air-based battery thermal management system via model predictive control," *Appl Energy*, vol. 263, Apr. 2020, doi: 10.1016/j.apenergy.2020.114640.
[5] M. S. Patil *et al.*, "Numerical study on sensitivity analysis of factors influencing liquid cooling with double cold-plate for lithium-ion pouch cell," Int J Energy Res, vol. 45, no. 2, pp. 2533–2559, Feb. 2021, doi: 10.1002/er.5946.
[6] P. Qin *et al.* , "Experimental and numerical study on a novel hybrid battery thermal management system integrated forced-air convection and phase change material," Energy Convers Manag, vol. 195, pp. 1371–1381, Sep. 2019, doi: 10.1016/j.enconman.2019.05.084.
[7] Chitta S.D. *et al.*, "Comparison of lumped and 1D electrochemical models for prismatic 20Ah LiFePO4 battery sandwich between minichannel", *Appl. Therm. Eng.*, 199 (2021), Article 117586.
[8] C. Akkaldevi *et al.* , "Coupled Electrochemical-Thermal Simulations and Validation of Minichannel Cold-Plate Water-Cooled Prismatic 20 Ah LiFePO4 Battery," Electrochem, vol. 2, no. 4, pp. 643–663, Dec. 2021, doi: 10.3390/electrochem2040040.
[9] Y. Huo and Z. Rao, "The numerical investigation of nanofluid based cylinder battery thermal management using lattice Boltzmann method," *Int J Heat Mass Transf*, vol. 91, pp. 374–384, Aug. 2015, doi: 10.1016/j.ijheatmasstransfer.2015.07.128.
[10] Al Qubeissi *et al.*, "Comparative Analysis of Battery Thermal Management System Using Biodiesel Fuels", *Energies*, 2023, 16, 565. https://doi.org/10.3390/en16010565
[11] L. Sheng *et al.*, "Numerical investigation on a lithium-ion battery thermal management utilizing a serpentine-channel liquid cooling plate exchanger," *Int J Heat Mass Transf*, vol. 141, pp. 658–668, Oct. 2019, doi: 10.1016/j.ijheatmasstransfer.2019.07.033.
[12] A. Adeniran *et al*. J., "Optimizing single-phase immersion cooling system for lithium-ion battery modules in electric vehicles: A multi-objective design approach," International Journal of Thermal Sciences, vol. 210, Apr. 2025, doi: 10.1016/j.ijthermalsci.2024.109636.
[13] L. Sheng *et al.* , "Quantitative measurement of thermal performance of a cylindrical lithium-ion battery," *Measurement* (Lond), vol. 239, Jan. 2025, doi: 10.1016/j.measurement.2024.115458.
[14] S. Panchal *et al.* , "Experimental and simulated temperature variations in a LiFePO4-20 Ah battery during discharge process," *Appl Energy*, vol. 180, pp. 504–515, Oct. 2016, doi: 10.1016/j.apenergy.2016.08.008.