

DEVELOPMENT OF PARAFFIN WAX AS A PHASE CHANGE MATERIAL
FOR THERMAL MANAGEMENT IN
ELECTRONIC SYSTEMS

by

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Abstract

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Increasing development in electronic technologies has improved functionality and reduced physical constraints, while managing to impart higher power and performance in smaller and compact devices. As a result of this size reduction, there is also a reduction in the surface area required for heat dissipation. Due to this the thermal management problem has been further intensified. The end result is that the power density continues to rise even with improved thermal management strategies incorporated into the system. Thermal management hence plays an important aspect especially when the design of compact electronic devices is concerned.

For most electronic applications thermal loads are a function of time, and hence vary throughout. Thermal loads fluctuate between maximum and minimum load limits. Hence the existing industrial trend used is to size up thermal management components in anticipation of this maximum thermal load, which is not always the case. Increased size and energy consumption from these devices has become a major hurdle to overcome as they severely restrict compactness.

To mitigate this problem we studied the emerging technique of utilizing Phase Change Materials (PCMs) for managing temperature in electronics. Due to the intermittent load pattern, PCMs can play a vital role in absorbing the heat from electronic components during maximum operational requirement and release this heat to the ambient when the load requirement drops.

For this study we selected a paraffin wax (Octacosane) due to its high heat of fusion and desirable melting point, which fits within the purview of operating temperature of electronics. The melting point is important of a PCM is an important parameter, as it is during this solid-liquid phase transition that the PCM absorbs the maximum amount of heat while maintaining a constant temperature.

This study mainly concentrated on improving the thermal conductivity and the thermal storage capacity of the PCM. A nanofluid was synthesized by doping the Octacosane with polyethylene glycol and Silica (SiO_2) nanoparticles. An enhancement in specific heat by 7.30% and thermal conductivity by 25.14% was obtained in the nanofluid as compared to the pure Octacosane.

These improvements in the thermal properties of the nanofluid will help reduce the size of existing thermal management techniques. And in turn will help to improve the compactness of electronic devices and efficiency of thermal management strategies.

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Chapter-1

Introduction

1.1 Introduction to Thermal Management

Enhancements in electronic technology have increased functionality and reduced physical constraints, while still managing to impart higher power in smaller sized devices [1]. As the size of electronics reduces due to devices becoming smaller, compact and more portable, there is also a reduction in the available surface area for heat dissipation. With the advent of enhanced power consuming devices and applications, the thermal management problem is further intensified. Hence the power density continues to increase even with improved thermal management strategies implemented in the hardware and software [2]. As a result thermal management has become an important aspect especially when designing of portable electronics is concerned.

In most of the electronic applications, thermal loads are a function of time, and hence are not constant throughout. They fluctuate between maximum and minimum load limits [3]. Hence the current industrial trend is to size up these components in anticipation of the maximum thermal load, which is not generally the case. Increased size and energy consumption from these devices has become a major hurdle to overcome. Also another aspect is that as the parts end up being oversized they further reduce the compactness of portable devices.

Hence as an alternative to complete active and passive cooling technologies, a hybrid passive technique using Phase Change Materials (PCMs) is investigated, due to high energy storage capacity and temperature stability of PCMs [1].

This study proposes a method which includes filling the gaps between the fins of a heat sink with PCM. Since heat generation is not always constant, the PCM can be used to absorb heat during periods of maximum heat generation. This heat can then be released via the fin structures of the heat sink to the ambient during periods of lower heat generation, thus maintaining the electronic parts at a constant temperature.

The PCM selected should have a melting point close to the temperature at which the electronic components have to be maintained.

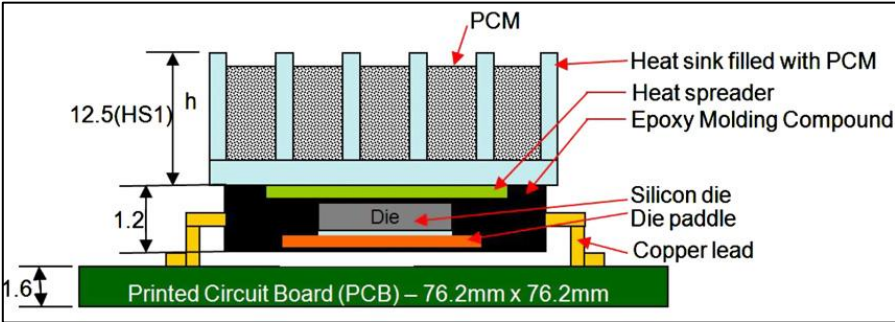


Figure 1.1 Cross - Sectional Schematic of a PCM Filled Heatsink [1]

1.2 Common Cooling Methods

1.2.1 Active cooling

This cooling technique uses energy to cool a device. A coolant is circulated and used as a heat transfer medium to achieve the desired cooling effect. [4]

1.2.1.1 Types of Active Cooling Techniques

1.2.1.1.1 Forced air cooling: - In this method air is blown by a fan or blower over the heat source. This is generally used in combination with a heat sink, to speed up the heat dissipation process and ensure faster cooling rates. This type of cooling is generally used in closed spaces where the heat needs to be directed out through the ventilation ducts. Larger fans aid in faster heat dissipation. [4]

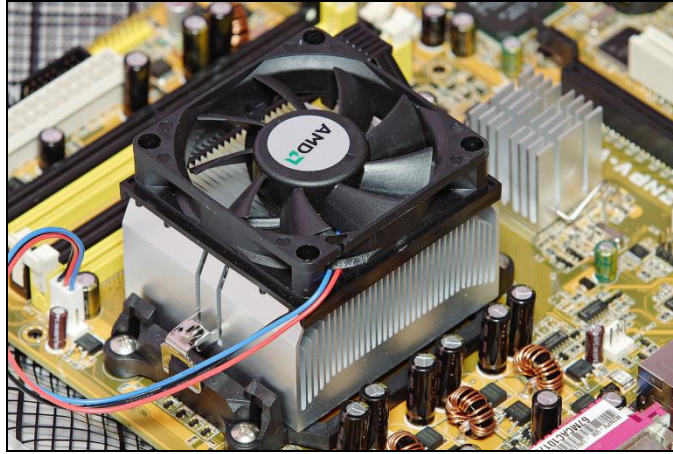


Figure 1.2 Forced Air Cooling [4]

1.2.1.1.2 Forced liquid cooling: - This is a closed loop system of cooling, and consists of pumping a liquid coolant through tubing to remove heat from the area of heat generation. When utilized for cooling electronic components, a cold plate is the most frequently use. A cold plate essentially is a thermal conductive metallic block, which contains tubes for permitting a liquid coolant to flow in a continuous loop. It absorbs the heat from the heat source, which causes a temperature to rise in the coolant, the hotter coolant then circulates to a condenser at which point it releases the absorbed heat and becomes cooler. This liquid is then returned back by the pump and the cycle repeats again [4]. This method of cooling is highly efficient but a major concern is of coolant leakage, which could severely damage the electronic components.

1.2.1.1.3 Thermoelectric heat pump: - It is also called a Peltier cooler and is basically a solid state heat pump which uses two types of semiconductors (P-type and N-type) to transfer heat from one side of the surface to the other. The semiconductors are connected electrically in series and thermally in parallel with each other. When the terminals of the two semiconductors are connected to a DC power supply, current flows across the junction of the semiconductors. This causes a temperature difference to develop, due to which one side of the cooling plate absorbs heat; this heat is then moved to the other side of the device. This phenomenon facilitates the desired cooling effect. [5]

1.2.2 Passive cooling

This is a cooling technique that does not employ any external energy source, but relies on thermal properties of conduction, convection and radiation to achieve the desired heat transfer process. Heat is dissipated by using a heat sink or protruding fins, which have high surface area so that the heat is naturally dissipated to the ambient. Heat pipes are another such method that uses both thermal conductivity and phase change to achieve the required cooling. [4]

1.2.2.1 Types of Passive Cooling Techniques

1.2.2.1.1 Heat pipes: - In a heat pipe the liquid coolant absorbs heat from the region to be cooled, due to which the liquid undergoes phase transition and becomes vapor. This vapor then travels along the grooves within the heat pipe to a condenser to release the absorbed heat. This vapor again undergoes phase transition and converts in liquid. In this way the cooling cycle continuously repeats itself. [4]

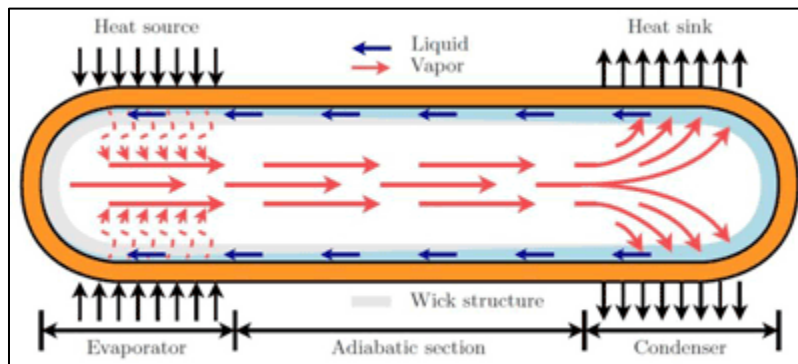


Figure 1.3 Heat Pipe [4]

1.2.2.1.2 Heat sinks: - Heat sinks are some of the most commonly used passive cooling devices. They are made of metals with high thermal conductivity such as copper or aluminum and are fixed to a heat producing object. Heat is transferred from the part to the heat sink by means of thermal conduction and then through free convection to the atmosphere.

The bulk mass of the heat sinks enables it to dissipate a larger amount of heat than a component could do on its own. The heat transfer capability is further improved with the addition of fin structures, thus increasing the overall available surface area for convection and radiation. [4]

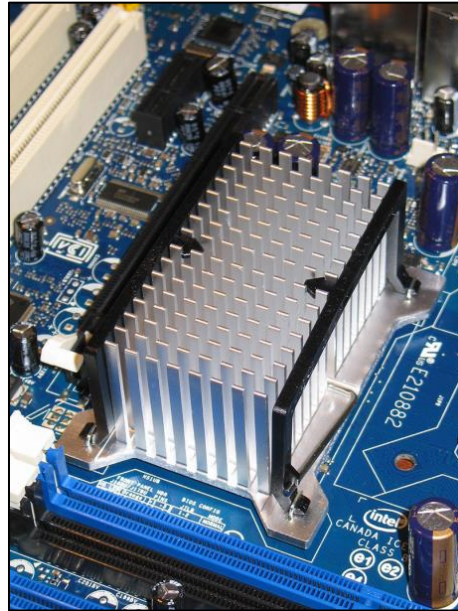


Figure 1.4 Heat Sink

1.2.2.1.3 Heat Spreaders: - Heat spreaders are metallic plates or foils made up of thermally conductive materials and are used to distribute the heat over a wider area. They are generally used as an interface material between a heat source and an exchanger such as a heat sink. [4]

1.3 Types of Thermal Energy Storage

1.3.1 Sensible Heat Storage

This is called sensible heat storage because the change in the material temperature caused by heat exchange can be easily sensed/ detected. There is no phase change involved in this method of heat storage. The material to be used as the storage medium absorbs/ releases heat and due to this heat, increases/decreases its core temperature. Hence the specific heat capacity is a very important property for determining the sensible heat storage capacity of a material. As the specific heat capacity (C_p) of a

material is defined as the amount of heat needed by a gram of material to increase its temperature by one degree Celsius. Hence the higher the specific heat capacity of a material, the higher is the energy retention in that material, as the material will be able to absorb more amount of energy to raise its temperature by 1°C.

It is given by the expression, $Q = mC_p\Delta T$ [6]

Where Q – Sensible energy stored in the storage material, m – mass of the storage material, C_p – Specific heat of the storage material, ΔT –temperature gradient during the process [6].

1.3.2 Latent Heat Storage

Latent heat is the amount of heat absorbed or released by a material as it undergoes phase transformation. As a material undergoes phase transformation, there is no temperature change in the material. It absorbs/releases heat while maintaining a constant temperature. Materials which possess high latent heat of fusion and clean phase transition are termed as phase change materials for energy storage purposes. Heat is absorbed by a material as it changes phase from solid to liquid to gas. While heat is released by a material as it changes phases from a gas to liquid to solid. For our study, we selected a material for phase transition from solid to liquid due to low volumetric change, ease of handling and a higher thermal storage capacity [6].

Latent heat stored in a material is given by

$$Q = mL$$

Where: m – mass of the thermal storage material, L - Specific latent heat of the material [6]

1.3.3 Thermochemical Energy storage

In thermochemical energy storage, energy is stored during dissociation reaction of chemicals and energy is recovered through a chemically reversible reaction. It is based on the principle that when heat is provided to a particular material, it absorbs the heat and dissociates into two different materials. Energy is in thus stored in these separate materials. When these separate materials come in contact with each other they release the stored energy

Thermochemical Energy storage has higher storage density than other types of thermal energy storage mediums such as specific heat or latent heat. Thus large quantity of energy can be stored while utilizing small quantities of storage material. [6]

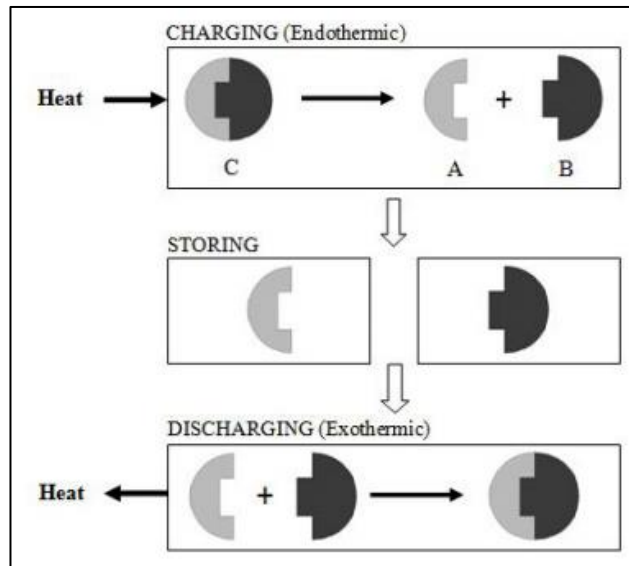


Figure 1.5 Thermochemical Storage Cycle [6]

1.4 Desired Properties in Phase Change Materials

A phase change material should possess the following properties [7]

1. Melting point within the desired temperature range
2. High latent heat of fusion
3. High specific heat capacity

4. High thermal conductivity
5. High density
6. Small volumetric change during to phase transition
7. Low vapor pressure at operating temperature
8. Uniform melting
9. High nucleation rate to avoid super cooling of material
10. Chemically stable
11. Reversible melting - solidification cycle
12. Negligible degradation after multiple melting – solidification cycle
13. Non-corrosiveness
14. Safe to use

Primary criteria used for selecting Phase Change Materials in this study

1. High heat of fusion
2. Melting point between 40 to 90°C
3. Self-nucleating properties
4. Low vapor pressure
5. Chemically stable
6. Safe to use

1.5 Commercial Phase Change Materials

Table 1.1 Commercial Phase Change Materials with melting point between 40 to 90°C [8]

PCM Name	Material type	Melting point (°C)	Latent heat (J/g)	Density (Kg/m ³)
RT - 40	Paraffin	43	181	-
STL47	Salt Hydrate	47	221	1.34
ClimSel C 48	-	48	227	1.36

Table 1.1 - Continued

STL52	Salt Hydrate	52	201	1.3
RT50	Paraffin	54	195	-
STL55	Salt Hydrate	55	242	1.29
TH58	-	58	226	-
ClimSel C 58	-	58	259	1.46
RT65	Paraffin	64	207	-
ClimSel C 70	-	70	194	1.7
PCM 72	Salt Hydrate	72	-	-
RT80	Paraffin	79	209	-
TH89	-	89	149	-
RT90	Paraffin	90	197	-

Based on the requirements of high heat of fusion and melting point, paraffin wax and salt hydrates were found to be the most promising for the application as a PCM.

1.6 Comparison between Paraffin Wax and Salt Hydrates.

Paraffin Waxes [9]

- High heat of fusion
- Self-nucleating properties
- Negligible segregation during melting and solidification
- Chemically stable
- Safe to use
- Low thermal conductivity

Inorganic Salt Hydrates [9]

- High heat of fusion
- High thermal conductivity
- High volumetric change
- Super-cooling during liquid to solid phase transition
- Nucleating agents are generally necessary
- Nucleating agent become ineffective after repeated thermal cycling

By comparing the merits and demerits of each material, paraffin waxes were found to have much more desirable properties compared to inorganic salt hydrates. Hence paraffin wax was selected for this study. The property of self-nucleation in paraffin wax was a very desirable property. The main demerits of paraffin waxes are that they have a lower thermal conductivity compared to inorganic salt hydrates.

1.7 Paraffin Wax - Octacosane

The paraffin wax selected for this study was Octacosane because it has a melting point of 61.2°C [10], which fits within the purview of the safe operating temperature / junction temperature of many electronic components. Another reason Octacosane was selected was due to its high latent heat of fusion. The molecular formula for Octacosane is $C_{28}H_{58}$.

Table 1.1 Properties of Octacosane

Material	Melting Point (°C)	Density (Kg/m ³)	Molecular Weight (g/mole)	Latent Heat (KJ/Kg)	Specific Heat (J/mole.C)		Thermal Conductivity (W/m.K)
					at 25°C	at 80°C	
Octacosane	61.2 [10]	803 [10]	394.76 [11]	254 [10]	752.8 [10]	937.0 [10]	0.167[8,12]

$$\begin{aligned}\text{Specific Heat at } 25^{\circ}\text{C} &= \frac{752.8 \left(\frac{\text{J}}{\text{mole.C}}\right)}{394.76 \left(\frac{\text{g}}{\text{mole}}\right)} \\ &= 1.90 \text{ J/g. C}\end{aligned}$$

$$\begin{aligned} \text{Specific Heat at } 80^{\circ}\text{C} &= \frac{937 \left(\frac{\text{J}}{\text{mole}\cdot\text{C}}\right)}{394.76 \left(\frac{\text{g}}{\text{mole}}\right)} \\ &= 2.37 \text{ J/g. C} \end{aligned}$$

1.8 Commonly Used Techniques for Thermal Conductivity Improvement

To improve the thermal conductivity of the base material, the commonly used techniques currently employed is to introduce metallic fins, wires, plates, meshes etc. into the bulk of the PCM. Apart from metallic fins, graphite flakes and graphite strands are also used to improve the thermal conductivity.

Table 1.2 Thermal Conductivity Improvement of PCM

Author	Base PCM	Thermal Conductivity Enhancement Technique
Mills, Andrew, et al.	Paraffin Wax	Graphite flakes
I.M. Bugaje [13]	Paraffin wax	Internal Aluminum fins
J. Eftekhari et al. [14]	Paraffin wax	Fins
Knowles and Webb [15]	Paraffin wax (Hexadecane)	Plate fins and wires
Nakaso, Koichi, et al. [16]	Paraffin wax	Carbon fiber cloths

The above mentioned studies show that there is significant improvement in the thermal conductivity of the bulk material, but at the expense of utilizing a large amount of volume reserved for the bulk material. Due to this the overall thermal storage potential of the bulk PCM is significantly reduced. Hence additional technologies were investigated such as doping the base material with nanoparticles to improve the thermal properties.

1.9 Nanoparticles

Nanomaterials/ nanoparticles are nanometer sized particles generally of metals, oxides, carbon nanotubes and carbides. When these nanoparticles are dispersed as colloidal suspensions into the base fluid they are called nanofluids [17]. These nanofluids are engineered to improve the thermal properties and other characteristics of the base fluid.

1.10 Improvement of Thermal Properties Due to the Addition of Nanoparticles

Various studies conducted have shown that a dispersion of a small amount of nanoparticles in a base material can significantly improve the thermal properties of the material. Some of the research studies conducted using nanoparticles are mentioned below.

Table 1.3 Enhancement of Thermal Properties using Nanoparticles

Author	Base material	Material for enhancement	Property enhanced	Enhancement %
Donghyun Shin, Debjyoti Banerjee [18]	Li ₂ CO ₃ – K ₂ CO ₃ 62-38%	SiO ₂ Nanoparticles	Specific Heat,	5-15%,
			Thermal Conductivity	35-45 %
Jifen Wang et al. [19]	Palmitic acid	Multi- walled Carbon nanotubes	Thermal conductivity	30%
Shadab Shaikh et al. [20]	Shell wax	Single-walled Carbon nanotubes	Latent heat	13%
A V Waghmare , A T Pise[21]	Paraffin Wax	Al ₂ O ₃ Nanoparticles	Thermal conductivity	2%
Chieruzzi, Manila, et al. [22]	NaNO ₃ -KNO ₃ 60-40%	SiO ₂ -Al ₂ O ₃ nanoparticles	Specific heat capacity	22%

Shin and Banerjee used a 1% concentration of SiO₂ nanoparticles to improve the specific heat by 5-15% and thermal conductivity by 35-45% in a eutectic mixture of lithium carbonate and potassium carbonate [18]. While Jifen Wang et al. doped Palmitic acid with a 1% concentration of multi walled carbon nanotubes to improve the thermal conductivity by 30% [19].

1.11 Objective

The objective of this study was to improve the thermal properties of paraffin wax for the application as a phase change material in the thermal management of electronic systems. This research focuses on enhancing the thermal conductivity and the specific heat capacity of the base paraffin by dispersing a small quantity of nanoparticles into the base paraffin matrix.

1.12 Significance of this Study

In this study a novel nanofluid is synthesized with improved thermal properties to be used as a phase change material for electronic cooling. The existing methods used for thermal management of electronics are space and energy consuming, which seriously limits the compactness and energy efficiency of electronic devices. Hence we use PCMs for solving the problems associated with the existing methods. The newly engineered paraffin based PCM has higher specific heat and thermal conductivity compared to the pure material. Due to the enhancement in specific heat a smaller quantity of PCM can be used, thus making the electronic devices more compact. And due to the improvement in the thermal conductivity of the PCM, passive cooling methods such as heat sinks can be sized down or the number of fins can be reduced. Thus fully utilizing the thermal storage potential of the PCM.

Chapter 2

Experimental Procedure

2.1 Experiment Methodology

The paraffin selected was Octacosane. This was procured from Acros Organics. The assay percentage range was 99+%. The Polar ended material used was Polyethylene – block – poly (ethylene glycol) and it was procured from Sigma Aldrich. The nanomaterial used was silica (Silicon dioxide/ SiO₂) of 80nm size. The silica nanoparticles were procured from Fisher Scientific.

To obtain reference value for the specific heat and the latent heat capacity of the material the pure Octacosane was prepared and tested first. The sample preparation method for the pure and the nanofluids are different. The nanofluid consists of a three different materials i.e. pure Octacosane, Poly Ethylene Glycol and Silica nanoparticles mixed homogeneously together. These chemicals were mixed together in a ratio of 95 - 3 - 2 % respectively based on their mass fraction (wt. %). Individual samples of 200mg were prepared for each test. The chemical composition was Octacosane - 190mg, Poly Ethylene Glycol – 6mg and Silica -4mg respectively. The samples were weighed on microbalance (make: Sartorius- model: CPA225D). To ensure that the samples were mixed homogeneously, the samples were put through the process of ultra-sonication.

2.2 Homogeneous Mixing of the Sample

The sample needs to be thoroughly mixed to ensure uniform dispersion of the chemicals. After all the chemicals are weighed in a vial, the vial is closed and then lightly shaken manually. Then ethanol (ethyl alcohol) is poured into the vial till it fills 2/3rd of the vial. The vial was then closed and again shaken manually but this time more vigorously for a minute. Then the sample was placed in an ultra-sonicator (Branson-1510) and sonicated for 30 mins with the heating turned on. This process ensures that the Octacosane and ethylene glycol melts while the silica nanoparticles are uniformly dispersed due to the sonication. After the sonication, the vial is taken out of the sonicator and placed on a hotplate which was preheated at 160°C. The vial containing the sample is heated to promote faster evaporation of the ethanol

from the sample, thus leaving behind a homogeneous mix of nanofluid. Once all the ethanol gets evaporated from the sample, the vial is taken off the hot plate and cooled to room temperature. The sample is then scratched from the vial. This prepared sample can then be used with a Differential Scanning Calorimeter (DSC) for measuring its thermal properties.

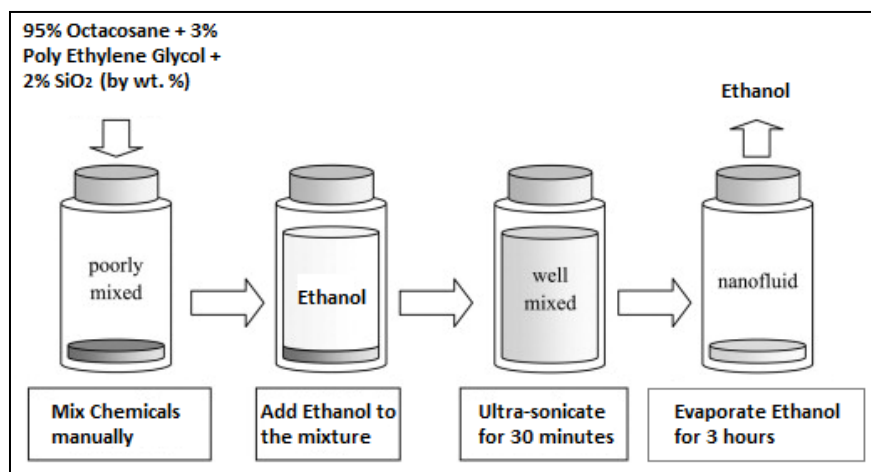


Figure 2.1 Nanofluid Synthesis Protocol [23]

2.3 Loading the Sample

To test the thermal properties of the sample in the DSC the sample needs to be loaded into test pans. For determining the specific heat capacity approximately 10mg of the sample obtained after scratching out from the vial is loaded into a T-zero Aluminum pan and placed onto a hot plate with a preset temperature of 120°C. This causes the sample in the pan to melt and become denser as compared to the powdery - flaky mixture obtained after scratching from the vial. This melting helps to accomplish easy and clean handling of the sample, thereby neglecting the possibility of the sample leaking from the pan during the DSC test. After this, the pan is taken off the hot plate and the sample is allowed to cool down to room temperature. The pan is then sealed with a T-zero Aluminum lid and weighed again. For testing the latent heat of the sample, approximately 12- 15mg of the sample is loaded into the T-zero aluminum pan. This pan is then placed on a hot plate preheated to 120°C till all the sample melts. The pan is then allowed to cool to room temperature. Once the sample has cooled and solidified, it is closed with an aluminum cover and weighed again. The pan is then crimped with a mechanical pan crimping fixture.

2.4 DSC Testing to Measure Specific Heat and Latent heat

A Modulated Differential Scanning calorimeter (MDSC) (make: TA Instruments, model- Q20) was used to measure the thermal properties of the sample. The Differential Scanning Calorimeter (DSC) is a thermo-analytical technique used to measure the thermal properties such as the specific and latent heat capacity of a material [26].

The calorimeter consists of a chamber with a reference holder and a sample holder. An empty hermetically sealed pan is loaded as the reference, and another sealed pan filled with the sample is placed on the sample holder. The sample weight is noted prior to loading the pans in the DSC. The underside of the pan holders contains temperature sensors and heaters. Throughout the experiment the pans are to be maintained at the same temperature. Hence the heater connected to the pan with the sample inside has to supply extra energy in order to melt the sample. This difference in the consumption of the heater powers to maintain the holders at the same temperature is used for calculating the thermal properties of the sample material. An inert atmosphere using nitrogen gas is maintained over the sample holders to prevent oxidation of the sample at high temperatures [27].

Two different measurement techniques were used for measuring the specific heat and the latent heat. The Modulated DSC mode was utilized to measure the specific heat while the standard DSC mode was used to measure the latent heat capacity of the sample.

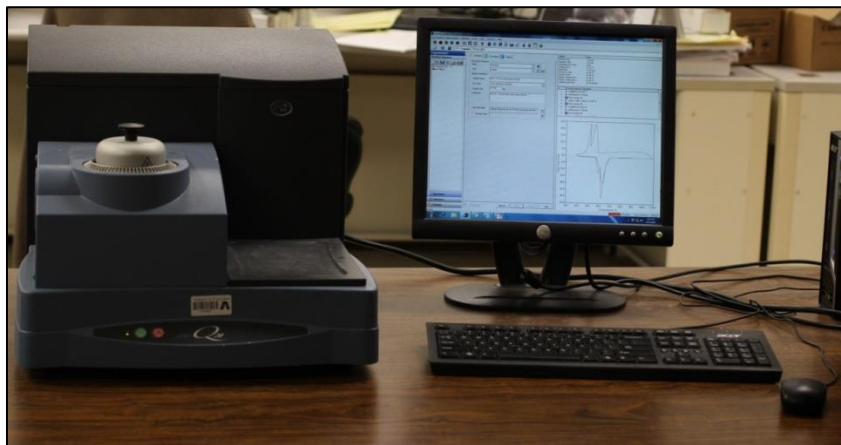


Figure 2.2 MDSC Test Equipment

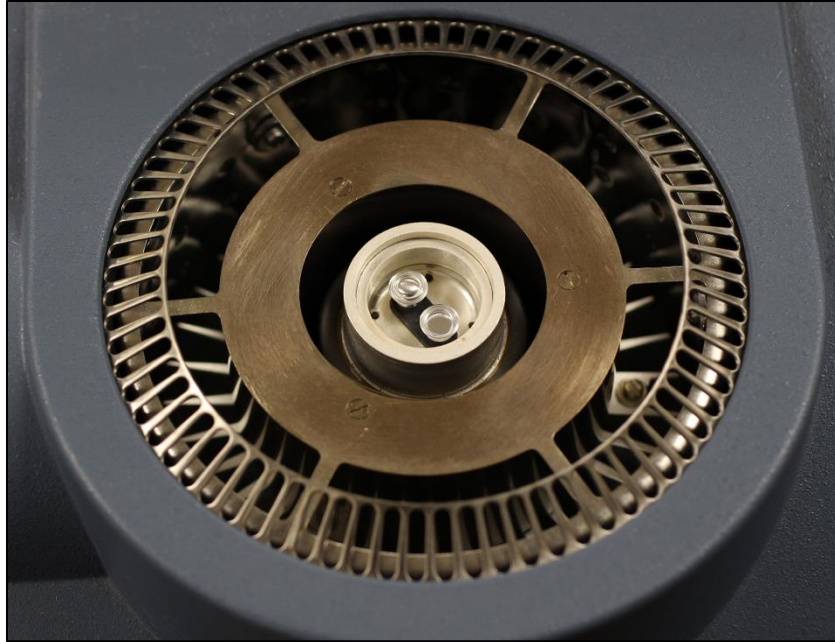


Figure 2.3 T-zero Aluminum Pans in the DSC Test Chamber

2.4.1 Test Protocol for Specific Heat Measurement

To measure the specific heat, the T-zero aluminum pans with the sample was loaded into the DSC.

The following DSC protocol was used for testing the sample.

1. Equilibrate at 40°C
2. Isothermal for 2 mins
3. Modulate $\pm 0.48^\circ\text{C}$ every 60 s
4. Data Storage ON
5. Ramp 3.00°C/min to 110°C

2.4.2 Test Protocol for Latent Heat Measurement

To measure the latent heat capacity, T-zero aluminum pans with the sample was loaded into the DSC.

The following DSC protocol was used for testing the sample.

1. Equilibrate at 40°C

2. Isothermal for 5mins
3. Data Storage ON
4. Ramp 3.00 °C/min to 100 °C

2.5 Thermal Conductivity Measurement

2.5.1 Thermal Conductivity Testing Procedure

A sample of pure Octacosane and nanofluid weighing 2000mg each was prepared and used for measuring the thermal conductivity. The nanofluid sample was prepared using the nanofluid synthesis protocol mentioned earlier. The pure sample was tested first to get a reference value for the measurement, and to compare the measured value with the literature.

The chamber used for testing the thermal conductivity consists of two halves. The sample to be tested was poured into the lower half of the testing chamber. The upper half of the chamber was then placed over it. The test chamber was then loaded into a furnace (make: Jeio Tech model: OV-11) set at 90°C. The chamber was kept in the furnace for 30 mins to allow the sample to melt. As the sample begins to melt, the upper half of the chamber moves downwards due to gravity and displaces the liquefied sample. Once the sample was completely melted and the flanges of the upper and lower half of the chamber are aligned with each other, the chamber was taken out of the furnace. Both the halves of the chamber were fastened together with Allen screws. Eight thermocouples were inserted into the test chamber and one was suspended in the furnace to measure the furnace temperature. The thermocouples were connected to a Data Acquisition System (DAS) (Make: National Instruments model: NI SCXI 1000). A hot wire was inserted into the center of the chamber. The ends of the hot wire were connected to a DC power source (Make: Keysight Model: E3644A) and to the DAS. By tapping into the hotwire and connecting it with the DAS, the voltage drop in the hotwire could be measured. The chamber was kept in the furnace for 1 hour to allow the temperature of the sample and chamber to stabilize and reach a steady state. Once the sample stabilized the DAS and the DC power supply was turned on. The power supply

was set at 9V DC, with an approximate current value of 2.135A. The LabVIEW program was then initiated and the thermal conductivity of the pure and nanofluid samples was measured.

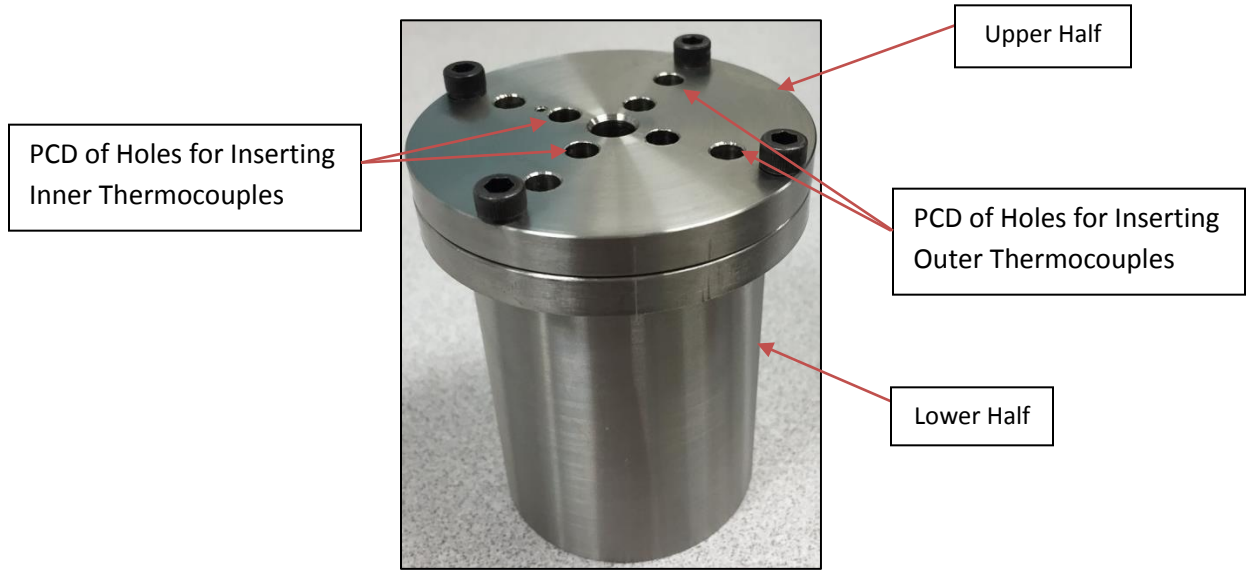


Figure 2.4 Test Chamber for Thermal Conductivity Measurement

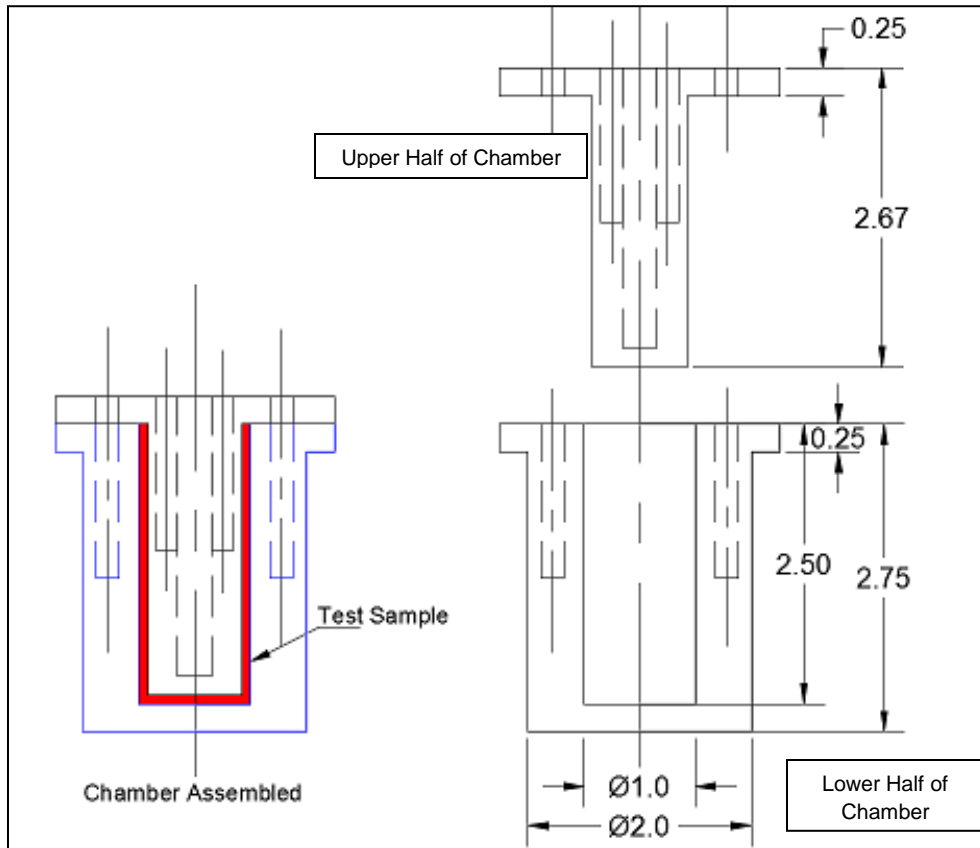


Figure 2.5 Drawing of Test Chamber



Figure 2.6 Thermal Conductivity Setup

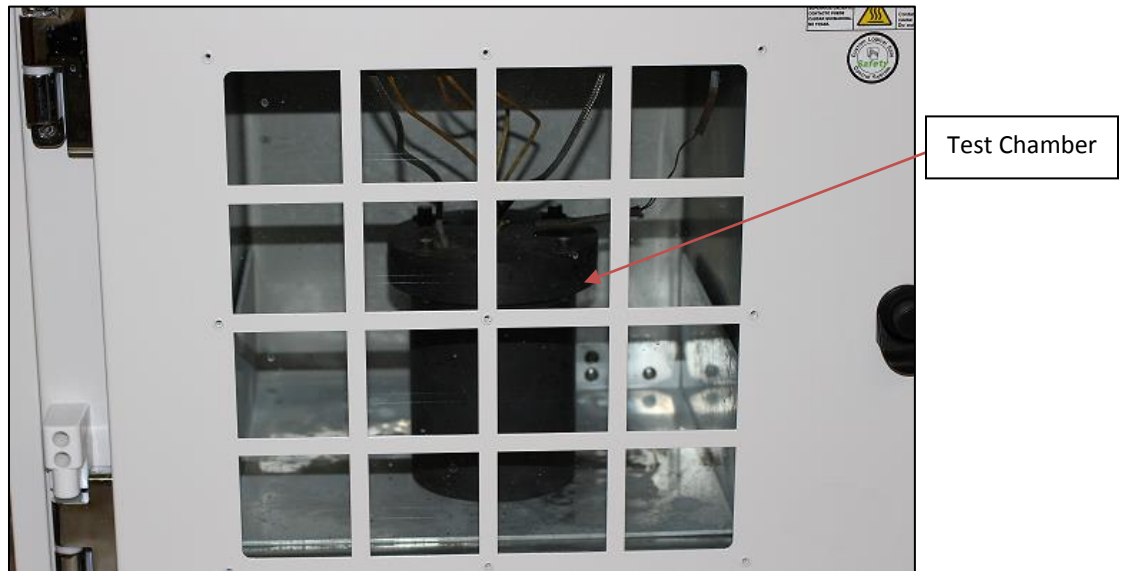


Figure 2.7 Test Chamber in the Furnace

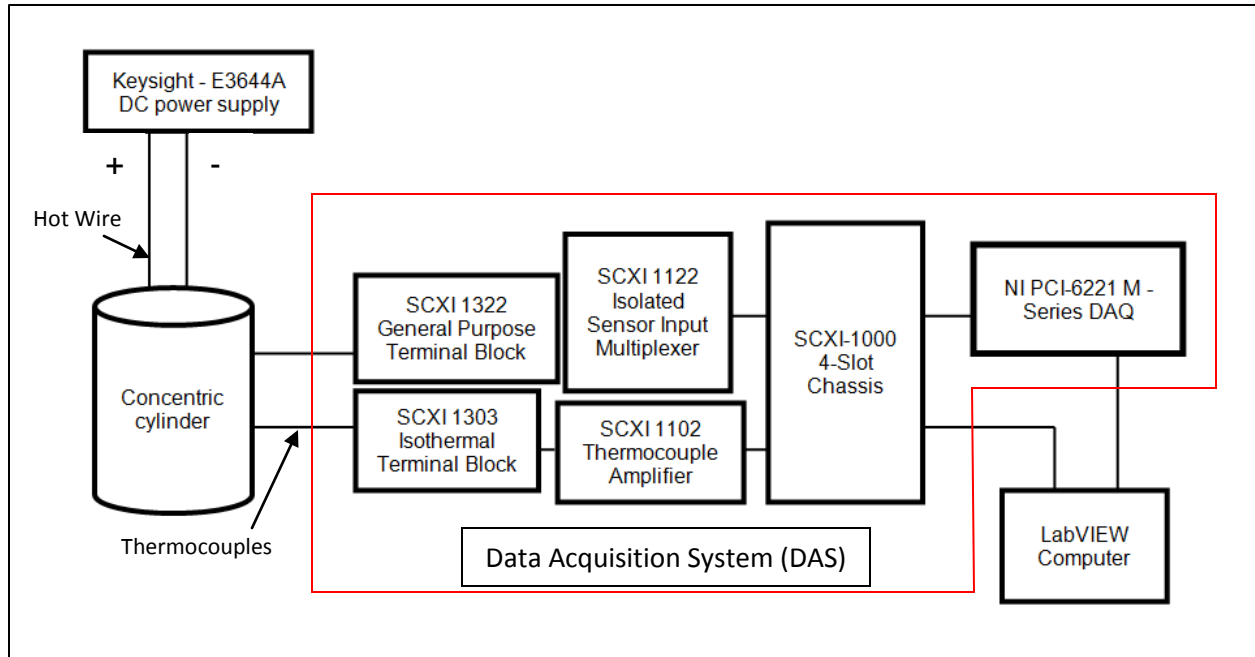


Figure 6 Schematic Diagram of the Physical Connection among Instruments

2.5.2 Working Principle of the Thermal conductivity Measurement Process

The cylindrical cell method was used to measure the thermal conductivity of the pure paraffin and nanofluid samples in this study. This is a common method used for measuring the thermal conductivity of nanofluids in the steady state. Another reason this method was utilized was due to its accuracy and speed of measurement. This method consists of utilizing a chamber with two halves. Each half consists of concentric cylinders. The sample which needs to be tested is filled in the annular gap between the two cylinders. The test chamber used was fabricated out of stainless steel. A hot wire was placed through the center of the inner cylinder; slits were cut through the glass fiber insulation at the point where the hot wire went into the inner chamber, to expose the bare metal. These slits were then connected to the data acquisition system with another wire to measure the voltage drop. The other ends of the hot wire were connected to a DC power supply. When the power supply is started, the hot wire heats up due to electric resistance in the wire and releases heat. The heat flux travels radially outwards from the hot wire, towards the nanofluid present in the annular opening. Temperature at different points in the radial direction of the chamber was measured using calibrated K- type thermocouples [24].

Using Fourier's equation the thermal conductivity of the nanofluid can be determined. Where T_{in1} , T_{in2} , T_{in3} , T_{in4} are the temperatures of inner thermocouples and T_{out1} , T_{out2} , T_{out3} , T_{out4} are the temperatures of outer thermocouples respectively.

r_1 – Radial distance of the inner thermocouples from the central axis of chamber

r_2 – Outer Radius of the inner concentric cylinder

r_3 – Inner radius of the outer concentric cylinder

r_4 - Radial distance of the outer thermocouples from the central axis of chamber

R – Thermal Resistance, K – Thermal conductivity

$K_{steel\ inner}$ & $K_{steel\ outer}$ - Thermal conductivity of upper and lower half of the steel chamber

Thermal Resistance $R = \frac{\Delta T}{Q}$

$$R = \frac{\ln\left(\frac{r_2}{r_1}\right)}{2K\pi L} \quad [25]$$

Rate of Heat Transfer $Q = \frac{(T_{in} - T_{out})(2K\pi L)}{\ln\left(\frac{r_2}{r_1}\right)} \quad [25]$

Thermal Resistance for:-

Inner concentric cylinder $R_1 = \frac{\Delta T}{Q} = \frac{\ln\left(\frac{r_2}{r_1}\right)}{2\pi L K_{Steel\ inner}}$

Nanofluid $R_2 = \frac{\ln\left(\frac{r_3}{r_2}\right)}{2\pi L K_{Nanofluid}}$

Outer concentric cylinder $R_3 = \frac{\ln\left(\frac{r_4}{r_3}\right)}{2\pi L K_{Steel\ outer}}$

$$\text{Total thermal resistance } (R_{tot}) = R_1 + R_2 + R_3 = \frac{T_{in} - T_{out}}{q}$$

$$\frac{T_{in} - T_{out}}{Q} = \frac{\ln \frac{r_2}{r_1}}{2\pi K_{steel\ inner} L} + \frac{\ln \frac{r_3}{r_2}}{2\pi k_{nanofluid} L} + \frac{\ln \frac{r_4}{r_3}}{2\pi k_{steel\ outer} L}$$

Thermal Conductivity of the Nanofluid

$$k_{nanofluid} = \frac{\ln \frac{r_3}{r_2}}{2\pi K_{steel} L \left(\frac{T_{in} - T_{out}}{Q} - \ln \left(\frac{r_2}{r_1} \right) - \ln \left(\frac{r_4}{r_3} \right) \right)} \quad [24]$$

This formula was used with the LabVIEW program and the thermal conductivity experiment was performed

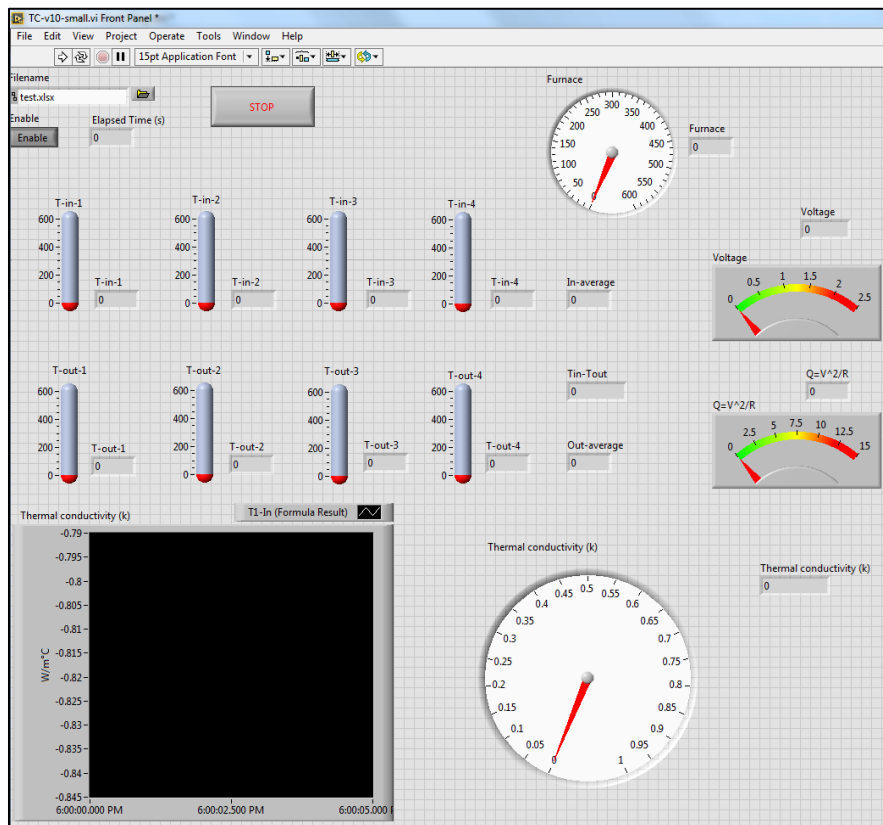


Figure 7 Visual Interface of LabVIEW Software

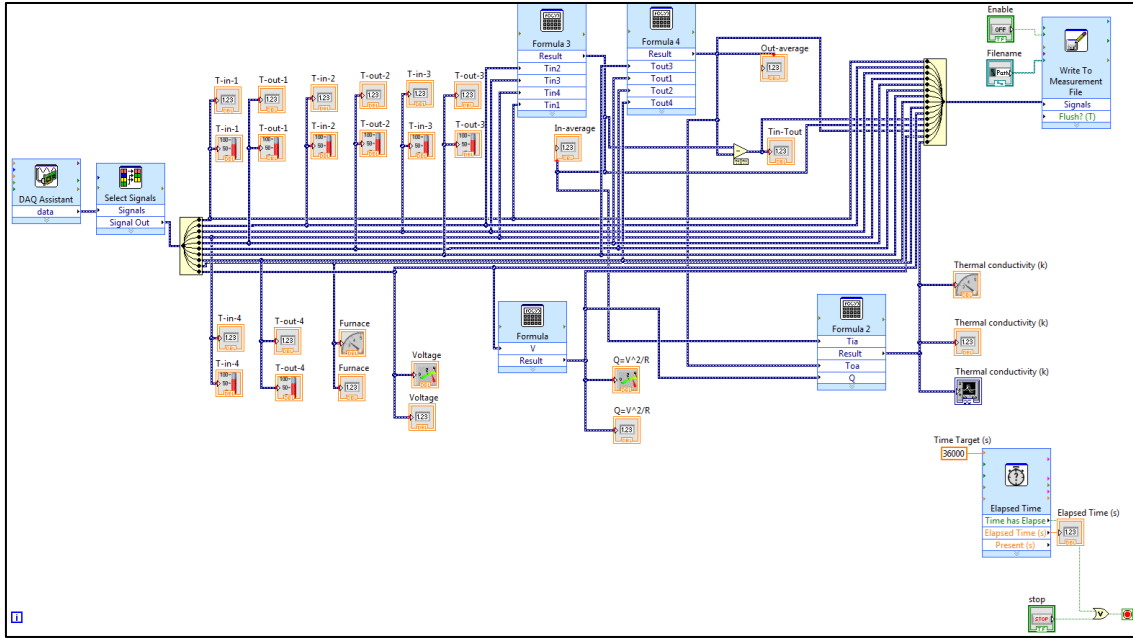


Figure 8 Block Diagram of the Internal Software Connections

Chapter 3

Results and Discussion

3.1 Specific Heat Results

The pure Octacosane sample and nano fluid mixture were tested separately using MDSC mode. Four pure samples were tested. The average specific heat capacity of the pure Octacosane sample measured at 80°C was 2.38 J/g.C. This was in agreement with the literature value of 2.37J/g.C. This was done to get a reference value of the sample. After this, the nanofluid was tested. Thirteen individual samples were prepared and tested to ensure repeatability of the measurements. The average specific heat of the samples was 2.554 J/g.C. A specific heat enhancement of 7.30% was observed in the nanofluid as compared to the pure Octacosane

Table 3.1 Specific Heat Results

Sample No.	Pure Octacosane Specific Heat at 80°C (J/g.C)	Nanofluid Specific heat at 80° (J/g.C)
1	2.389	2.595
2	2.4	2.615
3	2.349	2.597
4	2.385	2.55
5	-	2.543
6	-	2.542
7	-	2.555
8	-	2.552
9	-	2.548
10	-	2.551
11	-	2.53
12	-	2.522
13	-	2.51
Average Specific heat	2.38	2.554
% Enhancement	-	7.30
Std. Deviation	0.019	0.029

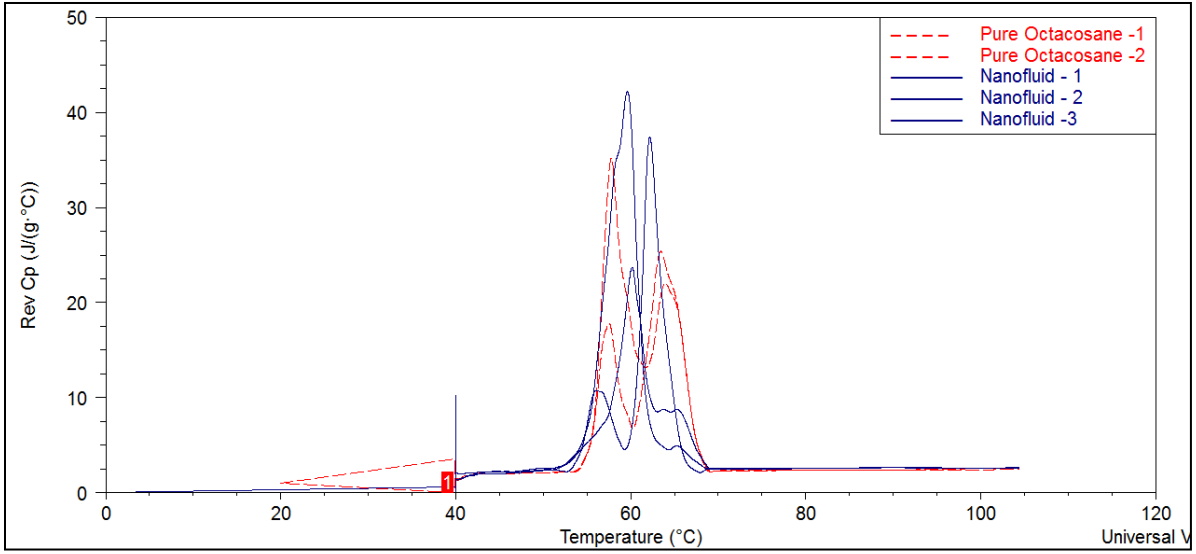


Figure 3.1 Overlapped MDSC Curves of the Pure and Nanofluid

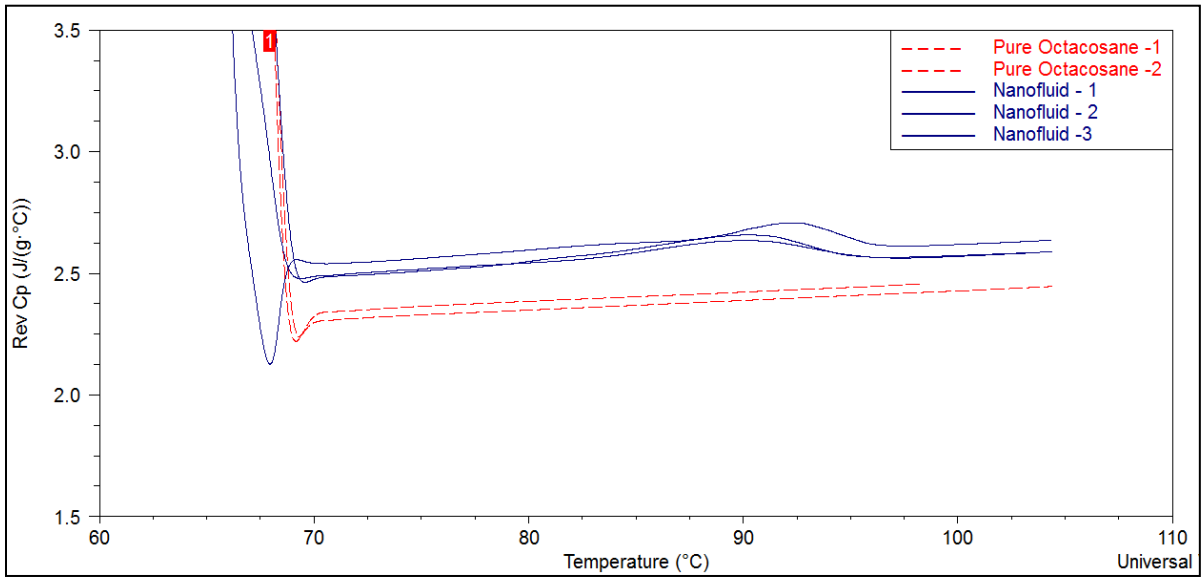


Figure 9 MDSC Curve Showing Enhancement in Specific Heat

3.2 Latent Heat Results

The latent heat of the sample was tested using the Standard DSC mode of the calorimeter. Three pure and nanofluid samples each were tested for determining the latent heat of fusion. The average experimental measured value of the pure Octacosane was 245.37 J/g. And the average experimental measured value of the nanofluid was 244.33 J/g. Thus it can be inferred from this that there was a negligible change in the latent heat of fusion between the pure and nanofluid, due to the addition of nanoparticles.

Table 3.2 Latent Heat Results

Sample number	Pure Octacosane (J/g)	Nanofluid (J/g)
1	242.5	242.0
2	247.4	246.5
3	246.2	244.5
Average Latent Heat	245.37	244.33
Standard Deviation	2.085	1.840

Thus by improving the specific heat capacity while still maintaining the latent heat we can improve the overall thermal storage capacity of the material.

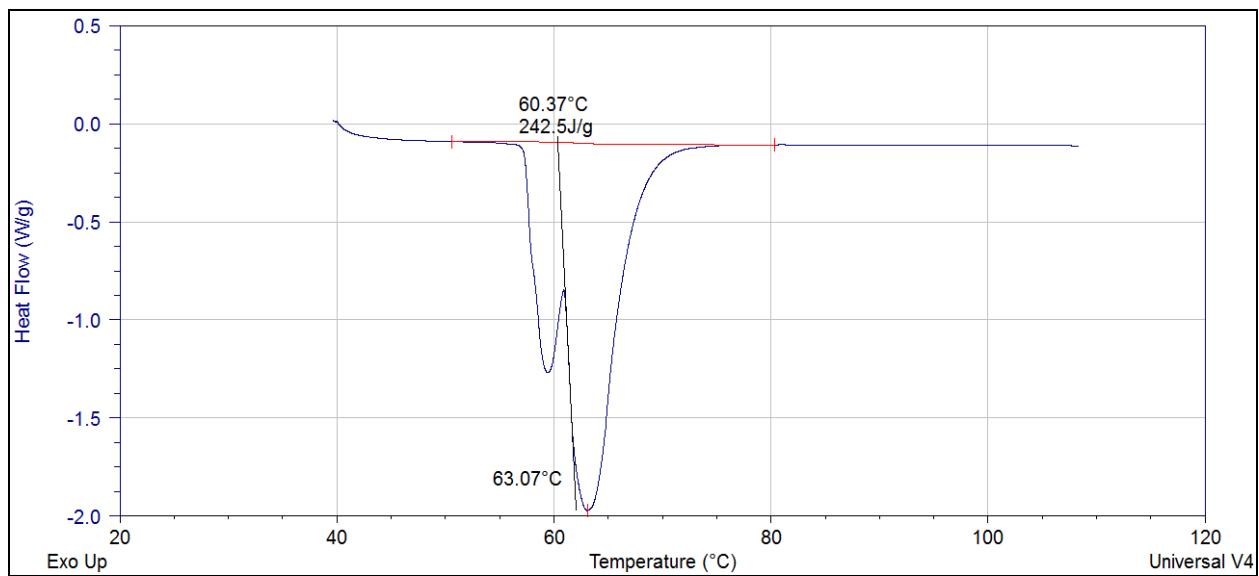


Figure 10 Endothermic Peak in pure Octacosane during Solid – Liquid Phase Transition

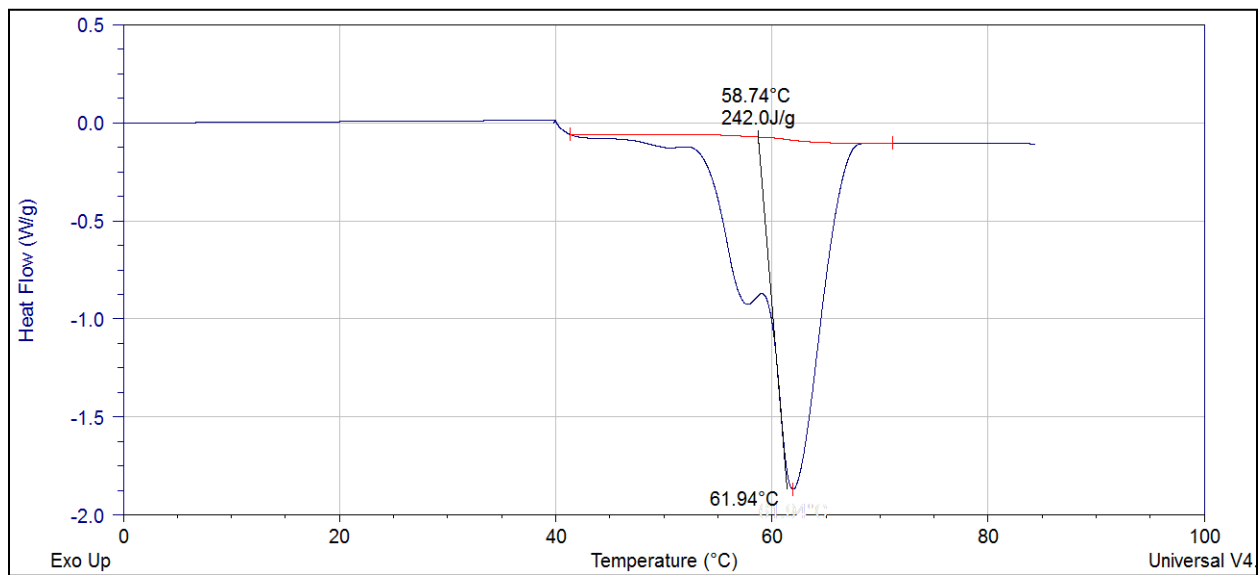


Figure 3.4 Endothermic Peak in Nanofluid during Solid – Liquid Phase Transition

3.3 Thermal Conductivity Results

The pure sample was tested four times to get an accurate and repeatable result. The average thermal conductivity of the pure Octacosane was 0.1603 W/m.C; this was in agreement with the literature value. Next the nanofluid was tested 5 times to ensure repeatability. The average thermal conductivity of the nanofluid sample was 0.20 W/m.C.

Table 3.3 Thermal Conductivity Results for Pure Octacosane

Reference Value (Pure)	0.167 W/m.C
Average Thermal Conductivity (Experimental)	0.1603 W/m.C
Operating Voltage	9 V (DC Supply)
Operating Current	2.134 A
Furnace thermocouple Temperature (Mean)	74.44°C
Inner thermocouple Temperature (Mean)	73.466°C
Outer thermocouple Temperature (Mean)	70.189°C

Table 3.4 Thermal Conductivity Results for Nanofluid

Reference Value (Pure)	0.167 W/m.C
Average Thermal Conductivity (Experimental)	0.2006W/m.C
Operating Voltage	9 V (DC Supply)
Operating Current	2.137 A
Furnace thermocouple Temperature (Mean)	72.07°C
Inner thermocouple Temperature (Mean)	73.869°C
Outer thermocouple Temperature (Mean)	70.871°C

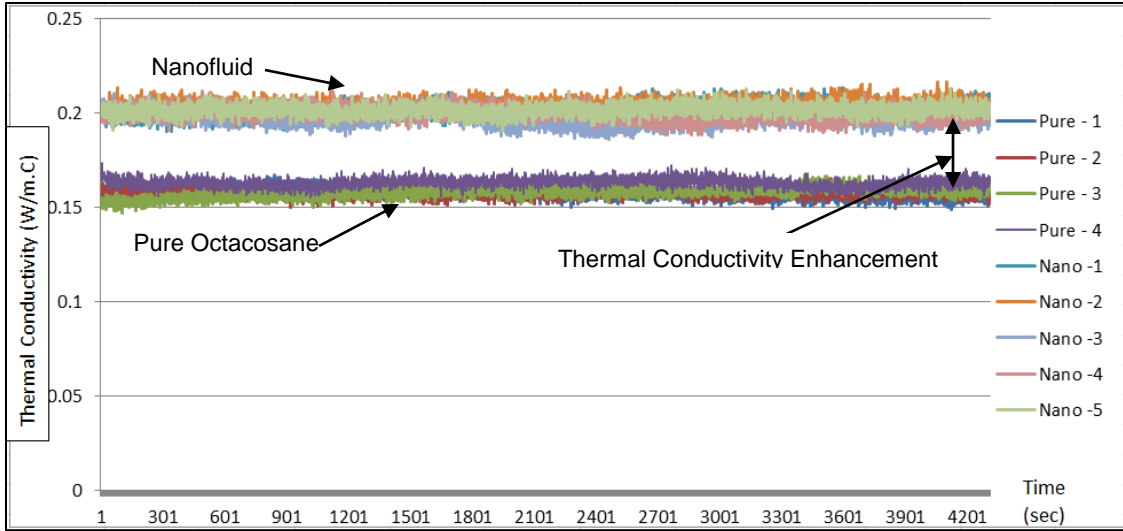


Figure 3.5 Thermal Conductivity Enhancement in the Nanofluid

Table 3.5 Comparative Enhancement in Thermal Conductivity

Reference Value (Pure)	0.16 W/m.C
Average Thermal Conductivity Pure (Experimental)	0.1603 W/m.C
Average Thermal Conductivity Nanofluid (Experimental)	0.2006 W/m.C
Percentage Enhancement	25.14%

As indicated in the graph and table above, a total enhancement of 25.14% was obtained by doping the pure Octacosane with 3% Polyethylene Glycol and 2% Silica nanoparticles.

Chapter 4 Conclusion and Future Work

4.1 Conclusion

In this study the effect of nanoparticles on the paraffin - ethylene glycol sample mixture was observed. Pure Octacosane was doped with 3% of poly ethylene glycol and 2% SiO₂ nanoparticles based on weight percentage. Using this sample mixture specific heat, latent heat and thermal conductivity tests were conducted. The specific and latent heat of the sample was measured using the modulated and standard modes of the DSC respectively. The thermal conductivity of the sample was measured using the cylindrical cell technique. An enhancement of 7.30% in specific heat capacity and 25.14% in thermal conductivity of the nanofluid was observed as compared to the undoped paraffin material. There was no reduction observed in the latent heat of the base sample due to the addition of the nanoparticles. This was a point of significance. Due to the enhancement in the specific heat of the sample; a smaller quantity of PCM can be utilized to achieve the desired cooling effect, thus keeping the size of the electronic devices to the minimum. Also by limiting the use of high space consuming methods such as metallic fins, wires, meshes, a larger quantity of PCM can be used, hence providing more material available for the actual thermal storage purpose.

4.2 Future Work

The future work proposed with the nanofluid.

1. Studying the effect of carbon nanotubes on the latent heat capacity of the sample.
2. Microencapsulation of paraffin wax to improve handling and applicability.
3. Further improvement in the specific heat and thermal conductivity of the sample.
4. Studying the effect of change in the size and concentration of nanoparticles on the thermal properties of the base sample.
5. Modifying the type of nanoparticles used, such as Alumina, Titania, Magnesia and carbon nanotubes to study the effect on the thermal properties.

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Biographical Information

Aditya Pinto is the eldest son of Melvyn and Lydia Pinto. He completed an associate's degree in Production Engineering from Agnel Technical College in May 2009 and a Bachelor's degree in Production Engineering from The University of Mumbai in May 2012. During his studies as an undergraduate he worked with Larsen & Toubro Ltd. for 1 year as an Engineering Intern. After graduating, he went on to work with Shini Plastics Technologies for two years as Senior Engineer – Quality Assurance. He worked independently as a Graduate Research Assistant for one year on an industrial project in The Nanomaterials Research Laboratory at The University of Texas at Arlington. In April 2016 he successfully defended his Thesis and graduated with a Master of Science degree in Mechanical Engineering on May 2016 from the University of Texas at Arlington.