Faculty of Mechanical Engineering

CFD STUDY OF COOLANT FOR BATTERY THERMAL MANAGEMENT SYSTEM

Muhammad Shahir bin Muhamad Zin

Master of Mechanical Engineering (Energy Engineering)

2022

DECLARATION

I declare that this thesis entitled "CFD study of coolant for battery thermal management system" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ....

Name : Muhammad Shahir bin Muhamad Zin

Date : 25/3/2022

APPROVAL

I hereby declare that I have read this report and in my opinion this report is sufficient in terms of scope and quality as a partial fulfilment of Master of Mechanical Engineering (Energy Engineering).

Signature : ....

Supervisor Name : Dr. Fatimah Al-Zahrah binti Mohd Sa'at

Date : 25/ 3 /2022

DEDICATION

For my beloved family who always supported me in this endless pursuit of knowledge.

ABSTRACT

The use of battery thermal management system (BTMS) is a smart solution to lower the temperature of batteries with the use of proper coolant. Batteries with faster charging and discharging rate were often faced with thermal issues that limit its capabilities to perform efficiently. The use of air as coolant in BTMS to improve its cooling performance and reducing the thermal issues were mainly focusing on the structural design optimization that alter the flow of air. The turbulence nature of air later causes the temperature on the battery surface to be fluctuating irregularly. Nanofluid is then proposed as an alternative coolant in this research to reduce the temperature fluctuations in the specified Z-type BTMS design using ANSYS Fluent software. Two-dimensional geometry of both the base model and the optimized parallel plate model were solved using the standard k-ε turbulence model equations with enhanced wall treatment option as the viscous model solver, which require lesser number of iterations needed than SST k-ω to achieve residuals convergence. The accuracy of the model shows considerably large temperature difference on the mesh generated, with 7.4 K and 12.9 K difference on the maximum and minimum temperature of battery compared to the benchmarked result, originating from the conflicted values on the volumetric heat generation (21.6 W instead of 11.8 W) found from published journals, which also contributes to the inaccurate validation of current model. Initial result using sample nanofluid however shows lower maximum temperature on the base model than the parallel plate model, and is selected for consequent simulations. Mixture of singular, oxidized and nitrogenized nanoparticles dispersed in water and ethylene glycol (EG) as the base fluid were then formulated using the general equation of nanofluid with User Defined Function (UDF) codes for temperature-dependent function of the nanofluid material. Characterization of nanofluid is focused first to study the effect of different type of nanofluid on the resultant temperature, with 4% Al_2O_3-water nanofluid (Case 5l) displayed the best cooling capabilities despite having Mouromtseff number of 1.08 at Reynolds number of 2300, lower than some other nanofluid described in this study. Further investigation on the parallel plates model using the selected nanofluid later shows increment of maximum temperature by 0.19 K on the surface area of the battery instead. These fluctuations of temperature and heat flux around the area of the parallel plates were found out to be affected by the swirling effect of the fluid caused by the flow obstruction. This study may help other researchers by establishing a baseline for the cooling performance comparison of coolant using dimensionless numbers of selected nanofluid, with suggestions on future research using even lower range of Reynolds number.

KAJIAN CFD PENYEJUK UNTUK SISTEM PENGURUSAN TERMA BATERI

ABSTRAK

Penggunaan sistem pengurusan haba bateri (BTMS) adalah satu penyelesaian yang pintar untuk menurunkan suhu bateri dengan menggunakan bahan penyejuk yang sesuai. Bateri dengan kadar pengecasan dan nyahcas yang lebih pantas sering berdepan dengan isu-isu haba yang mengehadkan keupayaannya untuk berfungsi dengan cekap. Penggunaan udara sebagai bahan penyejuk di dalam BTMS untuk meningkatkan prestasi penyejukan dan mengurangkan isu-isu terma adalah tertumpu terutamanya pada pengoptimuman reka bentuk struktur yang mengubah aliran udara. Sifat udara yang bergolak seterusnya menyebabkan suhu pada permukaan bateri menjadi berayun secara tidak teratur. Cecair nano kemudiannya dicadangkan sebagai penyejuk alternatif di dalam penyelidikan ini untuk mengurangkan ayunan suhu di dalam reka bentuk BTMS jenis-Z yang ditentukan menggunakan perisian ANSYS Fluent. Geometri dua dimensi bagi kedua-dua model asas dan model plat selari teroptimum telah diselesaikan menggunakan persamaan model pergolakan k-ε standard dengan pilihan rawatan dinding yang dipertingkatkan sebagai penyelesai model likat, yang memerlukan kurang bilangan lelaran diperlukan berbanding SST k-ω untuk mencapai penumpuan sisa. Ketepatan model menunjukkan perbezaan suhu yang agak besar pada jejaring yang dihasilkan, dengan perbezaan 7.4 K dan 12.9 K pada suhu maksimum dan minimum bateri berbanding hasil yang ditanda aras, berasal daripada nilai yang bercanggah pada penjanaan haba isipadu (21.6 W berbanding 11.8 W) yang ditemui daripada jurnal yang diterbitkan, turut menyumbang kepada pengesahan model semasa yang tidak tepat. Keputusan awal menggunakan cecair nano sampel bagaimanapun menunjukkan suhu maksimum yang lebih rendah pada model asas daripada model plat selari, dan dipilih untuk simulasi seterusnya. Campuran nanozarah tunggal, teroksida dan bernitrogen yang disebarkan dalam air dan etilena glikol (EG) sebagai bendalir asas kemudiannya dirumus menggunakan persamaan am cecair nano dengan kod Fungsi Ditentukan Pengguna (UDF) untuk fungsi yang bergantung kepada suhu bagi bahan cecair nano. Pencirian cecair nano difokuskan terlebih dahulu untuk mengkaji kesan jenis cecair nano yang berbeza pada suhu yang terhasil, dengan 4% Al_2O_3-air cecair nano (Kes 5l) menunjukkan keupayaan penyejukan terbaik walaupun mempunyai nombor Mouromtseff 1.08 pada nombor Reynolds 2300, yang lebih rendah berbanding beberapa cecair nano lain yang diterangkan dalam kajian ini. Penyiasatan lanjutan ke atas model plat selari menggunakan cecair nano yang terpilih kemudian menunjukkan kenaikan suhu maksimum sebanyak 0.19 K pada luas permukaan bateri. Ayunan suhu dan fluks haba di sekeliling kawasan plat selari ini didapati dipengaruhi oleh kesan putaran bendalir yang disebabkan oleh halangan aliran. Kajian ini boleh membantu penyelidik lain dengan mewujudkan garis asas bagi perbandingan prestasi penyejukan penyejuk menggunakan nombor tidak berdimensi bagi cecair nano terpilih, dengan cadangan mengenai penyelidikan pada masa hadapan menggunakan julat nombor Reynolds yang lebih rendah.

ACKNOWLEDGEMENTS

Alhamdulillah and praise to Allah the Almighty, for giving me the strength to complete this master project during this challenging time. I would like to express my sincere gratitude to my supervisor, Dr. Fatimah Al-Zahrah binti Mohd Sa'at from Faculty of Mechanical Engineering, Universiti Teknikal Malaysia Melaka (UTeM) for her endless support, patience and encouragement in guiding me throughout the completion of this report, in addition to the new knowledges gained from the sharing sessions conducted with the tasks given had helped me tremendously in achieving the results intended for this study. And also, special thanks to all my fellow postgraduates, colleagues, lectures and staffs that were directly or indirectly involved, for the assistance that contribute towards the fruition of this work.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background

The efficiency of battery in providing energy for practical usage has been the focus of many researchers to provide better performance in terms of its operating condition, life cycle stability, thermal uniformity, energy delivery, and structural design, just to name a few (Deng et al., 2018). As the work is done from the electrochemical reaction inside the battery, ionization process occurs of which causes the electron to flow, and therefore heat is consequently released due to these continuous reactions. These generation of heat may hinder the battery performance if it was not carefully removed from the system, as specific batteries have their own specific operating condition that must be met to avoid degradation.

In each different environment, ambient temperature is crucial in determining the amount of work done to remove or maintain the heat throughout the system. In a hot environment, battery applications at high charging/discharging rate with respect to its maximum capacity liquid cooling, also known as C-rate, is chosen as the most preferable method of controlling the temperature of the battery. Whereas in a cold environment, overheating may not be as bad but the battery module can still at times overheats due to heat generation mechanism especially during the charging/discharging activity and management of heat is still needed so that the battery can perform efficiently (Zhao et al., 2021). Most cooling methods use air as cooling medium due to simplicity of operation and maintenance and it is also easily available. But as technology evolves, the needs to remove the heat become bigger with more overheating conditions are found happening. This indicates that air-cooling method may not be able to provide enough cooling capacity to the battery module when subjected to extreme environment. This leads to degradation of both performance and life cycle of the battery due to low heat transfer coefficient of the air.

To solve this, cooling strategies must be employed to enhance the heat removal process while keeping the battery operation in a good working condition. Cooling method such as using gas, fluid, and phase change material were widely tested by various researchers, both experimentally and numerically, rather than changing the design structure of the battery and other components which may incur more cost. While the design of air cooling system is relatively simple, its low heat capacity especially on the heat removal of high energy density batteries is not as efficient as compared to liquid cooling which have more uniform temperature distribution at the cost of complex system layout (Lu et al., 2020). Among many types of cooling options that are available, nanofluid has emerged as one of the most promising materials to be used as coolant in a battery thermal management system (BTMS). Using nanoparticles that are suspended in a working fluid, the heat transfer on the battery was reported to be improved, and this also reduce the heat leakage of batteries that are close to one another. This heat leakage phenomenon is also known as thermal runaway, and usually happens at higher temperature range.

Nanofluid is associated with a condition where the base fluid is dispersed with micro-sized solid particles for increased thermal conductivity, at the expense of chemical inertness and stability for metal particles as compared to the use of metal oxide particles as the solid particle (Muneeshwaran et al., 2021). Different properties exhibited by different type of nanoparticles in different base fluid has urged researchers to find the optimum condition of each nanofluids at which mixture or concentration of coolant may show promising cooling result. As an example, instead of using mono nanofluid with single nanoparticles over a moving cylinder during a heat treatment cooling process, research showed that by implementing hybrid nanofluid consisting of multiple nanoparticles, the cooling rate is higher resulting from increased thermal boundary layer and reduced velocity of the flow (Elsaid and Abdel-Wahed, 2021). In terms of BTMS where the battery is static and of different shape, nanofluid has the potential to improve the temperature distribution on the surface of the battery due to their higher cooling capability.

1.2 Problem Statement

With the advancement of technologies, various shape, size, weight, and type of batteries have been produced and used in many applications. Commonly used is the lithium-ion battery that operates optimally within 15°C to 35°C temperature range, and any deviation from this range may inflict irreversible damage to the battery and facilitate thermal runaway (Jaguemont and Van Mierlo, 2020). Various studies in BTMS were done to reduce this temperature deviation problem, such as using different type of coolant on the heat transfer medium. The aim of this study is then to examine the effect of using nanofluid to remove heat and maintaining the best temperature of the battery when the BTMS is subjected to channels with parallel plates along its flow path. However, since the volumetric concentration of the nanoparticles correlates with its viscosity and thermal conductivity (Hussein et al., 2014), the pressure drop acting on the system has to be considered together.

Therefore, based on the research gaps found in the literatures, some problems related to BTMS were outlined where aspects related to the thermal properties of the system need to be focused and emphasized on further. These are:

i. Uneven temperature distribution on the BTMS when the coolant used is air or liquid alone (Buidin and Mariasiu, 2021).

ii. Insignificant effect of nanoparticles addition, depending on its type and concentration, to the base fluid on the battery heat rejection at low inlet flow rate (0.01 m/s, 0.05 m/s and 0.10 m/s) regardless of having higher thermal conductivity due to the reduction in heat capacity (Mondal et al., 2017).

iii. Characterization of another novel hybrid nanoparticle additive to enhance the thermal properties of the nanofluid used in a BTMS (Nfawa et al., 2021).

Nevertheless, the expectation for conducting this research is to address if not all, but some of the key underlying issues found in improving the cooling performance of the BTMS, as well as potentially enhancing the thermal properties of the coolant.

1.3 Research Objectives

The main objective of this research project is to develop a computational model of a Z-type BTMS using a finite element analysis (FEA) software and to validate the result obtained by doing comparison with published journals for reference while using different types of coolant to achieve better cooling performance. The validated results will then be evaluated with respect to different aspects of thermal-fluid behaviours such as temperature and velocity contour, as well as the amount of pressure drop within the system using post-processing tools readily available in the software. Dimensionless values such as Prandtl (*Pr*), Reynolds (*Re*) and Nusselt (*Nu*) numbers were therefore determined to accurately describe the state of coolant flow inside the BTMS, with Stanton (*St*) and Mouromtseff (*Mo*) number calculated for additional thermal behaviour characterization. At most, the outcomes that are to be expected from this research analysis are:

i. To model and validate a BTMS cooling system using ANSYS Fluent

ii. To evaluate temperature distribution on the surface of the battery when nanofluid is used as a coolant in BTMS.

1.4 Scope of Study

The focus of this research is mainly on the change of the working fluid of the coolant in the BTMS into nanofluid, in comparison with air as the coolant that were previously studied by past researchers using ANSYS commercial software. However, since there is various type of nanofluids available with different composition, only one is selectively chosen as the working fluid, depending on the specific characteristic exhibited by each nanofluid respectively. Numerical simulation of the research will be made by using:

i. Finite element analysis (FEA) of computational fluid dynamic (CFD) software such as ANSYS, in two-dimensional domain.
ii. Different type of coolant, primarily on mono nanofluid due to a greater number of resources available for references.

1.5 Research Questions

Since the development of nanofluid is relatively new, the data available from journals are limited and sometimes insufficient. Therefore, some questions are raised regarding to this research. Such questions are:

i. How to model the BTMS accurately using ANSYS with the right solver and accurate boundary condition?
ii. What is the impact of using nanofluid as cooling fluid for BTMS?

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter will briefly highlight on the basic of battery thermal management system (BTMS) as well as the development of nanofluid and its characterization, along with the roles and challenges faced in adapting nanofluid as coolant in BTMS.

2.2 Battery Thermal Management System (BTMS)

With the advancement of technology especially in electric vehicles (EV), power storage devices such as battery are expected to have high charging rate, high energy density and high power output (Sharma and Prabhakar, 2021) for efficient usage. The high electron transfer rate inside the battery had resulted some heat to be generated as well, due to internal resistance and electrochemical reactions (Aldosry et al., 2021). This heat generation mechanism will become more prevalent in colder environment due to ambient temperature difference. Thermodynamics studies has shown that the thermal generation of a lithium-ion battery are characterized by three criteria, which were called as reaction heat, polarization heat and Joule heat (Sato, 2001). As with any other systems where the thermal energy is generated internally, an efficient heat removal process from a battery is essential to prevent the power source from overheating. A good BTMS design ensures that the total amount of heat generated will be equal to the total amount of heat removed into the environment.

2.2.1 Classification of BTMSs

Managing heat energy are essential in achieving thermal equilibrium within a system, and for lithium-ion batteries which are highly sensitive to temperature, an environment where the battery can operate without adverse effect is needed to maintain its peak performance, life cycle and operational safety (Patel and Rathod, 2020; Yue et al., 2021). As lithium-ion batteries are widely adopted due to its high electrical performance, the electrochemical reaction inside the battery produces energy and heat, of which the latter need to be effectively removed out of the system. To design such system optimally, understanding the basis of BTMS is key to obtain the best cooling performance. Generally, BTMSs can be classified depending on the type of its cooling method, medium of heat transfer, contact of interaction, battery cell configuration, along with other techniques that involve external structures or cooling medium hybrids (Tete et al., 2021), as summarized in Figure 2.1.

Due to wide array of material selection that can be considered in designing BTMS, a proper physical structure of the enclosure and cooling channel with respect to the battery shape and sizes will affect the heat distribution of the battery. In the article of interest, optimized parallel plates were added on the battery cells at few selected channels to modify the distribution of airflow, inherently improving its cooling efficiency (Wang et al., 2021). Interestingly, the addition of spoilers within a similar Z-type BTMS structure as the experiment mentioned above but with 80° inclination angle at specific height in Figure 2.2 provide better performance in dissipating the heat, although at the cost of increased pressure drop (Zhang et al., 2021). In another example, on prismatic-shaped batteries in particular, a symmetrical BTMS enclosure design reduces the maximum temperature of the battery by 43% with 33% lesser energy consumption, compared with asymmetrical design (K. Chen et al., 2020) as shown in Figure 2.3.

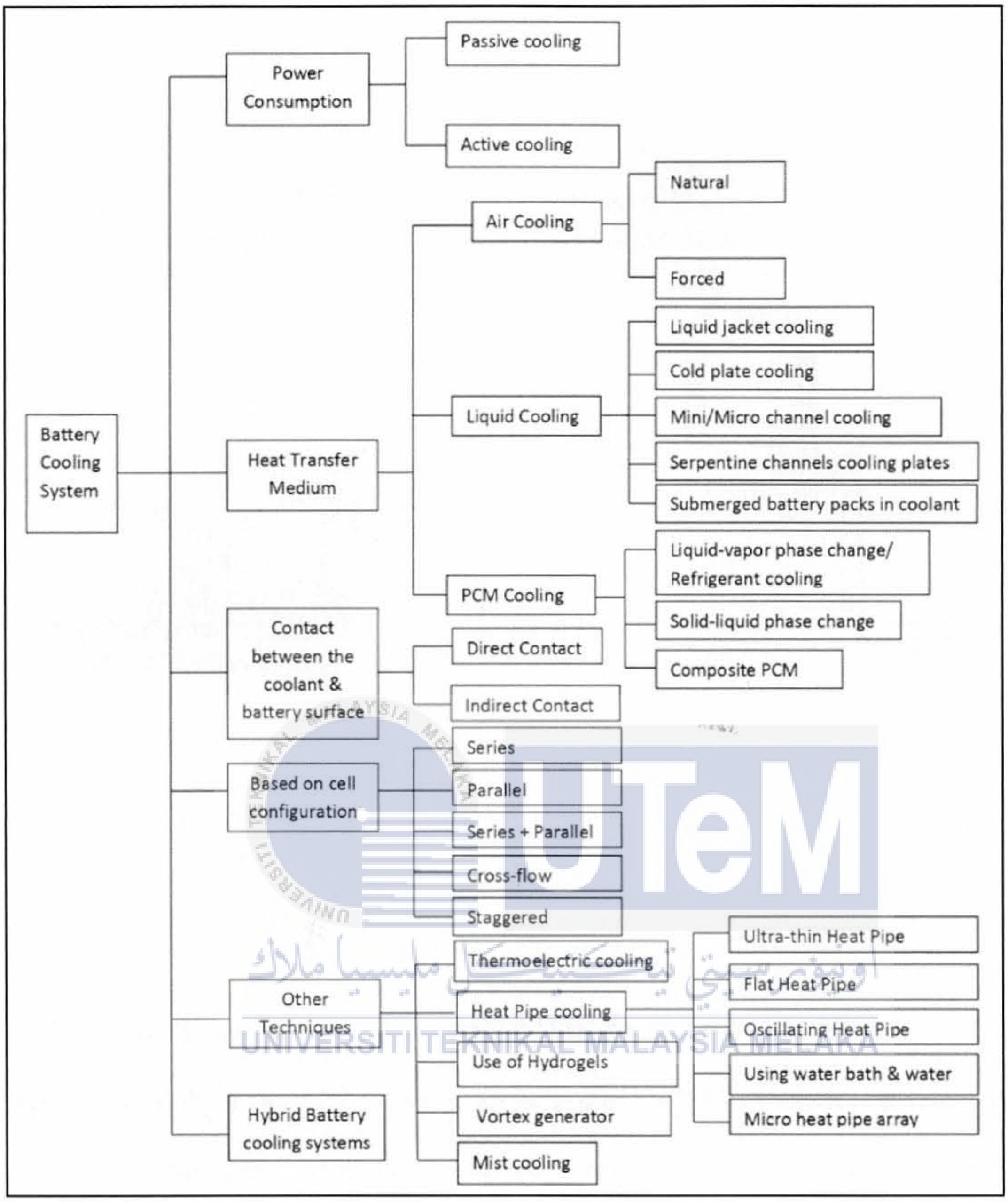

Figure 2.1: Extended classification of BTMS (Tete et al., 2021)

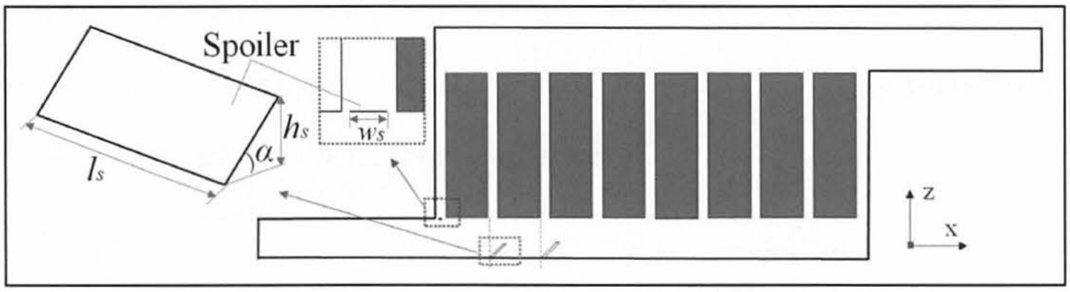

Figure 2.2: Z-type BTMS design with addition of spoilers (Zhang et al., 2021)