HEAT TRANSFER ENHANCEMENT OF LITHIUM-ION BATTERY USING NANOFLUIDS

by

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Thesis submitted in fulfilment of the requirements for Bachelor Degree of Aerospace Engineering (Honours) (Aerospace Engineering)

Endorsement

I, Muhammad Imran Salim Bin Asrab Ali hereby declare that all corrections and comments made by the supervisor and examiner have been taken into consideration and rectified accordingly.

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(Signature of Supervisor)

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(Signature of Examiner)

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DECLARATION

This thesis is a result of my own investigation, except where otherwise stated and has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any other degree.

(Signature of Student)

Date:

ACKNOWLEDGEMENT

First and foremost, I would express my sincere gratitude to Allah S.W.T that he granted me a good health during this project. I had my conflicts eased throughout this research and managed to finish this project in the timescale given.

Next, I would like to thank my supervisor, Ir. Dr. Hussin Bin Mamat for supporting me through this 9-month period with his knowledge. Without Dr. Hussin's encouragement and support, I would have not managed to complete this research. I have learnt a lot during my time under him and getting to know more on industries and recent advancements regarding thermodynamics.

Besides, Mr. Khairil Fadzli Bin Abu Bakar helped me a lot during experimental setup. He guided me with the dos and don'ts which helped me a lot. He suggested many ideas that can reduce heat loss during the experiment such as utilizing thermal paste, thermal tape and covering the test section with thermal insulators. I believe he had helped me to achieve better results during this research.

Apart from that, I would like to thank Mr. Nor Ridwan Bin Mohamed Yusuf who provided ample enough space for us to execute the experiment. He had also helped in getting the right equipment for the experiment without hesitating. He gave freedom in using the laboratory as well, which led to perform experiment without time restrictions.

Last but not least, I feel indebted to my parents Mr. Asrab Ali Bin Shaik Abdul Kader and Mrs. Jahir Nisha Binti O. Amir throughout this research. Since I am this eldest sibling in the house I had a few responsibilities on my younger siblings. Understanding the importance of this project, my parents gave me full freedom during this period of time and did not insist me in helping them by getting back to hometown when I am busy.

HEAT TRANSFER ENHANCEMENT OF LITHIUM-ION BATTERY USING NANOFLUIDS

ABSTRACT

Electric Vehicle (EV) and Hybrid Electric Vehicles (HEV) are seen as the future of motor vehicles. HEVs depend little on conventional fuel and EVs do not depend on conventional fuel. This lead to future vehicle to become more eco-friendly with its low gas emission. The engine of these vehicles is run mainly on electrical supply. A prominent resource for these vehicles is Lithium-ion battery. The performance of Lithium-ion battery is essential for the car to sustain a long-term performance. One of the key factors in ensuring Lithium-ion battery performs to its best is by ensuring the battery is run on its optimal temperature. Battery performance changes dramatically with temperature. Maintaining the temperature of battery is done by cooling. Coolers role in performance of cars has been much bigger for EVs and HEVs. This research focuses on thermal management of battery by thermal enhancement using nanofluids as coolant. Analysis is done experimentally and through simulation to study the best composition of nanoparticles required in nanofluid to enhance heat transfer that leads to maintaining temperature of battery.

PENINGKATAN PINDAHAN HABA BATERI LITHIUM-ION MENGGUNAKAN NANOFLUID

ABSTRAK

Kenderaan Elektrik dan Kenderaan Elektrik Hibrid dilihat sebagai masa depan kenderaan bermotor. Kenderaan Elektrik Hibrid bergantung pada bahan bakar konvensional serta elektrik manakala Kenderaan Elektrik bergantung sepenuhnya pada elektrik. Hal ini menyebabkan kenderaan bermotor pada masa depan lebih mesra alam kerana kenderaan-kenderaan ini mampu mengurangkan pelepasan gas-gas yang merbahaya. Engin kenderaan-kenderaan in mendapat tenaga melalui bateri. Salah satu bateri yang kerap digunakan dalam kenderaan ini ialah Bateri Ion-Lithium. Prestasi Bateri Ion-Lithium memainkan peranan penting dengan memanjangkan jangka hayat engine kenderaan elektrik. Salah satu langkah yang boleh diambil untuk memastikan Bateri Ion-Lithium berfungsi secara optimum adalah dengan mengawal suhu bateri. Prestasi bateri berubah secara drastik bergantung pada suhu. Suhu bateri dapat dikekalkan melalui penyejukan. Peranan penyejuk dalam kenderaan elektrik menjadi lebih penting. Penyelidikan ini memberi tumpuan terhadap pengurusan suhu dalam bateri degan meningkatkan pindahan haba menggunakan nanofluid sebagai penyejuk. Analisa telah dilakukan secara eksperimen dan melalui simulasi komputer untuk mengkaji amaun zarah nano yang sesuai dalam nanofluid untuk meningkatkan pindahan haba. Hal ini dapat mengekalkan suhu bateri pada tahap optimum.

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CHAPTER 1

INTRODUCTION

1.1 Overview

Nanofluid is a fluid engineered by dispersing nanoparticles into a base fluid. Nanoparticles size are usually less than 100 nm. Commonly used nanoparticles are silica dioxide(SiO2), carbon nanotube(CNT), titanium dioxide(TiO2) and zinc oxide(ZnO). There are various uses of nanoparticles. Nanoparticles are dispersed in industrial coatings to protect products made from wood, plastic and textiles from exposure to ultra-violet rays. Other than that, nanoparticles are used to fill in gaps between a material and provide a better strength. Nanoparticles also has an ability to increase heat transfer in fluids. Generally, most nanoparticles consist of metallic elements such as Zinc, Titanium and Silver. As we all know, metallic elements transfer heat better. But metallic elements are mostly in the form of large solids. In contrary, nanoparticles have the same ability to transfer heat but are in the form of granules. This enables the nanoparticles to be mixed in fluid. This leads to increase in thermal properties and improve heat transfer characteristics of base fluid. Since the surface of contact between nanoparticles and heated body has increased, the heat to be transferred quicker. While nanoparticles do have many advantages, some of them are harmful since they very minute is size. Nanoparticles may enter the respiratory system and may lead to certain complications since nanoparticles are mostly metallic substance. Other than that, they are able to pass through cell membranes in human, but the effects are still unknown. Therefore, it is important to wear safety equipment such as face mask, laboratory coats and goggles.

1.2 Motivation and Problem Statement

Nanofluids are being widely used in many applications as well as in thermal management. This is because of their thermal properties are better compared to just using conventional base fluids. By dispersing some nanofluids into conventional base fluids, thermal performance has been proven to increase. While there have been many studies conducted with respect to heat transfer of nanofluids most of them have been comparing several types of nanofluids regarding their performance. Although comparing different types of nanofluids are essential in the study of their heat transfer, the composition of nanofluid is equally important to enhance heat transfer rate. A recent experiment had been conducted with different range of nanoparticle weight percentage, but there were just a few compositions compared. Hence, this research will focus on nanofluids that uses the same nanoparticles but with varying composition of nanofluid will be studied in this experiment.

1.3 Objective

The research work described in this thesis is performed on the following objectives:

i) To produce a stable dispersion and mixing of nanoparticles into base fluid so that consistent dispersion is achieved.

ii) To create an experimental setup to determine the temperature difference when nanofluid is flowed through.

iii) To create a computer simulation of heated body and flow nanofluid through it.

iv) To determine the best composition of nanofluids that can optimally enhance the heat transfer of fluid.

1.4 Thesis Outline

Chapter 1: Introduction

In this chapter, a general introduction to nanoparticles and nanofluids are discussed. Next, this chapter will also be defining the problem statement and objectives regarding this thesis. Besides, thesis outline is described in this chapter to create awareness for the thesis' reader about the project.

Chapter 2: Literature Review

This chapter defines the key terms, terminology, definitions and equations for the thesis. Apart from that, it contains all the readings of journals, papers and articles with respect to the project.

Chapter 3: Methodology

Methodology demonstrates the procedures undergone throughout this project in achieving the results. This chapter includes preparation of material, setting up of experiment, data acquisition in experiment and computer simulation of the study.

Chapter 4: Results and Discussion

This chapter interprets the findings of this project. The results obtained, both in experiment and simulation will be analyzed based on objectives. This chapter also discusses the heat transfer differences in different samples and determines the best composition of nanofluid.

Chapter 5: Conclusion and Recommendations

Chapter 5 summarizes information that has been pointed out throughout this research and focuses slightly on the number of improvements that can be carried out in this research. All the suggestions are being to make sure heat transfer using nanofluids are better utilized in future.

CHAPTER 2

LITERATURE REVIEW

2.1 Electric Vehicle

Transportation has become the most growing factor of the world's fuel consumption, taking up to 49% of oil resources. The efficiency of oil utilization in vehicles is fairly low, so energy saving strategies in transportation will help reduce unnecessary energy consumption without providing extra utility and services. EV reduces up to 20% in GHG emission and further 40% is electricity is generated by renewable energies. High efficiency vehicles may cut CO_2 emissions to 2/3 of the level in 1990 by 2050 (Wang et al., 2016).

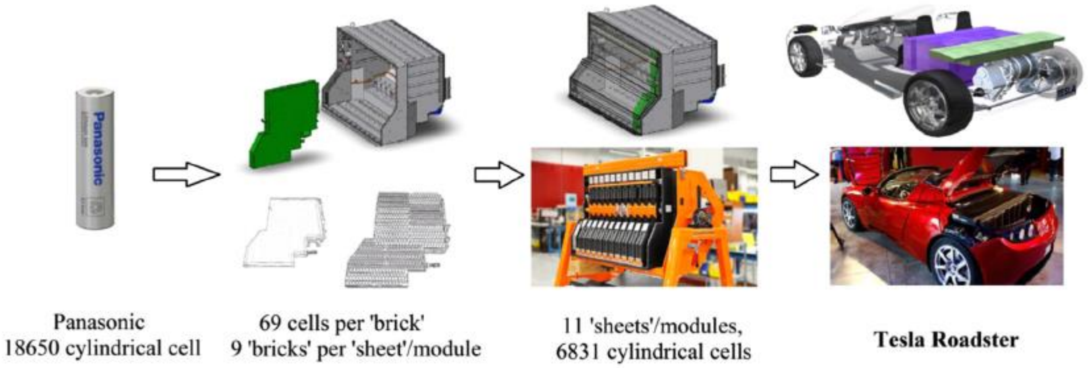
Manufacturers are forced to shift attention to green energy power vehicles due to energy shortage and pollution. EV, HEV and fuel cell electric vehicle are more energy efficient and provides cleaner energy. Electric vehicles demand high specific power and high specific energy to meet its demands. These batteries generate high amount of heat during rapid charge and discharge cycles. Until now, many researchers have concluded EVs, HEVs and FCEVs offer the best possibility for the use of new energy sources (Rao and Wang, 2011).

Table 1.1: Performance parameters of different vehicles (Rao and Wang, 2011)

Vehicle Type	Battery Used	Capacity(Ah)	Energy Efficiency	W/kg for 95% efficiency
Gasoline	-	-	15-20%	-
Diesel	-	-	18-24%	-
HEV	Lead-acid	25	64-87%	77
	Ni-MH	12		195
	Li-ion	12		256
EV	Li-ion (57 V)	106	95%	90
	Silver-Zinc (48V)	126	81%	255
	Li-ion	90	80%	47
	Lead-acid	60		46
	Ni-MH	85		40
FCEV	-	-	60-81%	

2.2 Li-ion Battery

Li-ion battery is a high prospect application in electric vehicle. Li-ion batteries are a leading candidate because EV are environmentally friendly means of transport. During battery operation, each cell warms up because of ohmic and chemical reaction heating as main heat source. According to electro-chemical behavior of the cells, thermal imbalance leads to heterogeneities of aging and state of charge. Therefore, battery thermal management system (BTMS) are required to control the temperature field of all the cells, enhancing safety and lifespan, even reducing its size (Hémery et al., 2014).



Panasonic
18650 cylindrical cell

69 cells per 'brick'
9 'bricks' per 'sheet'/module

11 'sheets'/modules,
6831 cylindrical cells

Tesla Roadster

Figure 2.1: Battery pack of Tesla Roadster

Li-ion batteries has some problems that limits wide usage in electric usage in electric vehicle. For most li-ion batteries, temperature range for discharging is -20℃ to 50℃ and 0℃ to 45℃ for charging(Li et al., 2014). Optimum temperature for Li-ion battery is between 25℃ to 30℃ and cell temperature difference should not exceed 10℃. Battery aging intensifies for a temperature above 45℃ and decomposition begin above 69℃ (Hémery et al., 2014).

Another surfacing problem is the uneven temperature distribution in battery pack leading to localized deterioration. Therefore, to achieve maximum life cycle of cell, module and pack, uniform temperature within a cell and from cell to cell is important (Rao and Wang, 2011). It is important to keep temperature below 60℃ and above 0℃ to avoid thermal runaway (Li et al., 2014) due to overcharging and short circuit (Hémery et al., 2014).

In sub-zero temperature, battery efficiency drops, leaving discharge capacity to be minimal. This affects vehicle mobility, driving range and life cycle of battery. For pure EVs, since there is no combustion engine present to provide heating, significant proportion of battery energy will be used for heating battery and cabin, reducing the range of travel by 30-40% (Wang et al., 2016). Nagasubramaniam states that only 5% of energy density and 1.25% of power density are available compare to battery at 20℃ in 18650 Li-ion battery, signifying importance of thermal management in Li-ion battery (Nagasubramanian, 2001).

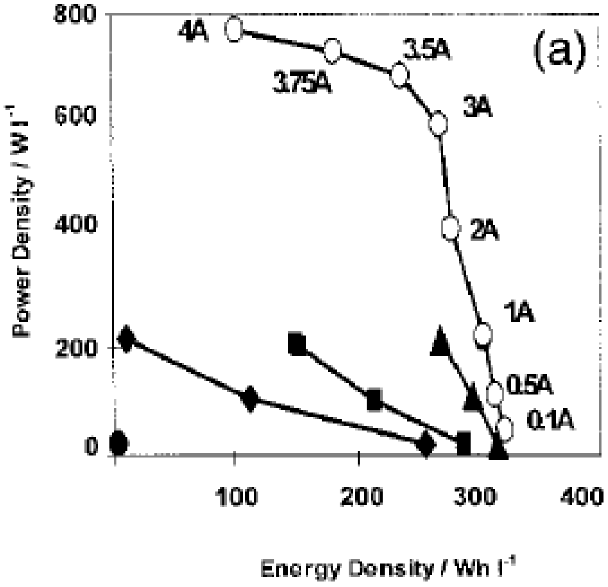


Figure 2.2: Power density against energy density at different temperatures (Nagasubramanian, 2001).

2.3 Battery Cooling System

Temperature effects, heat sources and sinks, EV/HEV batteries and temperature control should be considered before designing a good battery thermal management. Either low or high temperature will progressively reduce the cycle life and threat thermal runaway which leads to cell failure. Battery thermal management is therefore required to help the battery operate at a desirable working temperature range at all times preventing battery degradation.

The thermal management strategies can be either internal or external. Internal cooling is an alternative to allow heat to be rejected through battery surface. There are investigations carried on this subject by Choi and Yao.

Battery thermal management can be categorized into passive (only ambient environment involved), active (a built-in source provides heating or cooling) or based on medium such as air, liquid phase change material, heat pipe or combination of these (Wang et al., 2016).

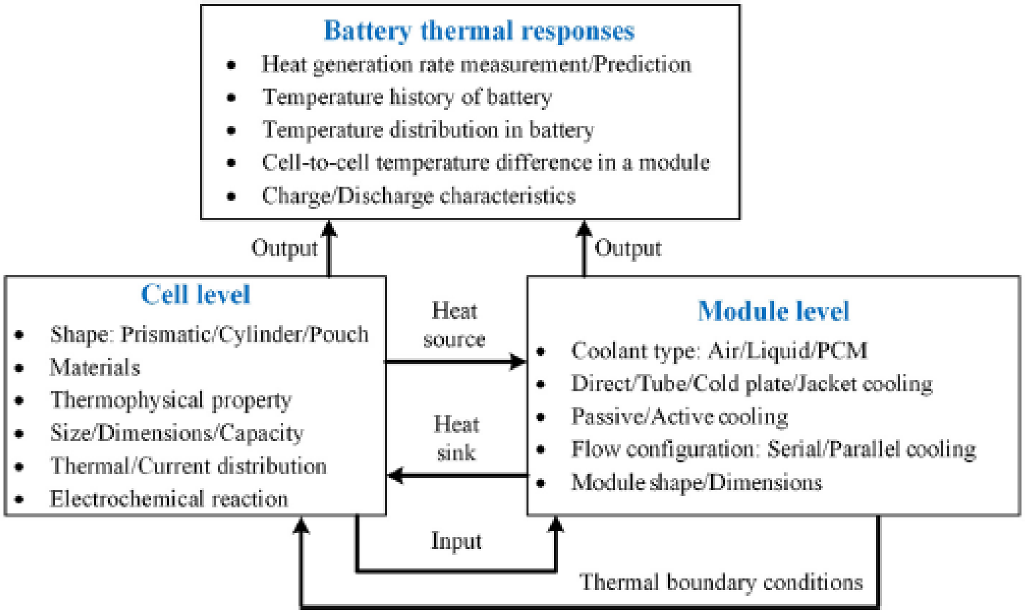


Figure 2.3: Thermal issues and cell module level (Xia et al., 2017)

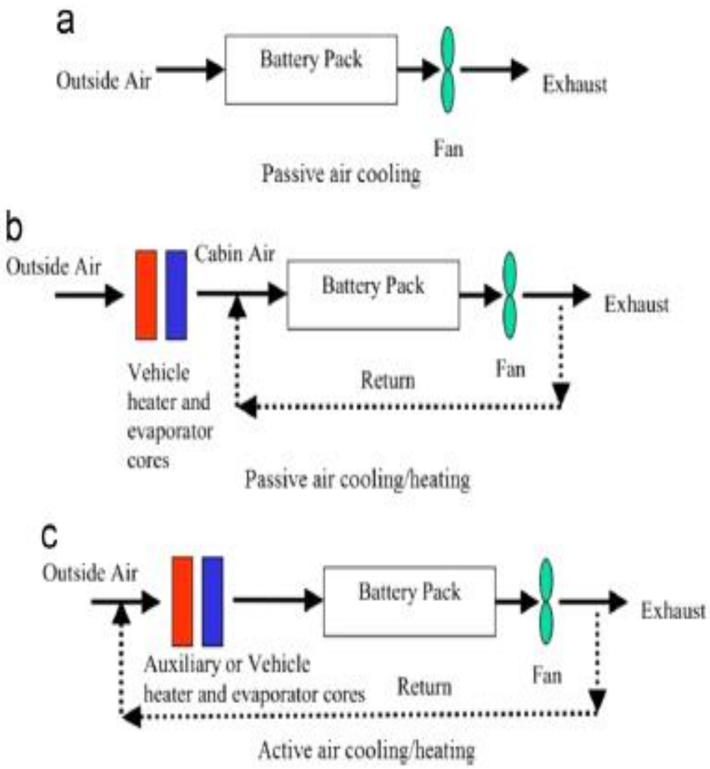


Figure 2.4: Air battery thermal management method (Wang et al., 2016)

Either natural or forced convection can be used for air battery thermal management. The figure above shows three methods of thermal management using air as medium including passive air cooling, passive air cooling/heating and active air cooling/heating. Kim and Pesaran claim that passive air cooling system is possible for application in batteries of low energy density but for high energy batteries such as lithium-ion batteries, active air cooling system is required (Wang et al., 2016).

As opposed to air, liquid has higher thermal conductivity and heat capacity. Liquid battery thermal management is regarded as better solution for. Liquid battery thermal management system can also be divided into passive and active thermal management system. Pesaran qualitatively compared air and liquid method in terms of heat transfer coefficient, thermal conductivity, viscosity, density and velocity of fluid. The degree of temperature distribution for the air flow system due to lower specific heat energy and thermal conductivity seems to be significant. Using oil achieved heat transfer coefficient 1.5 to 3 times higher than air (Pesaran, 2001) with water and glycol more than 3 times higher than air. This indicates that the temperature difference will be reduced to 1/3 of that obtained from air achieving fine temperature uniformity.

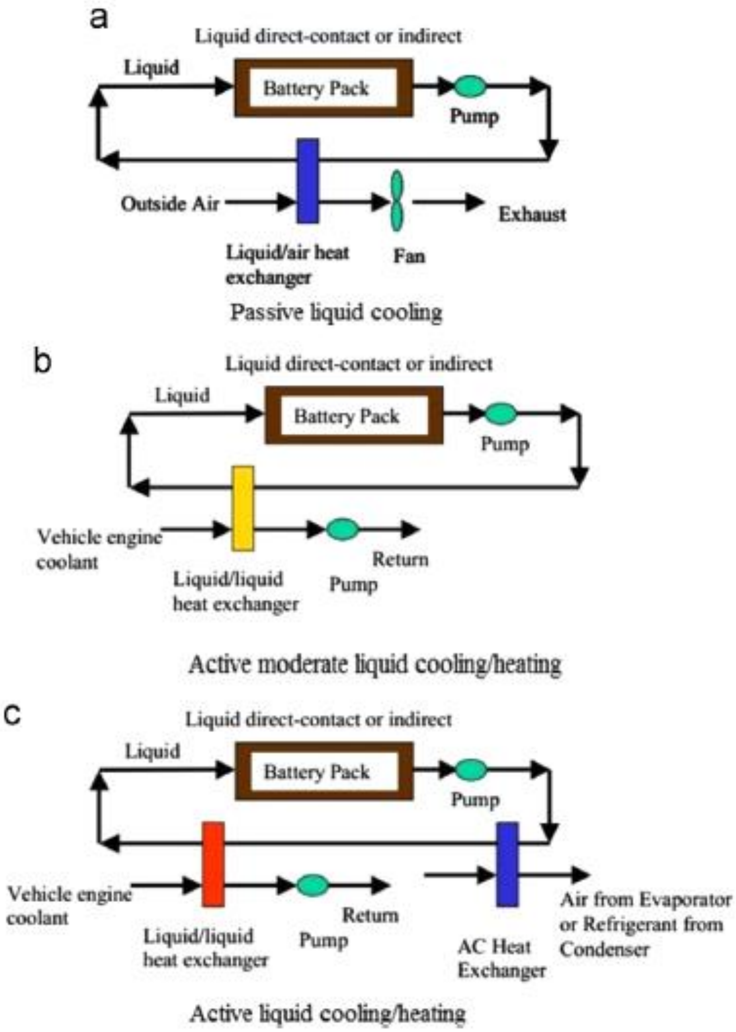


Figure 2.5: Liquid battery thermal management method (Wang et al., 2016)

2.4 Nanofluid

Nanoparticles are particle that measure between 1-100 nm in size. These fluids are used in many applications, especially in heat transfer. Many kind of metallic nanoparticles and oxide nanoparticles are used as additives of nanofluids. Among the additives are CuO, Al_2O_3, TiO_2, SiC and CNT are most commonly studied. The viscosity of nanofluids is one of the essential transport properties for application of heat transfer. Determining the viscosity of the nanofluid is essential for establishing adequate pumping power as well as convective heat transfer coefficient as Prandtl and Reynolds number will be influenced (Hemmat Esfe and Saedodin, 2014).

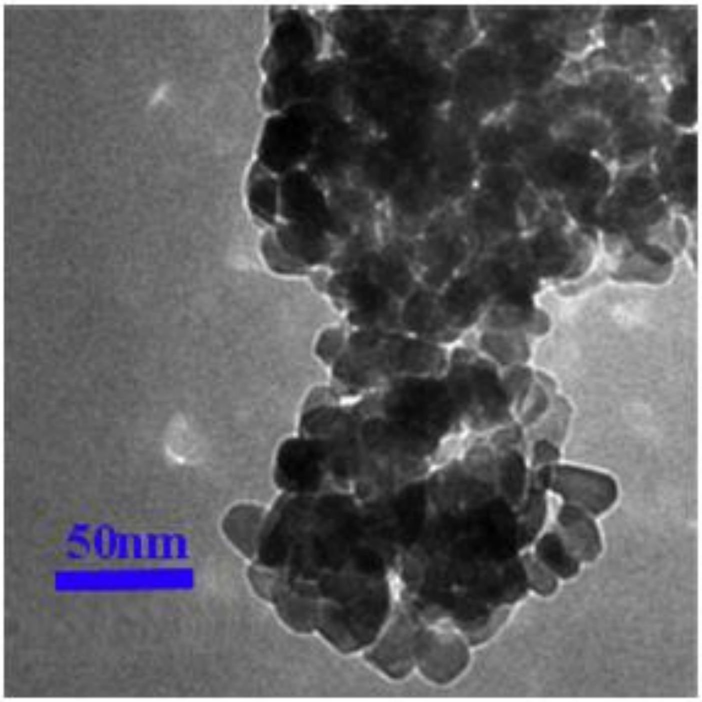


Figure 2.6: Image of ZnO nanoparticles (Li et al., 2014)

Einstein determined the effect of viscosity of a suspension of spherical solids as a function of volume fraction (volume concentration of less than 5%) using phenomenological hydrodynamic equation. This equation was expressed by:

$$\mu_{nf,Einstein} = (1 + 2.5\varphi)\mu_f \tag{2.1}$$

Where μ_{nf} is the viscosity of nanofluid, φ is the volume concentration of nanoparticle and μ_f is the viscosity of base fluid. The effect of Brownian motion on the effective viscosity was given by:

$$\mu_{nf,Batchelor} = (1 + 2.5\varphi + 6.2\varphi^2)\mu_f \tag{2.2}$$

Thermophysical properties of nanofluids are important to calculate the heat transfer enhancement. A well-known mixture model was used to determine the densities and heat capacities of mono and hybrid nanofluids as shown below(Hussien et al., 2017):

$$\rho_{nf} = \varphi_{np1}\rho_{np1} + \varphi_{np2}\rho_{np2} + \ldots + \varphi_{npn}\rho_{npn} + (1 - \varphi_{np})\rho_{bf} \tag{2.3}$$

Where ρ_{nf} is density of nanofluid, ρ_{np} represents the density of nanoparticle and ρ_{bf} is the density of base fluid. Otherwise, for specific heat capacity of nanofluid:

$$c_{nf} = \frac{\varphi_{np1}\rho_{np1}c_{np1} + \varphi_{np2}\rho_{np2}c_{np2} + \ldots + \varphi_{npn}\rho_{npn}c_{npn} + (1 - \varphi_{np})\rho_{bf}c_{bf}}{\rho_{nf}} \tag{2.4}$$

In this equation, c_{nf}represents specific heat capacity of nanofluid, c_{np} represents specific heat capacity of nanoparticle and c_{bf} is the specific heat capacity of base fluid. The Hamilton and Crosser Model was adopted to predict the thermal conductivity of nanofluids. However, Duangthongsuk and Wongwise found that conventional models have no significant effect on thermophysical properties in predicting the convective heat transfer coefficient for low concentrations of nanofluids (Uddin et al., 2016).

$$k_{eff}(T) = k_{bf}(T)\frac{k_p + (n-1)k_{bf}(T) + (n-1)(k_p - k_{bf}(T))\varphi_v}{k_p + (n-1)k_{bf}(T) - (k_p - k_{bf}(T))\varphi_v} \qquad (2.5)$$

$k_{eff}(T)$ represents the thermal conductivity of nanofluid, $k_{bf}(T)$ representing thermal conductivity of base fluid and k_p is the thermal conductivity of nanoparticle.

2.5 Preparation of Nanofluid

Dispersing the nanoparticles uniformly and suspending the stably in the base fluid is critical in producing high-quality nanofluids. Good dispersion and stable suspension are prerequisites for the study of nanofluids properties and for application. The key in producing extremely stable nanofluids is to disperse mono-sized nanoparticles before they agglomerate. Many one-step and two-step chemical processes had been developed for making nanofluids. These processes are summarized as follows:

2.5.1 One-Step Method

The one step method is the process of combining the preparation of nanoparticles with synthesis of nanofluids for which nanoparticles are directly prepared by physical vapor deposition (PVD) technique or liquid chemical method. In this method, the processes of desiccating storage, transportation and discrete distribution of nanoparticles are avoided so that the accumulation of nanoparticles is reduced and stability of fluids is amplified. This one-step process was developed to overcome the van der Waals forces between nanoparticles and produce stable suspension of Cu nanoparticles without any dispersants.

There are some disadvantages for one-step method. One of them is that the residual reactants are left in the nanofluids due to incomplete reaction of stabilization.

2.5.2 Two-Step Method

For two-step method, nanoparticles are first produced as a dry powder by physical or chemical methods such as inert gas condensation and chemical vapor deposition. Since 1930s, the inert gas evaporation-condensation technique has been widely used in the synthesis of ultrafine metal particles. Also, the basic chemical method to make nanoparticles is to have some compound, typically halide, containing a metal atom, as well as reducing agent which removes other parts of the compound.

This is the followed by powder dispersion in liquid. The main advantage of two-step process is aggregation of nanoparticles. Kwak and Kim showed that particles strongly aggregated before dispersion and after dispersion in ethylene glycol with 9 hours of sonication (Uddin et al., 2016).

2.5.3 Some Other Methods

Yuet et al. developed continuous flow microfluidic micro-reactor to synthesize copper nanofluids. By this method, copper nanofluids can be continuously synthesized and their microstructure properties can be varied b adjusting parameters such as reactant concentration, flow rate and additives (Yu et al., 2011). Zhu et al. showed that CuO with high solid volume fraction can be synthesized through a novel precursor transformation method with the help of ultrasonic and microwave irradiation (Wei et al., 2009). Chen and Wang illustrated that phase transfer method is also a facile way to obtain monodisperse noble metal colloids (Chen and Wang, 2008).

2.6 Heat Transfer

There are certain parameters that is required to be determined after the experiment. This is done to find the value of heat transfer coefficient, h and heat flux, q as well as few other parameters. Firstly, to determine heat transfer coefficient, h and Nusselt number, Nu the following equation is applied.

$$h(Z) = \frac{q}{(T_{wi}(Z) - T_f(Z))} \tag{2.6}$$

$$Nu(Z) = \frac{h(Z) \cdot D_{in}}{k_{nf}} \tag{2.7}$$

Where, q is heat flux gained by nanofluids, T_{wi} is inner wall temperature of, Z is the specific distance from initial position of fluid is flown and k_{nf} is the effective thermal conductivity of nanofluid. Heat flux gained by nanofluids can be calculated using equation 2.8

$$q = \frac{Q_{thermal}}{\pi D_i L} \tag{2.8}$$

$$Q_{thermal} = \dot{m} c_{nf} \Delta T \tag{2.9}$$

Where, $\dot{m}$ is the mass flow rate of nanofluid, c_{nf} is specific heat capacity of nanofluid and ΔT is the temperature difference. Inner wall temperature and surface wall temperature is determined using equations below:

$$T_{wi}(Z) = T_{wo}(Z) + \frac{q ln(\frac{D_o}{D_i})}{2\pi l k_s} \tag{2.10}$$

$D_o$and D_i represent inner diameter and outer diameter of the tube used to flow nanofluids, l is the length of tube and k_s is the thermal conductivity of brass. The mean fluid temperature is then obtained using the equation below:

$$T_f(Z) = T_{in} + \frac{q\pi D_i Z}{\rho_{nf} c_{nf} u A} \tag{2.11}$$

T_{in} represents the initial temperature of fluid, u is the velocity of flowing fluid and A is the cross-sectional area of the tube being used.

One of the most famous equations defining the local Nusselt numbers in a circular tube is the Shah equation. These equations are based on experimental work validated with uniform heat flux boundary conditions. This is represented by

$$Nu = 1.953 {Z^*}^{0.333} \qquad Z^* \geq 33.33 \tag{2.12}$$

$$Nu = 4.364 + 0.0722 Z^* \qquad Z^* \leq 33.33 \tag{2.13}$$

Where $Z^* = RePr(\frac{D_{in}}{Z})$ and $Pr = \frac{c_{nf}\mu_{nf}}{k_{nf}}$.

The percentage of heat transfer coefficient can be calculated using the equation below:

$$h_{enhance}\% = \frac{h_{nf}(Z) - h_{water}(Z)}{h_{water}(Z)} \times 100\% \tag{2.14}$$

The mean velocity of the fluid can be calculated by dividing fluid flow rate with cross-sectional area as below:

$$u = \frac{Q}{A} \tag{2.15}$$

CHAPTER 3

METHODOLOGY

There are several stages involved throughout the completion of this project. This includes fundamental studies up until testing of set-up in both experimental and computational method. Initially it started with reading on topic of research, to gain knowledge and ideas on the project in hand. Reading materials consist of articles, journals and books. Then, planning of procedure on executing the project is done. This is done to optimize the resources and time provided for the project. Next, the experimental model is set-up to find the temperature drop in fluid so that heat transfer coefficient can be calculated. Figure below shows the overall chart of process undergone throughout the project:

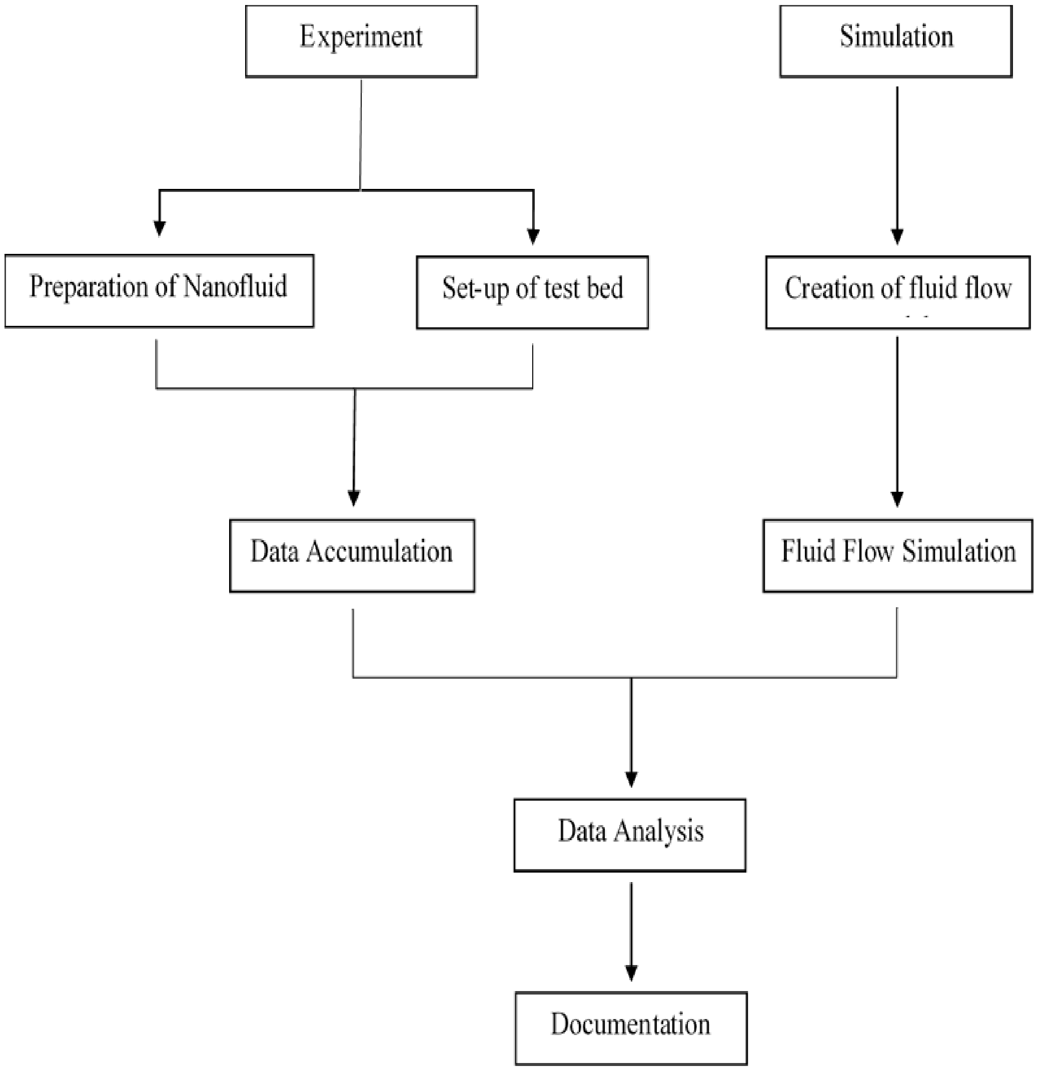


Figure 3.1: Overall flow chart of project

3.1 Experiment

There are a few steps in executing experimental procedure. Firstly, preparation of nanofluid is done. Since nanoparticle is insoluble when mixed with distilled water, few steps are taken so that the nanofluid is dispersed evenly in base fluid. Then, experiment is done to measure temperature drop on tube when fluid is run through.

3.1.1 Preparation of Material

The first attempt in making nanofluids is by purchasing nanoparticles from USAINS HOLDING Sdn. Bhd. and mixing them with base fluid. Multi-Walled Carbon Nanotube (MWCNT) is used as nanoparticle for this experiment and distilled water acts as base fluid. The nanoparticle properties are as shown below:

Table 3.1: Properties of MWCNT nanoparticle

Outer Diameter (nm)	15
Length (micron)	3
Carbon Purity (%)	95
Density (g/cm)	2.1
Thermal Conductivity (W/mK)	3

Nanoparticle weight percentage for the samples are 0.1%, 0.2%, 0.3%, 0.4% and 0.5%. Along with these samples, pure distilled water also was prepared to compare data with nanofluids. Weight of distilled water is set at constant with a value of 200g and nanoparticles are weighed to achieve weight percentage of samples mentioned above.

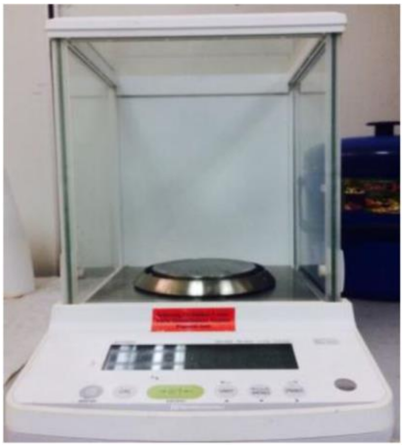


Figure 3.2: Weighing balance used to measure nanoparticle

Although nanofluid has been produced, the mixture is not yet stable. This is because MWCNT are not soluble in water. This causes MWCNT to silt at the bottom of beaker. To overcome this issue, magnetic augmentation is done so that the nanoparticles are dispersed evenly. Dispersant can be used in this case. However, since the experiment is done in a short span of time, dispersants are not used in the mixture.

Figure 3.3: Nanoparticles silt at the bottom of base fluid

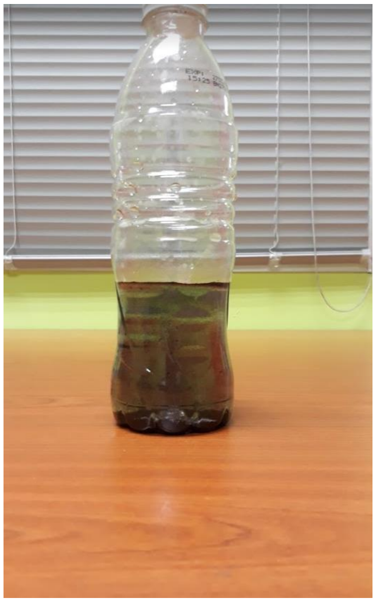


Figure 3.4: Solution is much stable after augmentation

Magnetic augmentation is done by spinning a magnetic capsule in a beaker on a magnetic stirrer. For a better dispersion distilled water is heated to 65°C. Each sample is stirred for 2 hours to gain a stable mixture of nanofluid.

Figure 3.3: Magnetic Stirrer

Figure 3.4: Magnetic Capsule

3.1.2 Experimental Setup

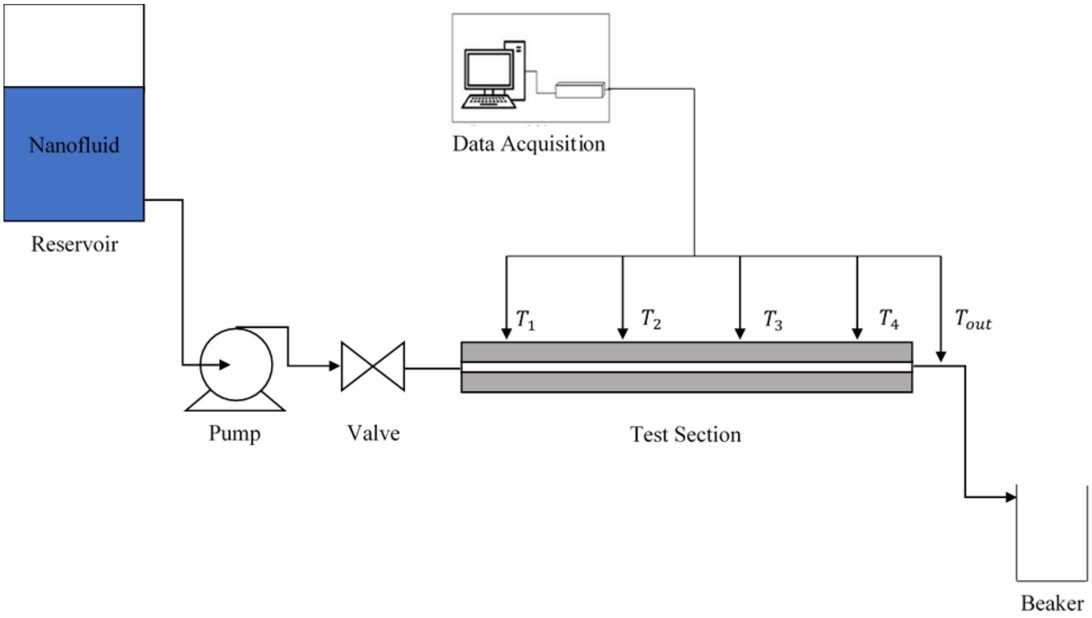


Figure 3.5: Schematic Diagram of Experimental Setup

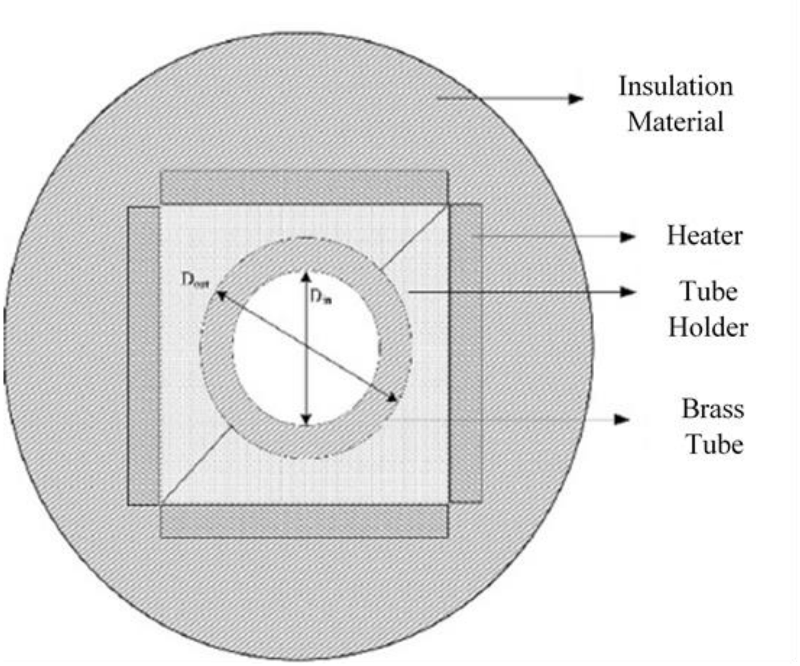


Figure 3.6: Cross-Sectional Area of Rig

An experimental model is setup where fluid is run through a heated rod and temperature difference in both rod and fluid is recorded. Heat is passed through to rod by rig that is surrounded by heater. The heater is connected to a power source that can regulate voltage and manipulate temperature of rod. Since initial temperature of rod is regulated to 50°C, voltage of power source is set to be 85V. For the rod to reach thermal equilibrium, it takes 45 minutes.