Electronic cooling by using Barium Titanate (IV) Nanofluid with Loop Heat Pipe (LHP)

By

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ENDORSEMENT

I, TAN AIK KWAN (Matrix No: 129179) hereby declare that all corrections and comments made by the supervisor and examiner have been taken consideration and rectified accordingly.

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(Signature of Supervisor)

Name:
Date:

(Signature of Examiner)

Name:
Date:

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:

ACKNOWLEDGEMENT

I could still vividly remember the moment I stepped into Ir. Dr. Hussin Bin Mamat's office to request the final year project titles. At the time, nanofluid was a totally new territory for me to embark and the curiosity drove me to go to go further and faster. Thanks to Ir. Dr. Hussin Bin Mamat's kindness and patience, I was able to do something that triggered my urge and curiosity to know more about the wonders of nanofluid and its respective properties. In the sense that, this study serves as an important stepping stone for me to achieve life long learning as well as to retain the thirst for new knowledge.

Indeed, it was a tough journey but it was also a fruitful journey to learn more about myself and my aptitudes towards the possible future. During my journey to complete the study, I was helped by different people and friends, hence I would once again express my gratitude to whom lent their helping hands when I was in difficulty. Lastly, I would like to thank my family to always welcome me back with opened heart. Words cannot express my feelings, nor my thanks for all your help. Enjoy the little things in life, for one day you may look back and realize they were the big things.

Electronic cooling by using Barium Titanate (IV) Nanofluid with Loop Heat Pipe (LHP)

ABSTRACT

The reduction of size and the exponential increment in the number of integrated electronic components have eventually increased the power density and heat flux of the circuit. Barium titanate (IV) nanofluid has been proposed to replace the conventional cooling fluid such as water and ethylene glycol (EG). Barium titanate (IV) nanofluid is prepared at 0.1 vol.%, 0.3 vol.% and 0.5 vol.% with Arabic Gum (AG) as the surfactant. The thermophysical properties are studied with the nanofluid under heat output of 20 W, 40 W and 60W in a closed loop fluid system. The addition of barium titanate (IV) nanofluid is proven to improve the thermal conductivity by maximum of 31.28% compared to distilled water at 0.5 vol.%. However, in term of Nusselt number (Nu), distilled water shows superior heat transfer capability than nanofluids with maximum difference of 46.5% with nanofluids. Lesser heat is convected out than the heat is conducted into the RAM water block by nanofluid which causes fluid contact surface temperature to be greater than the results from distilled water. Hence, the combination of RAM water block and barium titanate (IV) nanofluid is not suitable for electronic cooling application.

Penyejuk Elektronik dengan menggunakan Barium Titanate (IV) Bendalir Nano dalam Sistem Paip Gelung Haba

ABSTRAK

Pengurangan saiz dan kenaikan eksponen dalam bilangan komponen elektronik bersepadu akan meningkatkan kepadatan kuasa dan fluks haba litar. Bendalir nano barium titanate (IV) telah dicadangkan untuk menggantikan cecair penyejukan konvensional seperti air dan etilena glikol (EG). Bendalir nano barium titanate (IV) disediakan dalam kepekatan volum 0.1 vol.%, 0.3 vol.% dan 0.5 vol.% dengan Gam Arab (GA) sebagai surfaktan. Ciri-ciri termofizikal dikaji dengan bendalir nano dengan dikenalkan 20 W, 40 W dan 60W dalam sistem paip gelung haba. Penambahan bendalir nano barium titanate (IV) terbukti dapat meningkatkan pengaliran terma sehingga maksimum 31.28% berbanding dengan air suling. Walau bagaimanapun, dari segi nombor Nusselt (Nu), air suling menunjukkan keupayaan pemindahan haba lebih baik daripada bendalir nano dengan perbezaan maksimum sebanyak 46.5%. Haba masuk secara pengaliran lebih tinggi daripada haba keluar melalui perolakan telah menyebabkan suhu permukaan sentuhan cecair menjadi lebih tinggi berbanding dengan air suling dengan penggunaan bendalir nano. Oleh itu, kombinasi RAM blok air dengan bendalir nano barium titanate (IV) tidak sesuai untuk aplikasi penyejukan elektronik.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF NOMENCLATURE AND SUBSCRIPTS

Nomenclature

Φ	particle Volume Concentration (%)
m	mass (g)
ρ	density (g/cm3)
T	temperature (ºC)
H	height (m)
A	area (m2)
$\dot{Q}$	heat dissipated from heating element (W)
D	hydraulic Diameter (m)
k	thermal conductivity (W/m·K)
h	heat transfer coefficient (W/m2·K)
HTC	heat transfer coefficient (W/m2·K)
v	velocity (m/s)
μ	dynamic viscosity of the working fluid (Ns/m2)
$\dot{V}$	volume Flow rate (m3/hour)
η	efficiency 100%
Cp	specific Heat (J/kg·K)
$\dot{m}$	mass flow rate (kg/s)

Subscript

b	bottom surface of RAM water block
Cs	contact surface with nanofluid
Tp	high Conductive Thermal Pad
he	heating Element
nf	nanofluid
np	nanoparticle
In	inlet
Out	outlet
mn	mean
bf	base fluid
hs	transparent oil hose for the experiment
nom	nominal
eql	Equilibrium
rwb	RAM water block

CHAPTER 1

INTRODUCTION

1.1 Overview

Electronic cooling by using Barium Titanate nanofluid with loop heat pipe (LHP). Based on the title, there are 3 key phrases that describe the nature of the project. The words are electronic cooling, nanofluid and loop heat pipe. In the later sections, the details of each phrases will be discussed as well as the objectives of the study.

1.2 Background

The emerging of miniaturization technology has caused the exponential increment of heat flux acting on a small processor. Hence, to make sure the processor able to work within operating temperatures, researchers had devised different heat removal methods to suit the needs for various electronic applications. Here are some of the conventional cooling methods and their classifications based on the heat transfer mechanism and cooling effectiveness (Murshed and Castro, 2017).

a) Radiation and free convection

b) Forced air-cooling

c) Forced liquid cooling (forced convection)

d) Liquid evaporation

A study by Scott and Allan in 1974 compared the temperature of the heat transfer surfaces with the ambient temperature. Maximum temperature reduction of 80°C had been estimated by these four different traditional methods and the results are summarized in Figure 1.1. The findings show liquid evaporation is the best technique to be applied since more heat has been removed from the surface by mean of state changes from liquid to vapor. Forced liquid cooling places the second whereas forced convection by air places the third (Scott, 1974). Due to low cost and safety characteristics, forced air-cooling has been widely used even though the heat removal capability is relatively low.

Evaporative cooling is mostly applied to extreme temperature conditions such as in space environment where the gap between maximum and minimum temperature is huge or industries that required a stable temperature environment such as a semiconductor manufacturing factory. An evaporative cooling system using ejector is an alternative to a cooling system with viable cost. Ejectors are simple devices governed by Bernoulli's principle, where a flow of air, water, or steam as fluid movement produces a pressure drop that can be used to suck up the vapor from the primary refrigerant; evaporation then occurs cooling it. Cooling occurs by removing the sensible heat of the fluid by evaporation (Oliveira et al., 2014). Hence, due to its complexity and extreme conditions, it is quite difficult to apply to the electronic cooling application.

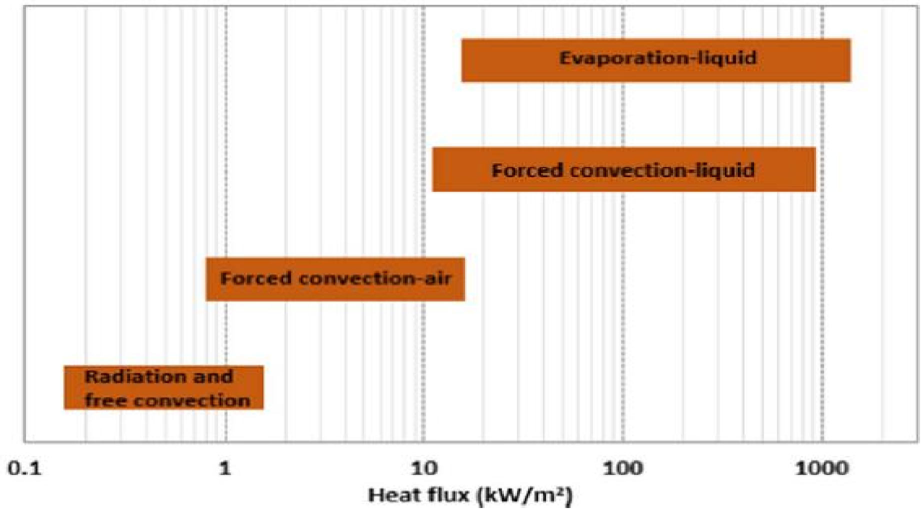


Figure 1.1: Comparisons of heat transfer effectiveness of conventional methods (Oliveira et al., 2014)

By reduction method, forced convection by using liquid becomes the potential method to remove heat from electronics with better heat transfer effectiveness than forced convection by using air and relatively simpler compared to evaporative cooling. Overall heat transfer coefficient becomes a key parameter to evaluate the effectiveness of different fluids for liquid forced convection. Sohel Murshed et al. (2017) presented typical ranges of heat transfer coefficient of mostly used coolants such as air and coolant in different cooling mode and the results are summarized in Table 1. 1.

Table 1.1: Range of Heat Transfer Coefficient of Air and Water (Murshed and Castro, 2017)

Cooling Modes	Heat Transfer Coefficient of Air (W/m^2k)	Heat Transfer Coefficient of Water (W/m^2k)
Free Convection	5-100	100-1200
Forced Convection (moderate flow speed)	10-350	500-3000
Boiling	-	3000-100,000

The utilization of air and water as a coolant no longer able to meet with the demands of modern electronic devices or systems due to their poor thermal properties which introduce a limitation to the cooling performance. To solve this problem, a newly emerging coolant such as nanofluid has been introduced. Nanofluid is produced by suspending the nanoparticles into the base fluid to enhance the thermal conductivity and heat transfer coefficient of the base fluid. Since metals and metal oxides have greater thermal conductivity than conventional coolants, dispersion of metal and metal oxides particles into the coolant will enhance the thermal conductivity of the base coolant. This idea becomes a hot topic for investigations as it is a potential solution to meet thermal control requirements (Gupta et al., 2017). Nanofluid which exhibits superior thermal properties becomes a potential solution to solve the overheating issue of electronic devices. The next step will be discussing what kind of heat transfer mechanism that can be used to transfer and remove heat from the processors (heat source) by using nanofluid as the coolant.

1.2.1 Heat Pipe (HP)

From previous sections, we learned about the importance of heat removal in the electronic application as well as the suggested fluid that has superior thermal conductivity than conventional coolants. There are two mechanisms that can be applied in electronic cooling which are heat pipe (HP) and loop heat pipe (LHP). Let's start with the definition of a heat pipe (HP) and how it works to remove heat from the high heat flux density region.

Heat pipe is deemed to be one of the most effective methods to transfer heat passively and it is structured with a very high thermal conductivity that enables the transportation of heat while maintaining almost uniform temperature distribution along its heated and cooled sections. Generally, heat pipe has been designed to transport heat over relatively long distances without using complicated mechanical aids and there is no moving part at all. The physics behind a heat pipe is using phase-change processes and vapor diffusion where the main structure of a heat pipe consists of an evacuated tube partially filled with a working fluid (water or coolants) that exists in both liquid and vapor phase (Jouhara et al., 2017). Figure 1.2 shows the simplified model of a heat pipe taken from a heat pipe system for the nuclear seawater desalination process. The model contains three main compartments which are evaporator, transport section, and condenser (Srimuang and Amatachaya, 2012).

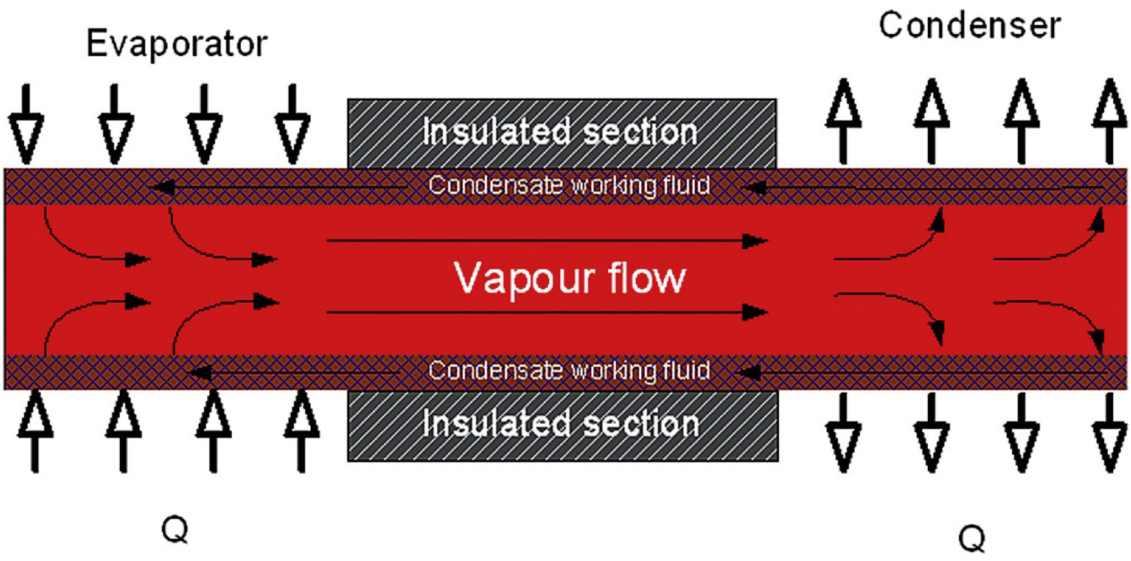
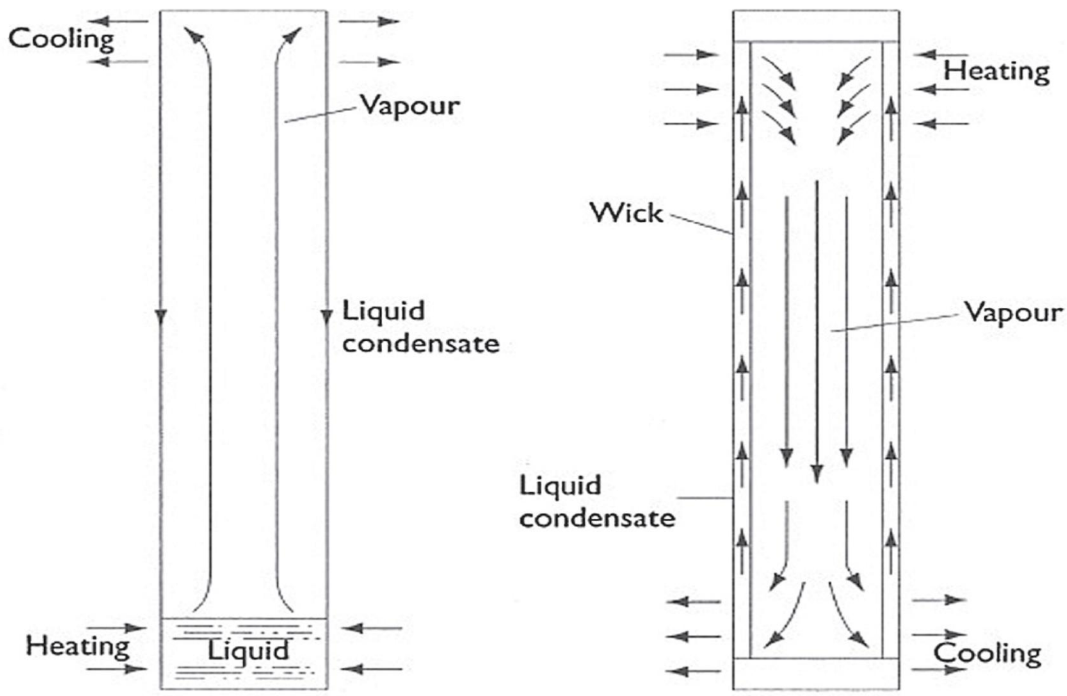


Figure 1.2: Heat Pipe Working Cycle (Srimuang and Amatachaya, 2012)

From Figure 1.2, heat (Q) has been inputted into the evaporator and transferred to the working fluid. The working fluid absorbs the heat from its surrounding and it experiences phase-change which is from liquid to vapor. During this physical phase-change, specific heat capacity and specific latent heat of the working liquid becomes a major consideration to determine how much heat will be carried away. After vaporization, the vapor is transported to the condenser along an insulated section where it is almost not heat is lost during the transportation process. At condenser, the vapor will experience another phase-change from vapour to liquid. Condensation process occurs when there is a temperature difference between the heat pipe and external surrounding where the external temperature is lower than the vapor temperature inside the heat pipe. During the condensation process, latent heat is released, and the working fluid is transported back to the evaporator. This working cycle is not applicable for some occasions such as the vapor temperature is the same as the external temperature or the situation where the external temperature is higher than the vapor temperature inside the heat tube. Another example based on the heat pipe concept will be the thermosyphons and wicked heat pipes.



(a) (b)

Figure 1.3: (a) Structure of thermosyphons; (b) wicked heat pipes (Srimuang and Amatachaya, 2012)

1.2.2 Loop Heat Pipe (LHP)

Heat pipe (HP) and loop heat pipe (LHP) both utilized the similar concept of evaporation, transportation and condensation, but the design and mechanisms are slightly different. The configuration of LHP is a closed circuit in which the vapor and liquid flow in different channels which makes evaporator and condenser become two separate solitary entities. One of the distinct differences between LHP and HP will be the presence of the compensation chamber. The compensation chamber serves as the reservoir that is temporarily filled with working liquid and saturated vapour, which allows the volumetric proportion to change according to the heat input. It helps to maintain and regulate the continuous flow of the working liquid in LHP. As the heat input increases, the mass flow rate is increased and causes more liquid and vapour to be pushed into the compensation chamber. When the condenser is saturated, liquid displaced will be displaced fully into the compensation chamber to create a constant conductance (Chan et al., 2015). Figure 1.4 shows an example of LHP.

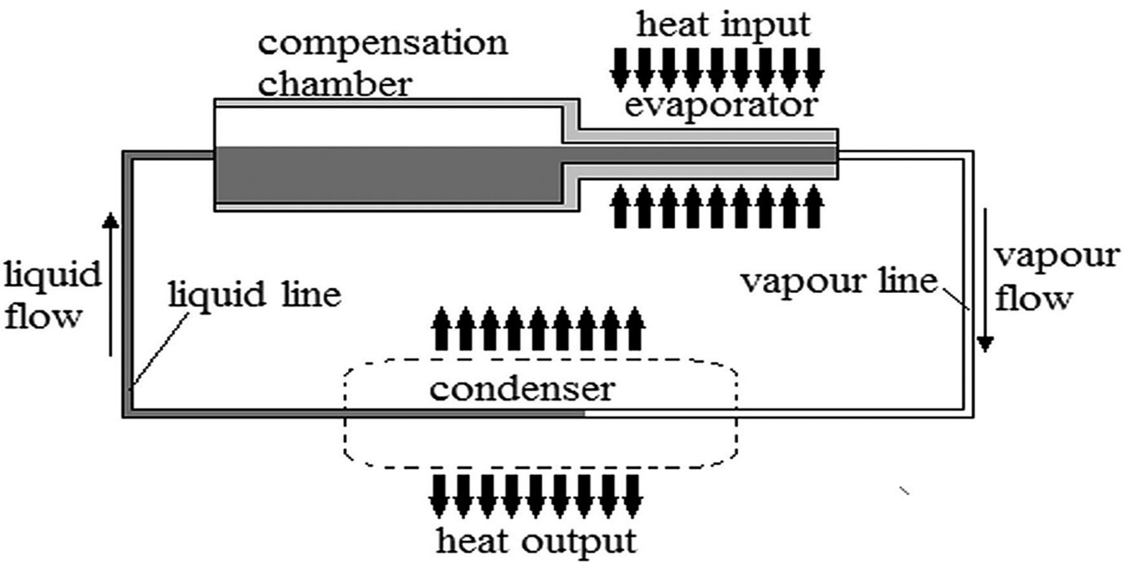
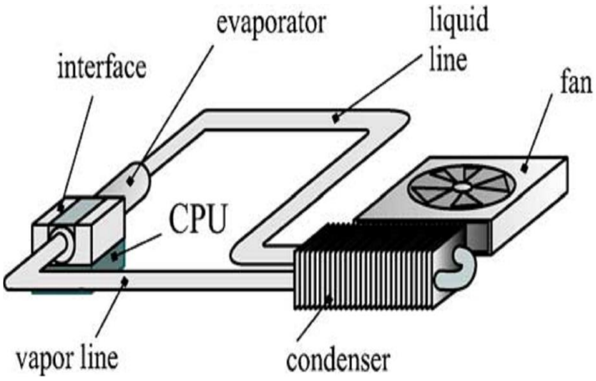


Figure 1.4: Loop Heat Pipe (LHP) (Chan et al., 2015)

In another perspective, LHP is more suitable to perform electronic cooling than HP does due to a few considerations. HP often exists in a fixed single unit structure where the modification can be difficult. Not only that, HP is sensitive to changes of orientation under gravitational conditions where HP must be placed at an upright position to function. When the working liquid is heated, the liquid becomes hot vapour which is less dense and rises to the condenser. If the evaporation zone is above the condensation zone, there will be an abrupt decrease in heat-transfer capacity (Jouhara et al., 2017). On the other hand, LHP shows no effect on the orientation as evaporator and condenser are separated. Besides attaining the heat transfer objective, LHP allows a variety of different design embodiments to suit the desired case study such as installing valves and flowmeters in between evaporator and condenser. Hence, LHP is a better option for electronic cooling where different kind of equipment can be installed depends on the scope of the study. The idea of using LHP in electronic cooling dates to the end of the seventies, when the heat dissipated by computer becomes a major concern to engineers. Researchers had created CPU cooler that used the LHP concept to cool down the CPU. The evaporator must be resized to suit the application requirement. For electronic cooling, a water block interface (Figure 1.5) can be used to replace evaporator since it allows nanofluid to flow into and out to take away heat by mean of forced convection.



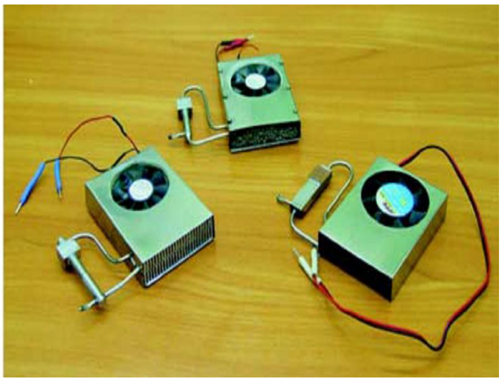


Figure 1.5: Scheme and general view of CPU coolers with an LHP (Chan et al., 2015)

At the end of the day, electronic cooling serves the purpose to remove heat from the processors and RAM as fast as possible to ensure its performances are not compromised.

1.3 Problem Statement

The emerging demand for high processing power electronic devices has upscaled the development in semiconductor and another mini-scale and micro-scale electronic technologies. The development trend has been shifted to make this electronic technology towards miniaturization and able to be fitted into handy electronic gadgets such as smartphones and watches. This miniaturization has changed how people live and act in the world as well as improving the speed of solving complex problems. Indeed, these technologies come in handy in solving our daily tasks, but it possessed challenges where researchers spend decades to solve. The challenges are the thermal management and control of electronic devices.

Continued miniaturization has led to the increment in power density in a small area which means it causes the processor to be heated-up faster than the heat can be dissipated to the surrounding of the processor itself. The two main technical challenges are inadequate heat removal of ever-increasing heat flux and highly non-uniform heat dissipation (Murshed, 2016). These two challenges dictate the capability of the processors as well as the health and quality of the electronic devices. To further explain how heat can possess huge damage to the electronic devices, we need to understand how heat damages electronic components. Electronic components such as integrated circuits, diodes, resistors, transistors and capacitors are carefully designed to function well under the prescribed temperature range and they are also designed to withstand certain extent of heat. When the circuit is closed, these electronic components will produce heat at their respective positions in the circuit board. To explain how the heat has been produced, it can be described with electrons as the mini balls which bounce around randomly (Brownian Motion) in the semiconductor material such as silicon and germanium. When a user triggers changes of bit in the processor, the potential difference between input and the targeted nodes will produce an electric field which causes the electrons to drift. Electrons gain kinetic energy from the electric field and start to collide with the atomic nuclei of the semiconductor, hence, it is the collision which produces the heat. Miniaturization causes billions of these components to squeeze into a very small area, for instance, 42 mm × 28 mm (Intel® Core ™ i7-7920HQ Processor's Package Dimension) and making it more susceptible to overheating.

Figure 1.6: Intel Core i7 Processor (Retrieved from: https://www.techradar.com)

Studies found out that overheating causes material degradation at the micro-level and it can be further deteriorated by the presence of cracks, expansion and other structural deformation. At macro-level, overheating not only causing system failure but also becoming the health and safety issues to users as well as causing the loss to entire assembly for electronic industry (Almubarak, 2017). From here, it can be said that if the heat is not removed at a rate equal to or greater than its heat rate generation, components and device's internal temperature will keep increasing which significantly reduces the reliability and performances as well as failing the device. According to a device reliable study by U.S. Department of Defence, the failure factor, which is relative failure rate at any temperature over the failure rate at any temperature predicted that the failure rate increases exponentially with increasing the device temperature (Defense, 1974). The prediction is as shown in Figure 1.7. After 75 degree Celsius, the failure rate increases exponentially, and nowadays more and more electronic gadgets have installed a system that will keep track with the internal temperature of the gadgets. When the gadget has reached a certain temperature, let say 60 degree Celsius, the gadget will initiate self-forced blackout to reduce the risk for failure.

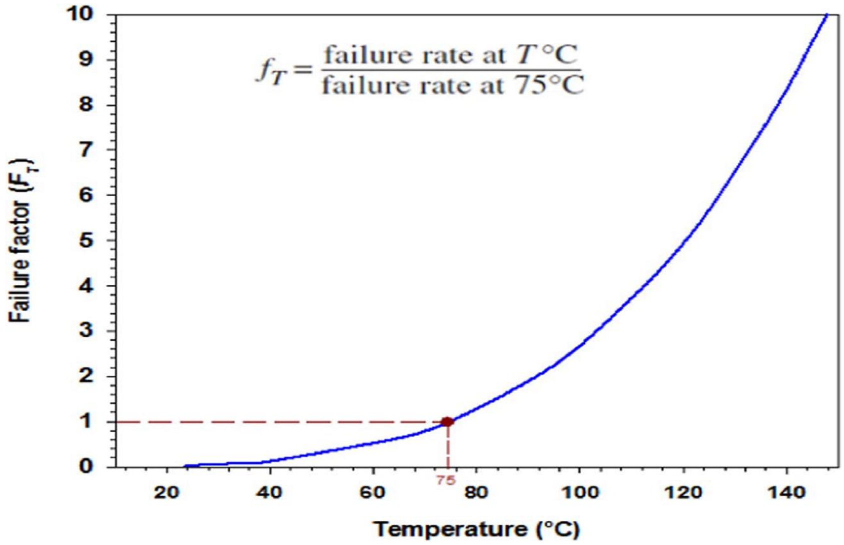


Figure 1.7: Graph of Failure Factor against Device Temperature. (Defense, 1974)

Hence, this study will explore the usage of nanofluid on electronic cooling to regulate temperature within the operating limits, so that the devices work efficiency and longevity is maintained.

1.4 Research Objectives

In a simple explanation, this study will focus on how to remove heat from a high heat flux area by using nanofluid and loop heat pipe system. After a brief introduction of problem statement, the objectives of the project must also be well defined. The objectives of the project will study the heat transfer performance by using loop heat pipe system with the nanofluid coolant to cool down a heating element with different power outputs which is assumed to be the processor or RAM of the computer. The objectives are as stated below.

a) To study the effect of nanoparticles volume concentration to heat removal performance in a loop heat pipe system by using commercial cooling kit.
b) To study the effect of nanofluid flow rate to the heat removal performance in a loop heat pipe system by using commercial cooling kit.

1.5 Thesis Outline

Chapter 1 discussed the current trend of miniaturization of electronic components and processors of electronic gadgets as well as the consequences of overheating without a proper heat control method. This chapter also exposed readers about different cooling methods and what is the possible coolant to be used to remove more heat from the heat generated devices. At the end of chapter 1, the differences and the operational concept between heat pipe (HP) and loop heat pipe (LHP) are discussed and the method that can be used to perform electronic cooling has been suggested.

In chapter 2, the related literature is reviewed to present what had been done by researchers so far in the efforts to improve thermophysical properties of conventional coolants and nanofluid. The reviews not only cover the characteristics of nanofluid but also how nanofluid implementations able to improve heat transfer performance in various applications. Thereafter, the interaction of surfactant and the stability of the nanofluid are discussed to study the challenges and feasibility of nanofluid in the real-life scenarios. Last part of chapter discussed some of the experimental results done by others within this 5 years.

Next, chapter 3 discusses the methodology and techniques that are implemented as well as the governing equations that are crucial in this project. It covers the stable nanofluid preparation procedure, the characteristics of the Barium Titanate (IV) nanoparticles and the setup of the experiment to fulfill the objectives of the project.

Chapter 4 covers the experimental data and the discussions of the results. The results are to be compared with different mathematical models that had been proposed by different researchers in the past. Based on the results, the correlation between different manipulated variables is studied.

Lastly, chapter 5 is going to present the significance of the study as the foundation to produce better cooling nanofluid in the future. The conclusion is to be made based on the correlation of parameters in the experiments. Some of the future research suggestions are made so that future researches have the idea to solve the limitation of this experiment as well as enhancing the heat transfer mechanism for electronic cooling.

CHAPTER 2

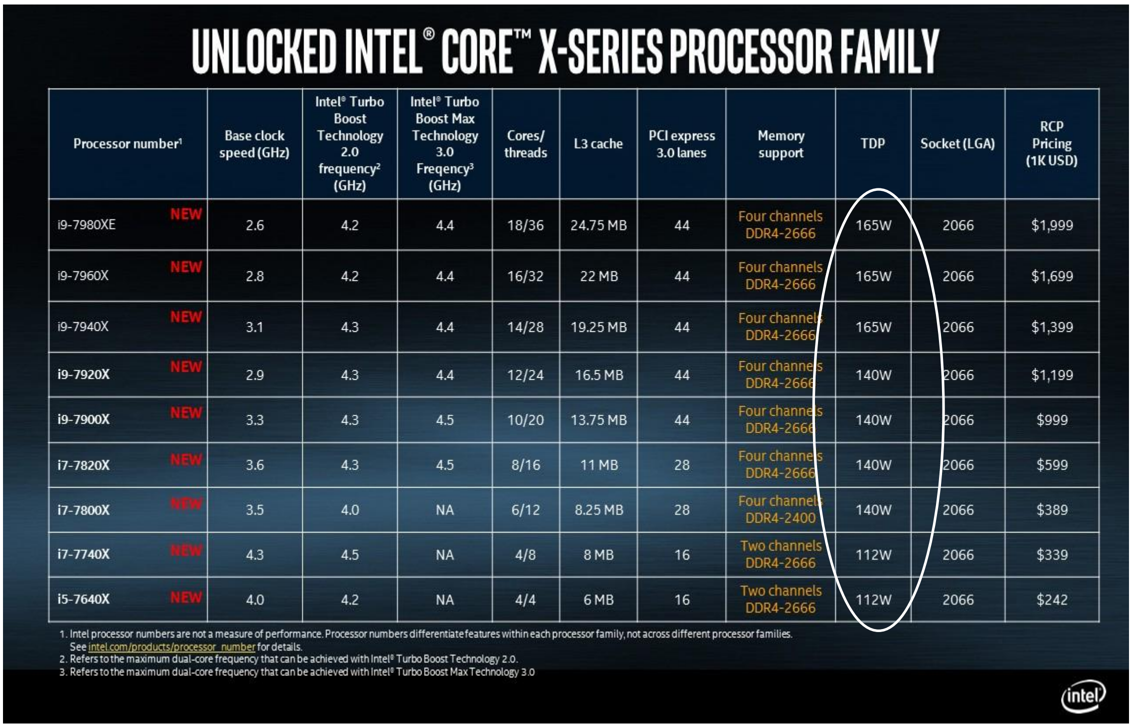
LITERATURE REVIEW

2.1 Introduction

The literature reviews will further explain the current computer processor heat outputs as well as the performances of the processor nowadays. Next, the chapter will also discuss about the improvement brought by using nanofluid in terms of thermophysical properties. After knowing the capability of nanofluid, this chapter discusses the method of producing nanofluid as well as the importance of surfactant to improve the stability of the nanofluid. The theory behind forced convection is discussed the difference of thermal conductivity and convective heat transfer in a constrained flow. The flow regime of the fluid is also part of the literature review to provide a clearer image of how turbulence flow and laminar flow able to affect the heat transfer performance of the nanofluid. Lastly, in the last part of the chapter, the current electronic cooling researches and find-outs are discussed.

2.2 Power Consumption of Processors

In the efforts of producing performance-oriented processors, manufacturers and researchers are digging various methods to breakthrough computing limit. From a single core processor to double cores, next to multithreaded technology and here comes the Intel® Core™ i9 X-series processor which has 16 cores in total. Its overwhelming processing power with a base frequency of 2.8 GHz incorporated with Turbo Boost Max 3.0 Technology which able to boost the frequency to 4.40 GHz. The high processing frequency is correlated to the power consumption which gives this processor a thermal design power (TDP) of 165 W (Intel, 2018). Bsed on the data sheet provided by Intel, Intel i5-7640X and i7-7740X give the minimum TDP of 112 W.



UNLOCKED INTEL® CORE™ X-SERIES PROCESSOR FAMILY

Processor number[1]	Base clock speed (GHz)	Intel® Turbo Boost Technology 2.0 frequency[2] (GHz)	Intel® Turbo Boost Max Technology 3.0 Freqency[3] (GHz)	Cores/ threads	L3 cache	PCI express 3.0 lanes	Memory support	TDP	Socket (LGA)	RCP Pricing (1K USD)
i9-7980XE NEW	2.6	4.2	4.4	18/36	24.75 MB	44	Four channels DDR4-2666	165W	2066	$1,999
i9-7960X NEW	2.8	4.2	4.4	16/32	22 MB	44	Four channels DDR4-2666	165W	2066	$1,699
i9-7940X NEW	3.1	4.3	4.4	14/28	19.25 MB	44	Four channels DDR4-2666	165W	2066	$1,399
i9-7920X NEW	2.9	4.3	4.4	12/24	16.5 MB	44	Four channels DDR4-2666	140W	2066	$1,199
i9-7900X NEW	3.3	4.3	4.5	10/20	13.75 MB	44	Four channels DDR4-2666	140W	2066	$999
i7-7820X NEW	3.6	4.3	4.5	8/16	11 MB	28	Four channels DDR4-2666	140W	2066	$599
i7-7800X NEW	3.5	4.0	NA	6/12	8.25 MB	28	Four channels DDR4-2400	140W	2066	$389
i7-7740X NEW	4.3	4.5	NA	4/8	8 MB	16	Two channels DDR4-2666	112W	2066	$339
i5-7640X NEW	4.0	4.2	NA	4/4	6 MB	16	Two channels DDR4-2666	112W	2066	$242

1. Intel processor numbers are not a measure of performance. Processor numbers differentiate features within each processor family, not across different processor families. See intel.com/products/processor_number for details.
2. Refers to the maximum dual-core frequency that can be achieved with Intel® Turbo Boost Technology 2.0.
3. Refers to the maximum dual-core frequency that can be achieved with Intel® Turbo Boost Max Technology 3.0

Figure 2.1: Intel Core i9 X-series Processor Family Profile (Intel, 2018)

To have a better comparison of how much 165 W is about, it can be said that the power consumed is approximately equivalent to four 40W typical fluorescent bulbs. It is enough to lighten a small house by using the power consumed. A study at Newcastle University in 2015 compared the power consumption of the Intel® Core™ i7-4820K with different CPU workloads and parallel computing had showed some interesting trends for the CPU (Shvets, 2018). Before digging into the results and discussions of the study, let's look at the specification of this Intel® Core™ i7-4820K.

Table 2.1: Intel Core i7-4820K Processor Specification (Shvets, 2018)

Type	CPU/Microprocessor
Family	Intel Core i7
Base Frequency	3.7 GHz
Maximum Turbo Frequency	3.9 GHz
Core Number	4
Number of threads	8
Maximum operating temperature	66.8°C
Thermal Design Power (TDP)	130 Watts

Theoretically, CPU's computing frequency is proportional to power consumption. The greater the computing frequency, the higher the power consumes. Hence, Intel i9 X-series processor consumes more power than Intel i7 4th generation processor due to the differences of maximum computing frequency which are 4.5 GHz (Base frequency of i9-7900X with turbo boost 3.0 technology) and 3.90 GHz (turbo boost frequency of i7-4820K) respectively. Throughout the study, the voltage across the processor increases as the computing frequency increases. The study suggested that voltage increases due to the complementary metal-oxide-semiconductor (CMOS) in the processor which acts as capacitance that constantly charged and discharged according to the computing frequency. However, when computing frequency's demand is greater than the capability of charging and discharging frequency of the capacitance, more supply voltage is required to resolve this problem or applying layering technology to the processor.

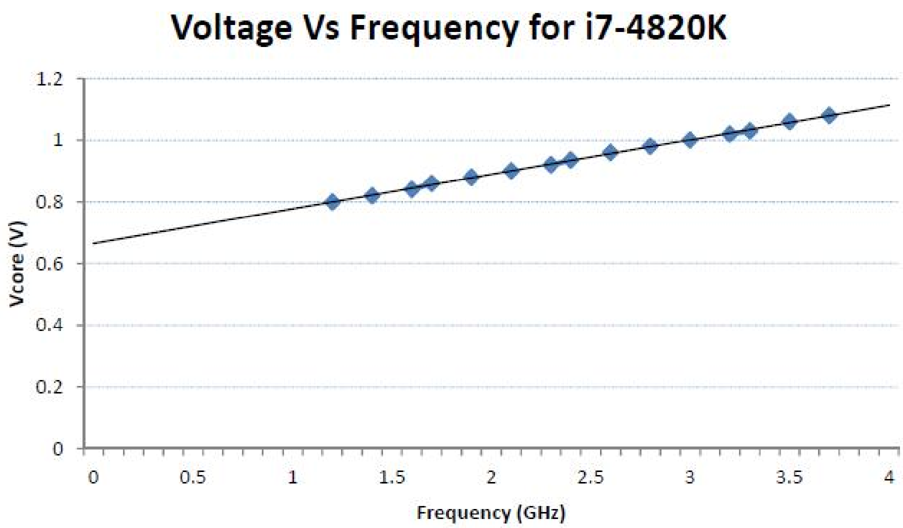


Figure 2.2: Relationship of voltage with frequency increases as set by Intel South Bridge C1 stepping (Shvets, 2018)

The study also subjected the CPU with a task which was calculating if numbers were a prime number or not up to 20000. The results were collected from Likwid Performance tool using Intel RAPL counters. In the result, the single core used the maximum power of 32W whereas hyperthreadeded cores and dual-core used the maximum power of 40W. Hence, it can be said that the power consumption of a CPU is highly relied to the voltage across the processor and the computing frequency required to complete the task given as well as the number of cores and connections within them. There is no fixed value to the power consumed by the CPU as the computing frequency always varies with the processes and tasks that happen in the background.

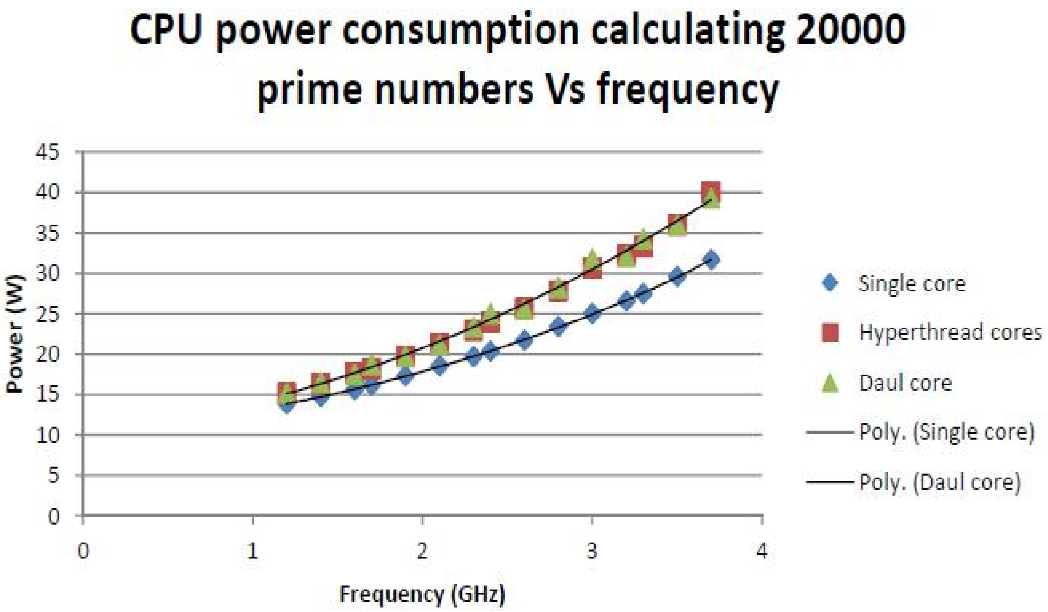


Figure 2.3: Graph of CPU consumptions VS Frequency (Shvets, 2018)

One of the authors from PC Perspective conducted the test with different software to trace the power consumption in the real situation and the data is as shown in Figure 2.4. In the test, the author equipped the PC with different processors which were from Intel® and AMD®. The equipped PC were tested under idle, gaming performance and high-quality graphics rendering software such as POV-ray. The result shows that the minimum power drawn from the power source is 3.1W while the maximum power drawn was 52.8W (Addison, 2018). Hence, it gives the idea that the heat dissipated from the CPU must lie within 60 W for normal usage as well as acting as the benchmark to compare the experimental results from the investigation.

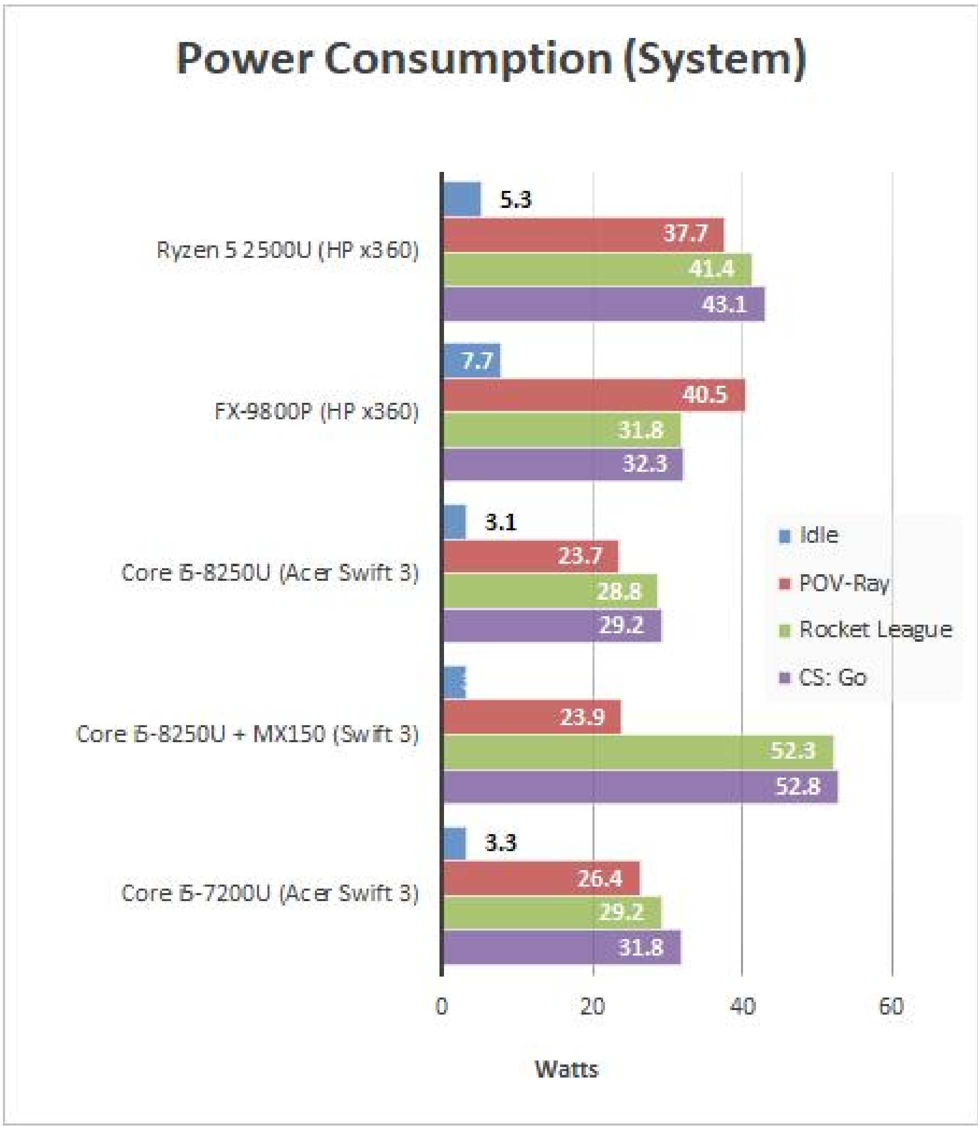


Figure 2.4: Power Consumption between AMD and Intel processors under Different Tasks (Addison, 2018)

2.3 Conventional Coolants

In the previous section, nanofluid is known as the new solution to solve the demand for higher heat removal rate for electronics. Before the emerging of nanofluid, different aqueous and non-aqueous coolants were introduced and utilized, these coolants are known as traditional coolant. The effectiveness of traditional coolant is dependent on the type of coolant and the heat transfer method. Water is the widely used traditional coolant as water gives the highest heat transfer coefficient in term of boiling and condensation. Since human beings are using electronics casually, the coolant used must satisfied certain requirements such as non-flammable, nontoxic, and inexpensive as well as exhibits excellent thermophysical properties such as high thermal conductivity, specific heat and heat transfer coefficient. Besides, the coolant mustn't exert too much of strain to the mechanical in the cooling system, hence, the viscosity of the coolant must be low and the cooling fluid must be non-corrosive (Mohapatra, 2006).

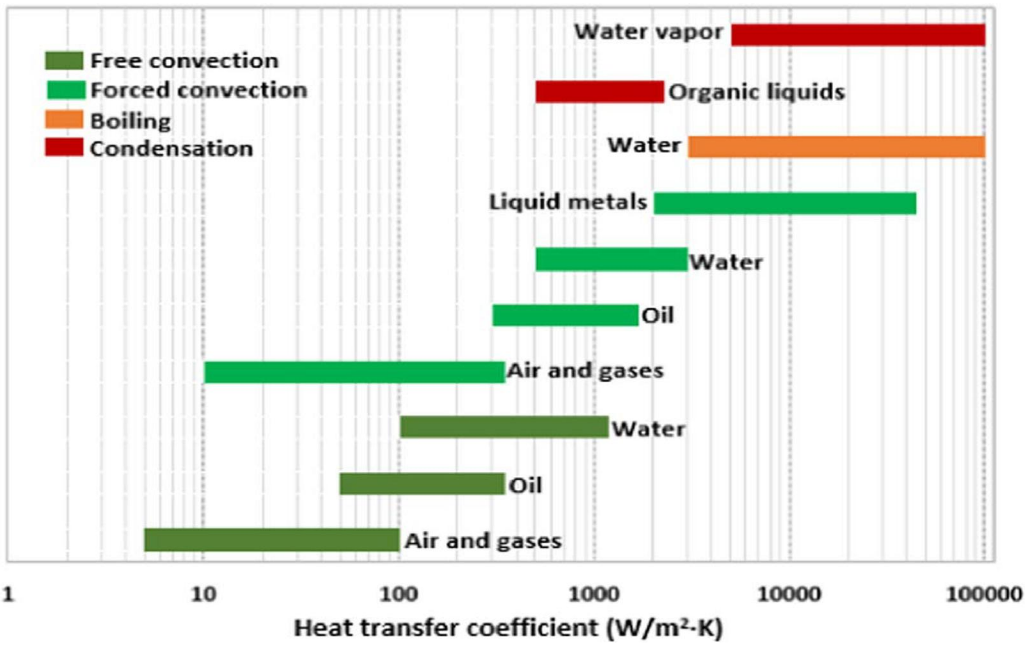


Figure 2.5: Range of overall heat transfer coefficients for different fluids and cooling method. (Mohapatra, 2006)

In Figure 2.5, water and liquid metals are both good at their heat transfer capabilities and water vapor placed at the top due to its extremely high specific latent heat possessed by water. However, water sometimes cannot be used for closed-loop systems due to its relatively higher freezing point and the expansive characteristics upon freezing. To overcome this problem, another two types of conventional coolant have been introduced which are called dielectric and non-dielectric fluids.

2.3.1 Dielectric fluid

A dielectric fluid is a dielectric material in liquid state. A dielectric material is an electrical insulator that can be polarized by applying electric field. It serves the purpose to prevent or rapidly quench of electric charges. This type of fluid is used for high voltage application such as transformer, capacitors and switchgear due to its electrical insulating characteristics. Examples of dielectric fluids are Coolanol 25R, silicon oil and fluorinated compound.

2.3.2 Non-dielectric fluid

This type of cooling fluid has been widely used as antifreeze in automotive engine cooling to deal with extreme temperature. One of the best examples of non-dielectric fluids will be ethylene glycol (EG). EG is colorless and odorless and is completely miscible with water. EG exhibits low corrosivity but it is classified as toxic where the ingestion of EG can be fatal. EG is used to increase the boiling point and decrease the freezing point of the radiator fluid. Other than EG, there is propylene glycol (PG) which exhibits similar function as EG but non-toxic. The only drawback of PG will be its higher viscosity and greater the manufacturing cost. In short, non-dielectric coolants are mostly water-based which allow them to exhibit a very high specific heat and the thermal conductivity (Atlanta, 2001).

Based on Table 2.2, the upper echelon is the coolants from dielectric and all their specific heat capacities are less than non-dielectric coolant due to the absence of water. To cope with the overwhelming heat removal demands, nanofluid incorporates with metal and metal oxide nanoparticles become the new solution to improve the thermal properties of the base fluid. Hence, the next section will discuss fundamentals of nanofluid and what are the improvements attained by the utilization of nanofluid.

Table 2.2: Properties of Different Liquid Coolant Chemistry at 20 degree Celsius (Mohapatra, 2006)

Coolant Chemistry	Freezing Pt (°C)	Flash Pt(°C)	Viscosity ($kg.m^{-1}s^{-1}$)	Thermal conductivity ($Wm^{-1}K^{-1}$)	Specific Heat ($Jkg^{-1}K^{-1}$)	Density ($kg.m^{-3}$)
Water	0	-	0.00089	0.613	4180	1000
Dielectric						
Aromatic (DEB)	< -80	57	0.001	0.14	1700	860
Silica-ester (Coolanol 25R)	< -50	> 175	0.009	0.132	1750	900
Aliphatic (PAO)	< -50	> 175	0.009	0.137	2150	770
Silicone (Syltherm XLT)	-111	46	0.0014	0.11	1600	850
Fluorocarbon (FC-77)	<-100	-	0.0011	0.06	1100	1800
Non-dielectric						
EG/Water (50:50 v/v)	-37.8	-	0.0038	0.37	3285	1087
PG/water (50:50 v/v)	-35	-	0.0064	0.36	3400	1062
Methanol/water (40:60 wt./wt.)	-40	29	0.002	0.4	3560	935
Ethanol/water (44:56 wt./wt.)	-32	27	0.003	0.38	3500	927

2.4 Nanofluids

"Nanoparticles (NPs) are wide class of materials that include particulate substances, which have one dimension less than 100 nm at least (Laurent et al., 2010)." A particle which has more than one dimensions which are less than 100 nm will be considered as nanoparticles. The Figure 2.6 shows different type of metal oxide NPs under electron microscopy.

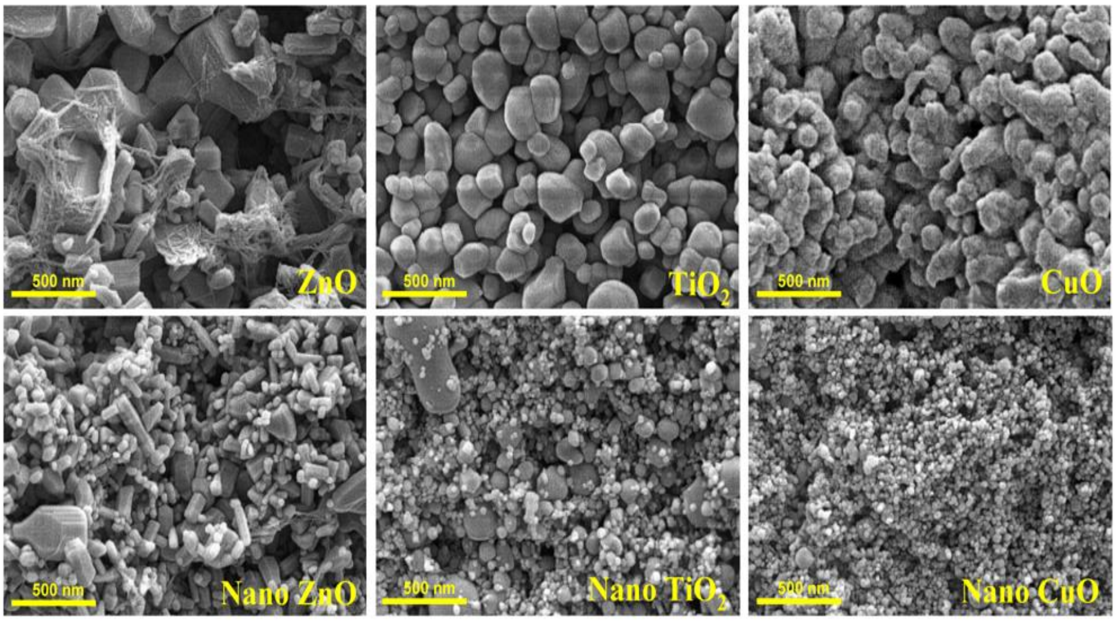


Figure 2.6: Metal Oxide Nanoparticles under TEM (retrived from: mdpi.com)

Throughout years of researches, different types of NPs have been produced and discovered. It has total of six classifications which are carbon-based, metal, ceramics, semiconductor, polymeric and liquid based (Khan et al., 2017). However, in electronic cooling purposes, only the metal or metal oxide NPs will be used as metal NPs have relatively higher thermal properties compared to other classes. Hence, the idea of mixing NPs to the coolant gave birth to nanofluid. Nanofluid is known as the advanced functional fluid that is designed by adding nanosized solid particles in a low to moderate volume fraction to the base fluid such as water and coolant, nanoparticles are remained suspended in the base fluid.

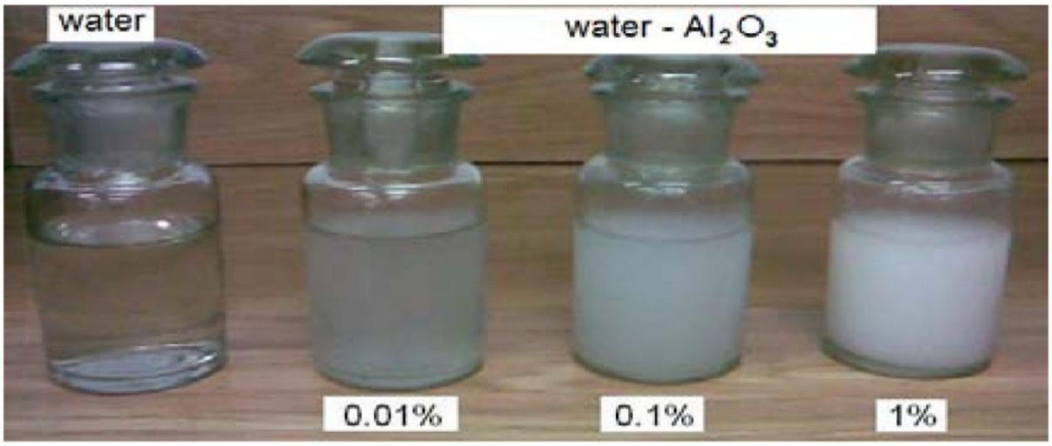


Figure 2.7: Aluminium Oxide Nanofluid with Different Volume Concentration (Cieslinski and Kaczmarczyk, 2011)

The thermophysical properties of nanofluid become the main scope to study when dealing with the heat transfer application. Generally, researchers applied two different methods to produce nanofluid which are single-step (one-step) and two-step method. One step method is a simultaneous synthesis method where production of nanoparticles and dispersion in the base fluid come together. Hence, no transportation and storing of NPs are required as well as minimizing the agglomeration of NPs in the base fluid. For two-step method, NPs are produced separately by physical or chemical processes. NPs are then dispersed into base fluid by means of magnetic stirring, homogenizing or ultrasonic agitation (Mukherjee et al., 2018). In the process of producing two-step method nanofluid, a surfactant can be added to improve the stability of nanofluid as well as minimizing agglomeration between NPs.

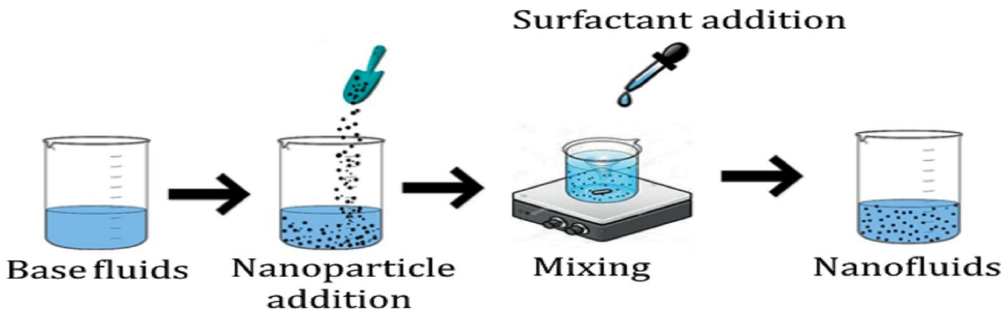


Figure 2.8: Two-step Preparation of Nanofluid (Mukherjee et al., 2018)

After knowing the basic concept of nanofluid and the methods to produce them, let's dig into factors that affect the thermophysical properties of nanofluid. Nanofluid's applications have been assimilate into various industries such as coolants in automobile transmission, electronic cooling, drilling fluids, solar water heating and radiator due to their superior thermal conductivity. Different combination of base fluid and NP will yield different results, hence the factors behind the changes worth to be studied. One of the most distinct factors will be the concentration of NPs in the base fluid regardless of volume fraction or weight fraction. Many studies showed a similar trend where the increment of NPs concentration also increased the thermal conductivity of nanofluid.

Elshazly et al. (2017) studied the thermal performance of shell and coil heat exchanger by using γ-Al_2O_3 /water nanofluid with the volume concentration range of 0 to 2% and the experiment was controlled under turbulent flow regime. The team established a parameter which was known as thermal performance index (TPI) which is the ratio between average convective heat transfer coefficient and changes of pressure between inlet and outlet. In their observation, Nusselt number ratio (Nu) increased from maximum of 23.5 at 0.5% volume fraction to maximum of 95.5 at 2% volume fraction. The average convective heat coefficient also increased from maximum 57.1% at 0.5% volume fraction to maximum 238.9 % at 2% volume fraction. The team suggested that the enhancement of heat transfer coefficient was attributed to the interactions of Brownian motion of NPs and the resulting disturbance of the boundary layer in addition to the enhanced thermal conductivity of nanofluid.

Another study conducted by Chaudhari et al. (2015) also showed similar outcomes where the heat performance of nanofluid was indeed better than base fluid. The team used a parabolic trough solar collector to examine the heat transfer coefficient of alumina/water nanofluid. 0.1% weight concentration of alumina nanofluid had been used and was prepared by using magnetic stirrer. The stirring process took 10 hours to improve dispersion behavior and minimize aggregation. In the experiment, it was found out the fluid outlet temperature by using nanofluid was higher than the controlled set (distilled water) and there was an increment to the thermal efficiency of the system by nearly 7%. The higher fluid outlet density also means that alumina nanofluid was able to bring more heat out from the high heat flux region. Not only thermal efficiency, the heat transfer coefficient enhanced by 32% compared to water and it was spotted that Nusselt number (Nu) also increased.

Alias and Ani (2017) conducted a thermal characteristics investigation to another metal oxide nanofluid which was titanium dioxide /EG nanofluid. The team used two-step method to prepare the nanofluid of different concentrations which were 0.25wt%, 0.50 wt%, 0.75 wt% and 1.00 wt%. Samples were sonicated under ultrasonic homogeniser for 2 hours, 0.50 wt% of Gum Arabic surfactant (GA) was added then and another 2 hours sonication. Not only to study how weight concentration, but the team did also vary the temperature to study samples' heat performance under elevated temperature. Throughout their experiment, the thermal conductivity of titanium dioxide nanofluid increased with the weight concentration at room temperature and elevated temperature. The maximum enhancement happened at 1.00 wt% where the thermal conductivity increased by 32%, 113% and 231% for 40 °C, 50 °C and 60 °C respectively. Hence, by increasing the concentration of NP, there are more collisions between particles which contribute to the improvement of heat transfer. From the literature, the nanofluid heat transfer performance not only affected by the concentration of NPs but also the temperature.

To further convince about the enhanced thermophysical properties of metal oxide nanofluid, Subhedar et al. (2018) conducted another experiment that studied the