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NANOFLUIDS IN BATTERY COOLING SYSTEM

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NANOFLUIDS IN

BATTERY

COOLING

SYSTEM

By

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ENDORSEMENT

I, Lee Chern Khai hereby declare that I have checked and revised the whole draft of dissertation as required by my supervisor.

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ENDORSEMENT

I, Lee Chern Khai hereby declare that all corrections and comments made by the supervisor and examiner have been taken consideration and rectified accordingly.

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DECLARATION

This thesis is the 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:

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NANOFLUIDS IN BATTERY COOLING SYSTEM

ABSTRACT

Thermal implications related to heat generation and potential temperature excursions during operation in lithium-ion batteries are of critical importance for electric vehicle safety, performance and life. Concurrently, appropriate thermal management strategies for lithium-ion batteries are crucial to maintain cell temperatures within a desired range. Hence, the development of nanofluids to improve heat transfer capabilities in car batteries have attracted intense research activities in recent years. Nanofluids, which are stably dispersed or suspended nanosized particles in heat transfer liquids have attracted substantial interest because they offer a promising alternative to the inherent problems of conventional working fluids. Besides, the nanoparticles do not settle in the fluid and do not cause clogging and damage to surfaces as with micron sized particles. The problem statement of the project is to analyze the efficiency of nanofluids as heat transfer fluids for active thermal management in car batteries. The research experimentally investigates the use of silica nanofluids and distilled water. In order to determine the efficiency of nanofluid as heat transfer fluids, experimental data such as Reynolds number, heat transfer coefficient and Nusselt number of water and water based silica nanofluid that flow through a circular tube (Di=0.8 mm) are obtained. The flow was assumed as fully laminar flow with uniform heat flux applied to the tube surface. Different weight concentrations of silica/water nanofluids (0.1, 0.2, 0.3, 0.4, 0.5wt %) were used in the experiment. Based on the data collected, graphs of heat transfer coefficient of nanofluids at different concentrations and distilled water versus axial distance over inner diameter of tube (Z/Di) and % heat transfer enhancement of nanofluis at different concentrations and distilled water versus (Z/Di) were plotted and analyzed. The results concluded that heat transfer coefficient and Nusselt number was significantly enhanced using silica nanofluids as compared to distilled water as heat transfer fluids. Higher values of heat transfer coefficient and Nusselt number indicate that more heat is being transferred from the tube to the fluid which results in a significant reduction of the overall tube surface temperature. The heat transfer enhancement was found to be dependent on the nanoparticle concentrations. The maximum enhancement was recorded for 0.4 wt. % silica nanofluids with 6.9% increase in heat transfer coefficient.

Keywords: Water; Silica nanofluids; thermal management; Reynolds number; Nusselt number; heat transfer coefficient

NANOFLUID DALAM SISTEM PENYEJUK BATERI

ABSTRAK

Implikasi daripada penjanaan haba dan peningkatan suhu semasa operasi bateri lithium-ion perlu diberi perhatian untuk keselamatan, prestasi dan fungsi kenderaan. Oleh itu, strategi pengurusan haba yang sesuai untuk bateri lithium-ion adalah penting untuk mengekalkan suhu optimum bateri. Kajian nanofluid untuk meningkatkan keupayaan pemindahan haba dalam bateri kereta telah berkembang maju pada kebelakangan ini. Nanofluid, iaitu partikel bersaiz nano yang tersebar secara stabil dalam cecair untuk pemindahan haba telah menarik minat para penyelidik kerana nanofluid mampu menyelesaikan masalah yang wujud dalam cecair biasa. Selain itu, nanopartikel tidak menetap dalam cecair dan tidak menyebabkan penyumbatan dan kerosakan pada permukaan sepertimana yang berlaku dengan penggunaan partikel berukuran mikron. Pernyataan masalah untuk projek ini adalah untuk menganalisis kecekapan nanofluid sebagai cecair pemindahan haba untuk pengurusan haba secara aktif dalam bateri kereta. Penyelidikan nanofluid dan air suling telah dijalankan melalui eksperimen. Untuk menentukan kecekapan nanofluid sebagai cecair pemindahan haba, data yang dikumpul melalui eksperimen seperti nombor Reynolds, pekali pemindahan haba dan nombor Nusselt air dan nanofluid yang mengalir melalui tiub berbentuk bulat (Di = 0.8 mm) telah diperoleh. Aliran ini dianggap sebagai aliran laminar penuh dengan fluks haba yang seragam pada permukaan tiub. Kepekatan yang berbeza untuk nanofluid (0.1, 0.2, 0.3, 0.4, 0.5 wt%) telah digunakan dalam eksperimen. Berdasarkan data yang dikumpul, graf pekali pemindahan haba nanofluid pada kepekatan yang berbeza dan air suling berbanding dengan jarak dibahagi dengan diameter tiub (Z / Di) dan graf peningkatan pemindahan haba nanofluid pada kepekatan yang berbeza dan air suling berbanding dengan (Z / Di) telah diplot dan dianalisis. Kesimpulannya, pekali pemindahan haba dan nombor Nusselt telah meningkat dengan ketara dengan penggunaan nanofluid berbanding dengan air suling sebagai cecair pemindahan haba. Nilai pekali pemindahan haba dan nombor Nusselt yang tinggi menunjukkan bahawa lebih banyak haba dipindahkan dari tiub ke cecair dan menyebabkan penurunan suhu pada permukaan tiub yang ketara. Peningkatan pemindahan haba didapati bergantung kepada kepekatan nanopartikel. Peningkatan maksimum direkodkan oleh nanofluid silika dengan kepekatan berat sebanyak 0.4 wt. % di mana peningkatan pemindahan haba adalah sebanyak 6.9%.

Kata kunci: Air; nanofluid silika; pengurusan haba; nombor Reynolds; nombor Nusselt; pekali pemindahan haba

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LIST OF ABBREVIATIONS

Al_2O_3	: Alumina
bf	: Base fluid
BTMS	: Battery Thermal Management System
CPU	: Computational processing units
CuO	: Copper (II) oxide
EG	: Ethylene Glycol
enhanc.	: Enhancement
Fe_2O_3	: Ferum(III) oxide
Li	: Lithium
LIB	: Lithium-ion batteries
MEG	: Mono-Ethylene Glycol
MgO	: Magnesium oxide
MWCNT	: Multi-walled carbon nanotube
nf	: Nanofluids
Nu	: Nusselt number
p	: Nanoparticle
Pr	: Prandtl number
Re	: Reynolds number
RMF	: Rotating magnetic field
SiO_2	: Silica
TiO_2	: Titanium oxide
WO3	: Tungsten (III) oxide
wt.	: Weightage
ZnO	: Zinc oxide

LIST OF SYMBOLS

A	: Cross-sectional area [m^2]
C	: Specific heat capacity [J/kg.K]
D_{in}	: Inner diameter [m]
D_o	: Outer diameter [m]
h	: Convective heat transfer coefficient [$W/m^2.K$]
k	: Thermal conductivity [W/m.K]
L	: Length of mini-tube [m]
n	: Empirical shape factor
q	: Heat flux [W/m^2]
Q	: Volume flow rate [m^3/s]
T_f	: Mean fluid temperature [K]
T_{in}	: Inlet temperature [K]
T_{out}	: Outlet temperature [K]
T_{wi}	: Mini-tube inner wall temperature [K]
T_{wo}	: Mini-tube outer wall temperature [K]
u	: Flow velocity [m/s]
Z	: Axial distance along mini-tube [m]
μ	: Dynamic viscosity [Pa.s]
ρ	: Density [kg/m^3]
ϕ_v	: Volume concentration [%]

CHAPTER 1

INTRODUCTION

This chapter presents the current heat transfer problem faced by conventional fluids and the importance of the development of nanofluids to improve the thermal performance in car battery cooling system. This chapter also sets forth the experimental hypothesis to be tested and the research objective to be attained.

1.1 Importance of Development of Nanofluids

Due to extensive usages of battery in many electronic devices and transport industry, Battery Thermal Management System (BTMS) has attracted extensive considerations and research in recent years (Xiong et al., 2014). Lithium-ion batteries (LIB) provide the best solution for energy storage in both small and large format applications such as consumer electronics and electric vehicles, due to their high specific energy and power capability. A battery module includes multiple Li-ion cells connected in series and parallel for use in electric vehicles. However, lithium-ion batteries are very sensitive to temperature compared to other chemistries, and can suffer both in safety and performance if exposed to high or imbalanced temperatures (Bandhauer et al., 2011). The range of operating temperature for lithium-ion battery is within 0-45°C. Local temperature enhancement in battery packs can damage batteries, cause battery imbalance, shorten battery life and reduce battery available power and/or energy. Therefore, efficient cooling strategies are very important issues in thermal management of battery system and these techniques should provide cost effective and energy saving solutions for temperature rise of the system during battery operation (Sefidan et al., 2010).

Various strategies have been employed for battery thermal management which can be classified into different types. In particular, there are two basic types of battery systems for hybrid car vehicle. The most common type is the passive cooling system which involves air movement and utilizes ambient air with no additional cooling. The other type is the active cooling system that utilizes a refrigeration system and can be divided into a liquid based cooling system and an air based cooling system.

In liquid based cooling system, it is clear that all conventional liquid coolants in used today exhibit rather poor thermal conductivity when compared to solid metals based on their thermal properties. Despite obvious improvement over air based cooling system, several methods have been proposed to further enhance the thermal conductivity of liquid coolants (Mondal et al., 2017). One way is to disperse nano-sized solid particles with high thermal conductivity into a liquid coolant to improve thermal properties of heat transfer fluids known as nanofluids. Nanofluids has since emerged as a new class of heat transfer fluids and has been the subject of significant contemporary research.

Nanofluids are colloidal suspensions of one nanoparticle in a base fluid (Mondal et al., 2017) while hybrid nanofluids contain two dissimilar nanoparticles dispersed in a single component base fluid or a mixture of base fluids (Hemmat et al., 1954). The characteristic dimension of a nanofluid is in the range of 1-100 nm. The commonly used nanoparticles types are silica, MWCNT and alumina while the base fluids used in the preparation of nanofluids are usually distilled water, oil and glycol. The addition of nanoparticles into a liquid alters its thermal properties such as thermal conductivity and viscosity. The higher thermal conductivity of nanofluids can be attributed to various molecular level mechanisms like micro-convection induced Brownian motion, interfacial liquid layering and particle clustering. The factors that influence the thermal conductivity and viscosity of nanofluids are size and shape of nanomaterials used, nanomaterial concentration, viscosity of base fluid, interaction between nanomaterial and base liquid molecues, surfactant used, dispersion PH etc. (Choi et al., 1995). The heat transfer coefficient of nanofluids depends on many factors such as Reynolds number, specific heat capacity of nanofluids and temperature difference between inlet and outlet. By increasing the Reynolds number, it results in higher mass flow rate and consequently higher heat transfer coefficient.

On the other hand, there is also disadvantage in the use of nanofluids. For a fixed value of Reynolds number, there exists a concentration limit of nanoparticles in the nanofluids Therefore, further increase in nanoparticles concentration beyond this limit would not result in any appreciable effect on the heat transfer enhancement due to agglomeration of nanoparticles.

1.2 Experimental Hypothesis and Research Objective

In the current research work, the experimental hypothesis to be tested is that silica nanofluids is a better heat transfer fluid as compared to distilled water. By increasing silica nanoparticle concentration, the thermal properties of silica nanofluids are enhanced. The main objective of this research paper is by utilizing silica water based nanofluids to increase the heat transfer coefficients and Nusselt number.

1.3 Thesis Outline

Chapter 1 presents the current heat transfer problem faced by conventional fluids and the importance of the development of nanofluids to improve the thermal performance in car battery cooling system as well as the experimental hypothesis to be tested and the research objective to be attained.

Chapter 2 presents the review of literature done on the history of development of nanofluids used in thermal applications such as car radiator, cooling system for computational processing units (CPU), solar system etc and the review of literature done on thermal enhancement of mono-nanofluids and hybrid nanofluids which act as a base for the determination of heat transfer enhancement of silica nanofluids in this paper.

Chapter 3 presents the technique used in the current research work on nanofluids in battery cooling system, the nanofluids specifications, nanofluids preparation process, experimental setup and all mathematical equations used for the calculation of heat transfer characteristics of nanofluids including the equation developed to validate the experimental results.

Chapter 4 presents all the theoretical and experimental data collected in the form of tables, experimental data analysis on the heat transfer enhancement of silica nanofluids and experimental validation in the form of figures and texts.

Chapter 5 presents the significance of the study on heat transfer enhancement of silica nanofluids, findings upon which a conclusion can be made in relation to the main objective set, limitations of the current study and suggestions on further research which may be carried out on thermal performance of nanofluids.

CHAPTER 2

LITERATURE REVIEW

This chapter presents the review of literature done on the history of development of nanofluids used in thermal applications such as car radiator, cooling system for computational processing units (CPU), solar system etc. This chapter also presents the review of literature done on thermal enhancement of mono-nanofluids and hybrid nanofluids which act as a base for the determination of heat transfer enhancement of silica nanofluids in this paper.

2.1 Literature Review on Development of Nanofluids

Due to extensive usages of battery in many electronic devices and transport industry, Battery Thermal Management System (BTMS) has attracted extensive considerations and research in recent years (Xiong et al., 2014). Before the introduction of nanotechnology in electric vehicle battery cooling system, there were only two battery thermal management methods used which include passive or forced air convection cooling system, oil cooling system and pure water cooling system. Efficient cooling strategies are very important issues in thermal management of battery system and these techniques should provide cost effective and energy saving solutions for temperature rise of the system during battery operation (Sefidan et al., 2010). Maxwell (1873) was the first person to propose the possibility of increasing thermal conductivity by increasing the volume fraction of solid particles in a solid-liquid mixture. However, large particles can cause low flow rate sedimentation, clogging and erosion of channels and pipes as well as increase in pressure drop. Choi (1995) from Argonne National Laboratory, USA introduced the concept of using nanotechnology in thermal engineering to develop efficient heat transfer fluids in which smaller nanoparticles are used in a new class of fluid called nanofluids to improve both thermal conductivity and suspension stability and presented the benefit of using the nanoparticles dispersed in a base fluid in different thermal systems to enhance the heat transfer rate.

2.2 Literature Review on Thermal Enhancement of Mono-Nanofluids

Bellos et al. (2018) investigated the thermal analysis of parabolic trough collector operating with 3% Al2O3/Oil and 3% TiO2/Oil conducted on turbulent flow conditions. They found that the thermal efficiency enhancement for the mono nanofluids is up to 0.7% for inlet temperatures from 300 K to 650 K. Dattatraya et al. (2018) carried out experimental investigation of heat transfer potential of Al2O3/Water-Mono Ethylene Glycol nanofluids as a car radiator coolant. They studied the nanoparticle volume fraction in the range of 0.2–0.8% and inlet temperature of 65-85% and showed that the heat transfer performance of radiator is enhanced by using nanofluids compared to conventional coolant with nanofluids of 0.2% volume fraction having a 30% rise in heat transfer being observed. Heidari et al. (2018) carried out experimental investigation on using ferrofluid and rotating magnetic field (RMF) for cooling enhancement in a photovoltaic cell. In the study, pure deionized water and Fe3O4-water nanofluids with different volume fractions (ϕ = 0.01, 0.02, 0.03, 0.04 and 0.05 (w/v)) were used as cooling mediums and thermal efficiency of 30% was attained for B = 880 mT, ω = 30 rad/s and ferrofluid concentration of 0.05 (w/v). Omer et al. (2018) studied the thermal conductivity and viscosity models of metallic oxides nanofluids (Al2O3, CuO, SiO2 and ZnO) for nanoparticle concentrations of 1–5 vol% at temperatures of 300–320 K and nanoparticle shapes (blades, platelets, cylindrical, bricks, and spherical). They showed that the effective thermal conductivity and thermal conductivity ratio of the metallic oxide nanofluids increase with temperature and nanoparticles volume fraction. Suhaib et al. (2017) carried out stability and thermal analysis of MWCNT-thermal oil-based nanofluids at concentrations of 0–1 wt. % and found that the effective density, effective viscosity and effective thermal conductivity increase with nanoparticle concentration but the effective specific heat capacity and coefficient of thermal expansion decrease with nanotube concentration.

2.3 Experimental Works on Metallic Oxide Nanofluids

Table 1 shows some of the recent experimental works on metallic oxide nanofluids and their applications.

Table 2.1: Experimental Works on Metallic Oxide Nanofluids

Reference	**Nanofluids**	**Application**	**Main finding**
Luo et al. (2014)	TiO_2, Al_2O_3, SiO_2, in Texatherm oil	DAC solar collector	Nanofluids improves efficiency of solar collector.
Aghayari et al. (2015)	Fe_2O_3/water	Double pipe heat exchanger	Addition of nanoparticles increases the heat transfer and the Nusselt number.
Mutuku (2016)	CuO, Al_2O_3, TiO_2	Automotive radiator	CuO–EG nanofluids lead to a rapid decrease of temperature at the boundary layer.
Dattatraya & B.M.Ramani (2017)	Al_2O_3/MEG–water	Car radiator coolant	8.5% enhancement in thermal conductivity observed for 0.8% volume fraction nanofluids at 30 °C.

2.4 Literature Review on Thermal Enhancement of Hybrid Nanofluids

Bellos et al. (2018) investigated the thermal analysis of parabolic trough collector operating with hybrid nanofluids (1.5% Al_2O_3-1.5% TiO_2/Oil) at inlet temperatures from 300 K to 650 K and discovered the thermal efficiency enhancement for the hybrid nanofluids reaches up to 1.8% due to Nusselt number enhancement for the hybrid nanofluids which is about 2.2 higher than the respective for operation with pure oil. Minea et al. (2018) investigated the influence of hybrid nanofluids on the performance of parabolic trough collectors in solar thermal systems. They noted an increase in average Nu is for the Cu-MgO hybrid at 2% volume concentration, where the escalation is almost 14% in comparison with the base fluid. . Plus, the collector efficiency rises while Re increase and the 2% Ag-MgO-water hybrid nanofluids offers the maximum efficiency of the solar collector. Kakavandi et al. (2018) carried out experimental investigation of thermal conductivity of nanofluids containing of hybrid nanoparticles suspended in binary base fluids and propose a new correlation. The thermal conductivity of the hybrid nanofluids was measured using KD2-Pro thermal analyzer and the KS-1 sensor at a temperature range of 25–50 °C and a solid volume fraction range of 0–0.75% and the results show the maximum thermal conductivity of the nanofluids increased up to 33% relative to the base fluid at a temperature of 50 °C and a concentration of 0.75%. Aberoumand et al. (2018) studied the preparation, stability, thermal conductivity and dielectric strength of Tungsten (III) oxide (WO_3) – silver/transformer oil hybrid nanofluids in three different weight fractions of 1%, 2% and 4% and temperature range of 40–100 °C. They found that thermal conductivity of applied hybrid nanofluids increased by 41% in higher weight fraction and 100 °C. Hussein (2017) studied the thermal performance and thermal properties of hybrid nanofluid under laminar flow in a double pipe heat exchanger. The aluminium nitride/ethylene glycol hybrid nanofluids is prepared with the volume fraction of 1–4% and having the size of diameter 30 nm and the results show that thermal performance of hybrid nanofluids could drastically augment the thermal performances of a heat exchanger in comparison with base fluid up to 35% at high volume fraction.

2.5 Literature Review on Preparation Method of Nanofluids

Beck et al. (2010) experimentally investigated the thermal conductivity of alumina nanofluids in water, ethylene glycol, and ethylene glycol + water mixtures. Nanofluids were prepared by dispersing pre-weighed quantities of alumina into either de-ionized water or ethylene glycol. The samples were subjected to ultrasonic agitation to break up any aggregates, and the pH was adjusted to a value of 4.0 ± 0.2 by the addition of HCl. Sekhar et al.(2015) studied the viscosity and specific heat capacity characteristics of water-based Al_2O_3 nanofluids at low particle concentrations. The nanofluids samples were prepared by adding a very small concentration of the sodium dodecylbenzene sulfonate surfactant to the base fluid which is much lower than its critical micelle concentration to improve the dispersion of the particles. Silambarasan et al. (2012) studies the viscosity and thermal conductivity of dispersions of sub-micron TiO2 particles in water prepared by stirred bead milling and ultrasonication. The nanofluids samples were prepared by mechanical milling. Milling was performed for a total time of 12 h; initial milling for 6 h was carried out using 0.4 mm grinding media while another 6 h of milling was carried out using 0.2 mm grinding media. Lee et al. (1999) measured the thermal conductivity of fluids containing oxide nanoparticles. Nanofluids are produced by dispersing nanometer-scale solid particles into liquids such as water, ethylene glycol, or oils. Gas-condensation processing was then used to produce nanocrystalline materials. Turgut et al. (2009) investigated the thermal conductivity and viscosity measurements of water-based TiO_2 nanofluids. The nanofluids was prepared by dispersing TiO2 nanoparticles in deionized water by using ultrasonic vibration to obtain well-dispersed nanofluids.

CHAPTER 3

METHODOLOGY

This chapter presents the technique used in the current research work on nanofluids in battery cooling system. This chapter presents the nanofluids specifications, nanofluids preparation process and the experimental setup. All mathematical equations used for the calculation of heat transfer characteristics of nanofluids including the equation developed to validate the experimental results are also discussed in this chapter.

3.1 Nanofluids Specifications

In this work, silica nanofluids is chosen as the heat transfer fluid due to its simple preparation, availability and reasonable cost. Silica nanofluids consist of silica nanoparticles dispersed in distilled water to enhance its heat transfer properties.

Therefore, in this section, the specifications of both silica nanoparticles and distilled water will be discussed further in detail.

3.1.1 Silica Nanoparticles Specifications

In this experiment, commercial SiO_2 were purchased from Sigma-Aldrich chemical company to prepare the silica water based nanofluids. The specifications of SiO_2 are presented in Table 3.1. These specifications are obtained from the supplier.

Table 3.1 Specifications of SiO_2

Property	Specifications
Assay	99.8% trace metals basis
Form	Nanopowder
Average particle size (nm)	12
Surface area (m^2/g)	160
Melting point (°C)	>1600
Boiling point (°C)	2230
Density (g/ml)	2.3
Thermal conductivity (W/m.K)	1.4
Specific heat (J/kg.K)	705

3.1.2 Distilled Water Specifications

In this experiment, distilled water or deionized car battery water is utilized as the base fluid to avoid any contaminants which could affect the thermal performance of nanofluids. The specifications of distilled water are presented in Table 3.2. These specifications are obtained from the source.

Table 3.2: Specifications of Distilled Water

Property	**Specifications**
Density (kg/m^{3})	1000
Thermal conductivity (W/m.K)	0.6
Specific heat (J/kg.K)	4182

3.2 Nanofluids Preparation

Currently, there are two methods used to prepare nanofluids which are the one-step and two-step methods. In the one-step method, nanoparticles are synthesized in base fluid mainly by means of chemical methods such as reducing copper sulfate by sodium hypophosphite using microwave irradiation in the case of preparing copper nanofluids. In the two-step method, nanoparticles are firstly prepared in a form of powders and then suspended in the base fluid. The current experiment performed the two-step method to prepare silica nanofluids as the two-step method is more widely used and easier to be performed as compared to the one-step method.

The procedure for silica nanofluids preparation is discussed as follow. First, to prepare 0.5 wt% silica nanofluids, 1g of silica nanopowder was poured into a plastic bottle and weighed using an analytical balance. 200g of distilled water/ deionized car battery water was poured into another plastic bottle and weighed using a weighing scale. Next, both plastic bottles containing silica nanoparticles and distilled water were poured into a beaker for mixing. The mixture was stirred for 2 hours using a magnetic stirrer to obtain a well-dispersed silica nanofluids. Similar mass ratio of silica nanoparticles to distilled water was used to prepare 0.2, 0.3, 0.4 and 0.5 wt% silica nanofluids respectively. The silica nanofluids showed good stability and uniformity without any sedimentation observed in all the samples prepared above. Figure 3.1 shows a simple two-step method used for nanofluids preparation.

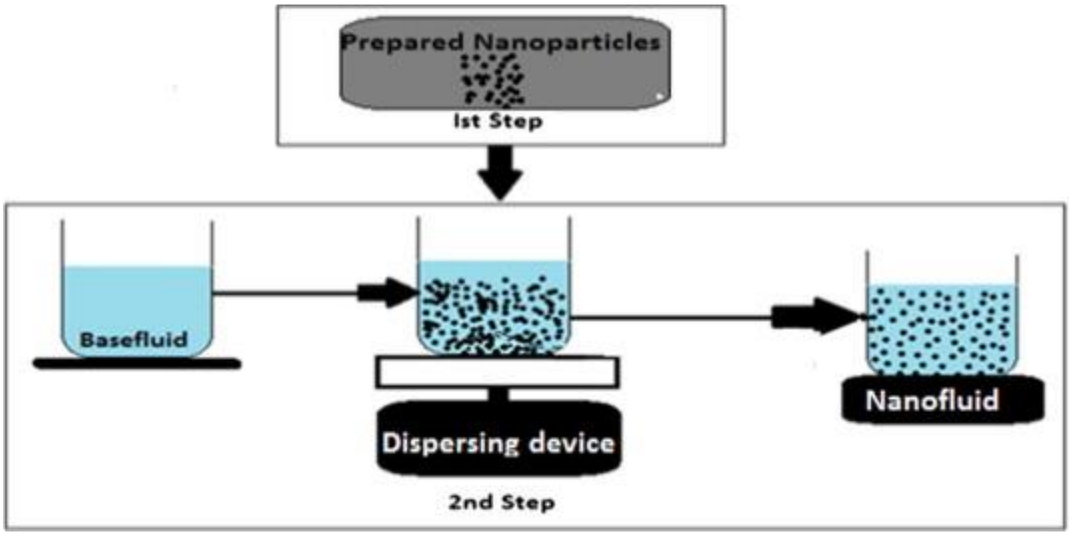

Figure 3.1: Simple Two-step Method for Nanofluids Preparation (Sharma, S. and S. M. Gupta, 2016)

3.3 Experimental Setup

An experimental rig was designed to achieve the objective of determining the heat transfer characteristics of silica nanofluids and distilled water. Figure 3.2 shows the experimental setup of the facilities.

Figure 3.2: Experimental Setup of Facilities

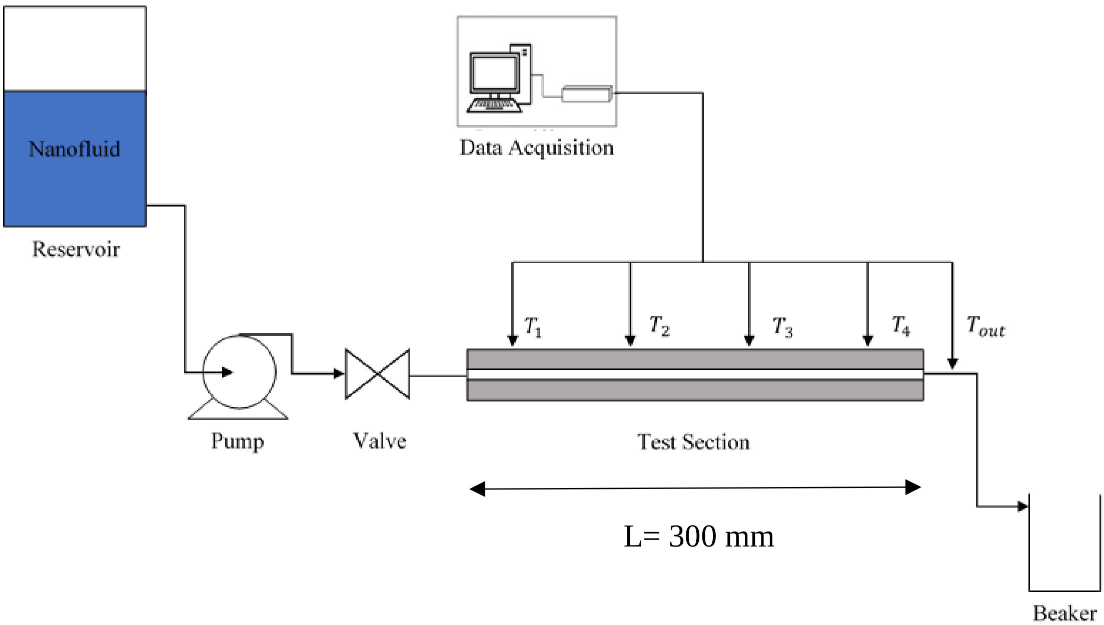

Figure 3.3: The Schematic Diagram of Experimental Setup

As shown in Figure 3.3, the experimental setup was an open flow consisting of a reservoir on one end and an empty beaker on the other end. A long tube was used to connect the test section and the reservoir. The tubing pump (Cole-Parmer, USA) was used to pump the working fluids from the reservoir to the test section through the tube at a low flow rate. The test section was setup to determine the heat transfer coefficient of the working fluids.

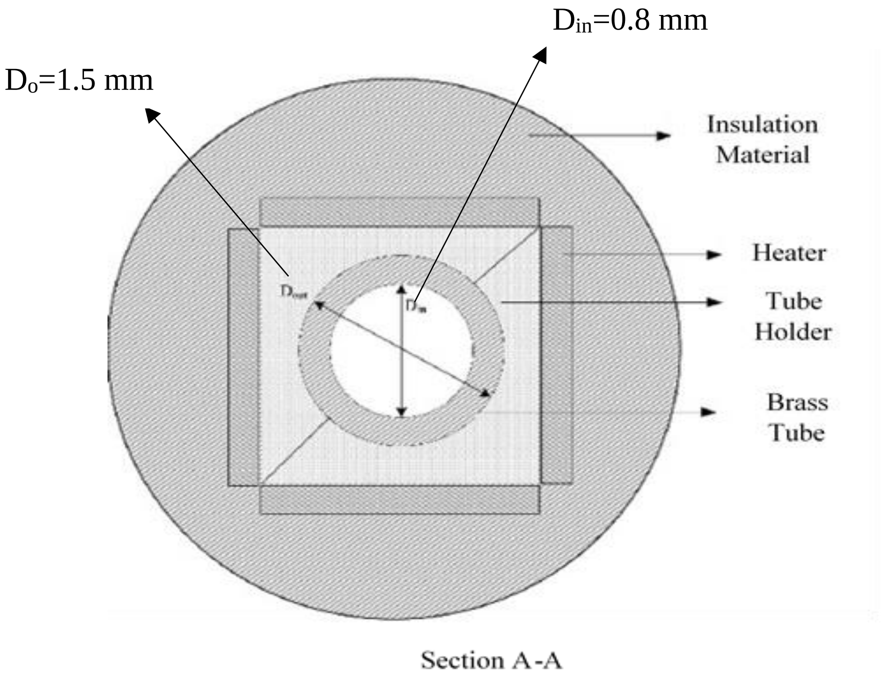

Figure 3.4: Front View Cross Sectional Area of Test Section

As shown in Figure 3.4, the section was consisted of a brass mini-tube covered by a stainless steel holder. Four electrical flat heaters were held at the edge of the mini-tube holder and insulated by a thick layer of woven fiberglass to prevent heat loss. The heaters were connected to the voltage supply to provide constant heat flux to the tube. The inner diameter, outer diameter and length of the mini-tube are 0.8, 1.5 and 300 mm respectively. Five K-type thermocouples were used to measure the desired temperatures, one was for measuring the outlet temperature, whereas the others were attached to the outer surface of the mini-tube to measure the surface wall temperatures at different axial locations from the inlet (Z= 41, 125, 207, 250 mm). The inlet temperature was taken as the room temperature (T_{in}= 23 °C). The thermocouples were connected to a portable Data Acquisition (DAQ) module (Advantech Co., Ltd, Taiwan) which was connected to a desktop computer. The contact areas between the thermocouples and the mini-tube were insulated with thermal compound to prevent any heat loss.

The procedure for collecting data is described as follow. First, sample of 200 g of distilled water was poured into the reservoir. The voltage supply was then turned on to heat up the mini-tube for about 45 minutes to reach the desired initial temperature of 50°C. After the initial temperature was reached, the tubing pump was switched on to pump the distilled water at a constant bulk velocity of 0.13 m/s through the mini-tube into the beaker. The distilled water was allowed to flow for 5 minutes. The pump was then switched off and the temperatures at each channel were recorded by DAQ at an interval of 0.1 s. The previous steps were repeated for at least 4 trials to obtain an average temperature at each channel. The same procedure was then repeated for different concentrations (0.1, 0.2, 0.3, 0.4, 0.5 wt. %) of silica nanofluids respectively.

3.4 Data Analysis

The experimental measurements are the inlet and outlet temperatures, the flow rate and the surface wall temperature at different axial locations (Z= 41, 125, 207, 250 mm).

In this section, the mathematical equations developed and used for the calculations of thermal performance of the working fluids will be discussed further in detail.

3.4.1 Thermophysical Properties of Nanofluids

The thermophysical properties of nanofluids are important parameters for calculating the heat transfer enhancement. The density, or more precisely, the volumetric mass density, of a fluid is its mass per unit volume. The specific heat capacity of a fluid is the amount of energy needed to change the temperature of 1 kg of the fluid by 1°C. Both densities and specific heat capacities of nanofluids can be determined using a well-known mixture model was shown in Equations (3.1) and (3.2) respectively:

$$\rho_{nf} = \phi_v \rho_p + (1 - \phi_v)\rho_{bf} \tag{3.1}$$

$$c_{nf} = \frac{\phi_v \rho_p c_p + (1 - \phi_v)\rho_{bf} c_{bf}}{\rho_{nf}} \tag{3.2}$$

The relationship between the volume concentration, ϕ_v and weight concentration, ϕ_w of nanoparticles can be obtained from Equation (3.3) below:

$$\phi_v = \frac{\phi_w \rho_{bf}}{\rho_p + \phi_w \rho_{bf} - \phi_w \rho_p} \tag{3.3}$$

The dynamic viscosity of working fluids is a significant parameter to study the forced convective heat transfer. Dynamic viscosity is defined as the measurement of the fluid's internal resistance to flow and can be estimated from the Einstein's viscosity equation for dilute suspension ($\phi \leq 2$ vol. %) below:

$$\mu = \mu_0 (1 + 2.5\phi_v) \tag{3.4}$$

The thermal conductivity of nanofluids is predicted by adopting the Hamilton and Crosser model as shown below:

$$k_{nf} = k_{bf} \frac{k_p + (n-1)k_{bf} + (n-1)(k_p - k_{bf})\phi_v}{k_p + (n-1)k_{bf} - (k_p - k_{bf})\phi_v} \tag{3.5}$$

Where n is the empirical shape factor. n is assumed to be 3 by assuming that all the silica nanoparticles in the silica nanofluids samples are completely spherical in shape.

3.4.2 Heat Transfer Characteristics of Nanofluids

The heat transfer characteristics of nanofluids can be determined quantitatively by calculating the convective heat transfer coefficient (h) and Nusselt number (Nu) based on Equations 3.6 and 3.7 respectively. The convective heat transfer coefficient or film coefficient is the proportionality constant between the heat flux and the thermodynamic driving force for the flow of heat while the Nusselt number is defined as the ratio of convective to conductive heat transfer across the boundary.

$$h(Z) = \frac{q}{(T_{wi}(Z) - T_f(Z))} \tag{3.6}$$

$$Nu(Z) = \frac{h(Z)D_{in}}{k_{nf}} \tag{3.7}$$

Where q, the actual heat flux gained by nanofluids can be determined from

Equation 3.8 as shown below:

$$q = \frac{\dot{m}c_{nf}(T_{in} - T_{out})}{\pi D_{in} L} \tag{3.8}$$

Radial heat conduction model was used to calculate the inner wall temperature, T_{wi} based on Equation 3.9.

$$T_{wi}(Z) = T_{wo}(Z) - \frac{q \ln\frac{D_o}{D_{in}}}{2\pi l k_s} \tag{3.9}$$

Where l is the length of mini-tube, k_s the thermal conductivity of brass and T_{wo} (Z) is the surface wall temperature at specific axial distance. The mean fluid temperature, T_f (Z) at specific axial distance is obtained from the energy balance as in Equation 3.10 below:

$$T_f(Z) = T_{in} + \frac{q\pi D_{in} Z}{\rho^{nf} c_{nf} u A} \tag{3.10}$$

In order to determine the efficiency of nanofluids as heat transfer fluids as compared to distilled water, the percentage heat transfer coefficient is calculated from Equation 3.11:

$$h_{enhanc.}\% = \frac{h_{nf}(Z) - h_{water}(Z)}{h_{water}(Z)} \times 100\% \tag{3.11}$$

The mean velocity can be calculated from the flow rate, Q and mini-channel cross sectional area, A in Equation 3.12 while the Reynolds number of the flow can be calculated from Equation 3.13:

$$u = \frac{Q}{A} \tag{3.12}$$

$$Re = \frac{\rho_{nf} D_{in} u}{\mu_{nf}} \tag{3.13}$$

Where μ_{nf} is the dynamic viscosity of the nanofluids.

3.4.3 Comparison with Other Correlation

In order to validate the research work, one of the most common equation used to define the local Nusselt number Nu in a circular tube is referred to and compared with the current experimental results. The Shah-London equation which is based on experimental work validated with constant heat flux boundary conditions can be presented as in Equation 3.14 below:

$$Nu = \begin{cases} 1.953Z^{*\frac{1}{3}}, & Z^* \geq 33.33 \\ 4.364 + 0.0722Z^*, & Z^* \leq 33.33 \end{cases} \tag{3.14}$$

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

3.5 Project Flow Chart

Materials and Equipment Selection

- Type of nanofluids
- Size of mini-tube
- Type of thermocouples

Experimental Setup

- Connect long tube to test section and reservoir
- Connect thermocouples to test section and DAQ module
- Fill nanofluids into reservoir
- Heat test section using electrical heaters
- Pump nanofluids through test section using tubing pump

Data Collection

- Record mini-tube wall temperatures using thermocouples
- Record outlet temperatures using thermocouples