USE OF NANOPARTICLE ENHANCED PHASE CHANGE MATERIAL (NEPCM) FOR DATA CENTER COOLING APPLICATION

by

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Abstract

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This study attempts to take advantage of nanoparticles with high thermal conductivity and the latent heat capacity of phase change materials together to enhance heat transfer rate. The main difficulty in using PCM for energy application is its low thermal conductivity in solid state. So, when solidification starts it makes it hard for evacuation of energy. A paraffin-based nanoparticle containing various volume fractions of Cu was applied.

The suspended nanoparticles caused an increase in thermal conductivity of nanoparticles enhanced phase change material (NEPCM) compared to conventional PCM, resulting in heat transfer enhancement and a higher melting rate. The higher temperature difference between the melting temperature and the hot wall temperature expedited the melting process of NEPCM. Present results show that dispersing nanoparticles in smaller volumetric fractions increase the heat transfer rate. The increase of the heat release rate of the nanoparticle-enhanced phase change materials shows its great potential for data center cooling applications.

A commercially available Computational Fluid Dynamics (CFD) tool is used for the analysis to determine the effect of improved thermal conductivity and cooling effectiveness. The objective of this project is to design and fabricate a shell- tube, phase change material (PCM) based heat exchanger.

Table of Contents

List of Illustrations

List of Tables

Chapter 1

Introduction

1.1 Data Center

The internet has given great importance to the value of information and which is why this is called as Information Age. And, the invent of second version of web, which allowed the users to input their own data to add to the ever-growing World Wide Web, led to a hike in average memory usage. To keep their sites running properly, web admins needed a new technology that would store massive amounts of data in a relatively small space. The data centers are built with only purpose of managing large amounts of data which became answer to all the problems. Data centers started during the very early days of computing systems, nevertheless increasingly grew in popularity during the dot com era. The significance of data centers in the modern world is becoming increasingly evident as more aspects today’s society moves towards digital storage technologies. Now a day, they are used by a multitude of technologies, such as global positioning systems, smartphones, and cloud processing, and organizations like governments, banks, and universities.

Large quantity of power is required to keep the data centers up and running. Power is the amount of work done per unit time, measured in units of Joules/second [28]. Most of the data center uses over one million Joules of energy every day. The second law of thermodynamics explains that the majority of this energy is released as heat, which can be dangerous to a data center server [29]. The main energy user in a data center is the central processing unit. Regrettably, the CPU is also the most affected by an increase in temperature. Semiconductors are the basis of computing, which are vulnerable to conditions called as leakage current and current resistance [28]. The semiconductors are made of many different types of resistant materials. These materials generate an internal heat when current runs through them. This internal heat can lead to problems with the hardware of the data center servers, with the worst case scenario being complete system failure [30].

The increased processing capabilities will lead to increased power consumption, which in turn will generate more heat that will create problems for data center servers. If data centers are to be kept running affordably and efficiently, new methods of analyzing and regulating their temperatures must be developed. ASHRAE which stands for American society of heating, refrigeration and air conditioning engineers has thermal guidelines for data processing environments which can be seen in the fig. [1]

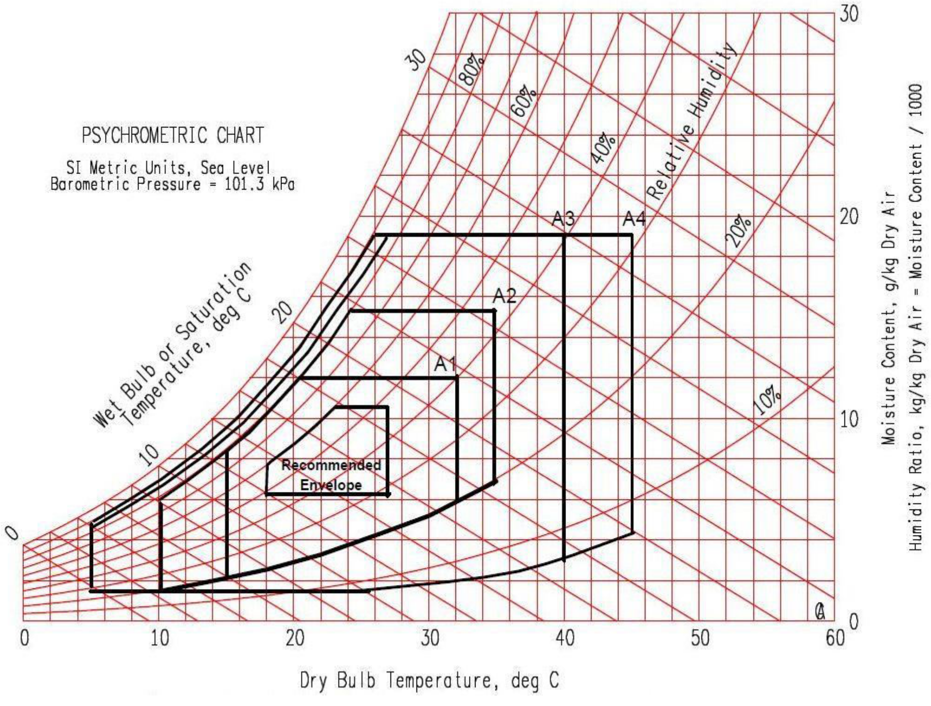

Figure 1.1 ASHRAE Environmental classes for Data Centers

There are many different devices and technologies available for cooling data centers. However, each comprises the following elements:

1 Heat transport: fans and/or pumps moving fluid (such as air or water) to transfer heat energy from the data center to the outdoor environment.

2 Heat exchange: coils or vents that transfer heat energy from one heat stream to the next. In all cases, there is a final heat exchanger to the outdoor environment or heat harvesting stream.

3 Source of cold: this can be a natural source, however also cold from a compressor system.

The data center has become an integral part of society. From blogs and social networks to bank statements and medical records, they house virtually every aspect of our lives, and while their computing capabilities are only getting more proficient each year, it is equally important to advance the systems which keep them efficient and operational. In order for the servers found in data centers to remain at a constant speed and not break down, it is essential to maintain a healthy environment to house these computing systems. A common reason for computers malfunctioning is overheating, and cooling systems can be put in place to stop this from happening. Throughout this paper, several cooling systems have been explained and analyzed in great detail, all of which are great options when it comes to cooling a data center. Some cooling systems described in this paper work better under certain conditions, some are more environmentally friendly, and some are more economical.

Liquid cooling systems are the expensive one, but can be cost effective in the long run if data centers operate for an extended period of time. They are the most advanced of all of the systems described, and have the ability to cool the densest of loads. Free cooling is the most economical and the most environmentally friendly, making it the best overall practice, but can only work under certain conditions. Both of these can be used in conjunction with thermal energy storage. Choosing the right cooling system for a data center depends on all kinds of factors, including economic standing, load sizes, existing infrastructure, surrounding environment, and much more. In today's computer world, processing speed is among the most essential features. This is all due to data centers and their maintained environment.

Thermal energy storage (TSE) is a method of both cooling and heating. TES is capable of executing three processes. The first process is collecting thermal energy from a source, usually from nature. The system will then store that energy for use at a later time when the energy can finally be used to alter the temperature of a desired location or process, or in this case, a data center. Energy used by a data center can be harnessed in a variety of ways. Mainly known methods are Sensible TSE and Latent TSE [31]. The following chapter explains the importance of thermal management.

Chapter 2

Significance of Thermal Management

The reliability of the product is most important characteristic of any device in service. The advancement of new technologies making equipment more complicated yet efficiency demands uninterrupted service life. Electronic, electrical devices have become a part of our lives so much so that we depend entirely on them for normal sustenance. Size of the product plays crucial role in determining its cost: target is to develop systems which are closely packed and integrated, increasing the density of systems. In particular, most processing equipment improvements are realized through increasing the ability of those devices to dissipate heat. The problem of heat dissipation starts at the sub-component level and grows out to the entire system.

The electronics industry has come a long way from developing low performing devices to advanced devices with high computational speed and power. The advancement in the industry led to an exponential increase in power densities, which in turn drove the innovation of smarter and smaller products. These advanced technologies, coupled with miniaturization requirements, guided innovation-driven thermal management in electronic devices. Thermal management is essential in electronics, as it improves reliability and enhances performance by removing heat generated by the devices.

There is an entire range of cooling and heating problems associated with all electronic and electric systems. Electronic devices are housed in small chasses or enclosures. Depending on the applications, these are further assembled in larger units. At each stage the problem of heat dissipation is encountered whether the system is large (composed of many subcomponents) or small. Thermal management of outdoor enclosure design and auxiliary equipment such as heat exchangers, battery backup units and air conditioning demands a different approach when compared to microelectronic devices as they present the challenges posed by high chip heat fluxes, ever more stringent performance and reliability constraints with increasing density in IC technology. In the study by Ming et al [1] it is seen that how over time traditional single-chip packaging has given way to multichip packaging, which has allowed the placement of chips as closely as possible on a single substrate to shorten the interconnection lengths between chips for high performance. Hence as feature sizes are reduced for high density packaging [2], it is increasingly more important to design packaging structures for quality and long-term reliability to reduce costs.

The term thermal management surrounds the technology of the generation, control and dissipation of heat generated in electronic devices and systems. Heat is an unavoidable by-product of every electronic device, and is usually disadvantageous to performance and reliability. The electronic packaging trend has been to reduce size and increase performance of the product, both of which contribute to exponential increase in power consumption of the system. In the past two decades, the conventional electronic industry has become digital savvy, where consumer needs and demands are driving the design and manufacture of products. The electronic industry responded to consumer demand with innovation, offering products which were more powerful than conventional ones, and matching the endless needs of the consumer.

The problems associated with the advent of more complex systems lies in the efficient handling of high temperature which is the main contributor to the failure of electronic devices. Failures result from steady high temperature to steady low temperature or temperature cycling above and below ambient temperature. Effect of steady-state operating temperature on power cycling durability of electronic assemblies has been studied by Kallis et al [6]. In their study it is concluded that by reducing the steady-state operating temperature, durability of the system can be improved. Also, most of the failures in electronic systems are due to high range of working temperature including other failure mode such as vibration and dust [7].

Air cooling was primarily used in computers till late 70's, after which complex circuit processors were introduced. The main advantages of air cooling being ease of application and availability. A simple arrangement of air moving devices was used at both ends of column of boards for high pressure drop capability. Sufficient air-flow rate was provided for the control of external thermal resistance from module to air. Heat transfer enhancement was achieved by placing the tubular strips to break up the boundary layer on the printed circuit cards. An increase in performance was noted as compared to simple circuit [8].

As the power density further increased as seen by the study of Chu et al [10], the cooling obtained from air-flow was not sufficient enough to provide adequate working temperature for uninterrupted working of electronic devices. As a result, air-water cooling was introduced in which forced air convection was used to cool the modules and before using it to cool other modules it was refreshed through air-water heat exchanger [9].

Although easy implementation of air cooling system, it was found to be insufficient when very high temperatures were reached due to reduction in system size and circuit density increase as indicated by Peterson et al [11]. As shown by Drexler et al [12] that in order to reach up to 3.8 × 1024 bits/second · cm2 switching speed for next generation computing devices a cooling capacity of order 105W/cm3 is required, which is impossible only by air cooling techniques.

Many other methods have been employed such as conduction cooling mainly used for the cooling of large multi-chip modules, water cooling systems which used a coolant distribution unit to distribute system cooling water to computer electronics frame, heat sinks, direct liquid cooling in which direct liquid immersion technique was used for cooling integrated circuit chips and packages, sub-ambient cooling etc. as mentioned in the study by Chu et al [9].

To minimize power consumption and total thermal resistance, new concepts followed in electronic cooling technologies such as micro-channels, micro pin fins, and impinging jets. Microscopic channels seemed more desirable as the heat transfer coefficient h varied with channel width for laminar flow in confined channels. Hence they used direct circulation of water in micro-channels fabricated in silicon chips. The pressure drop noted was large at 200kPa with plain micro-channels and 380kPa with pin fin-enhanced micro-channels. Micro-channel concept was first proposed by Tuckerman and Pease in 1981 [13].

Circular pin-fin and offset strip fin heat sinks are among other techniques used for the effective cooling of electronic equipment. Years of excruciating research has been carried out for heat transfer and flow around circular pin-fin and offset strip fin heat sinks. Compact heat exchangers that is the use of enhanced surfaces to reduce the exchanger size possesses a high ratio of heat transfer surface area to volume. Compact heat exchangers can be a finned-tube heat exchanger with flat fins, a finned tube heat exchanger with individually finned tubes, or a plate-fin heat exchanger. A broad review on various types of plate-fin geometries is presented in the work by Stone et al [14]. A wide range of plate-fin geometries have been used to obtain better heat transfer.

Offset strip fins became most popular of all the fin geometries. They were widely used due to their high degree of surface compactness. Forming of laminar boundary layers enhanced their heat transfer rate over uninterrupted channels and heat dissipation in fin wakes. One of the reasons for enhancement is due to periodic starting of flow. An increase in pressure drop is seen due to finite thickness of fins and also because of increased friction and form-drag. Offset strip fin surfaces were studied to prove the correlation between heat transfer and fin geometry as per the research done by Manglik et al [15].

The cooling method known as jet impingement is one of the cooling chip technique in which a coolant is forced through a small orifice to form a jet which removes large heat fluxes. The low pressure operation is the advantage it offers over micro channel cooling. The jet impingement to cool electronic devices is firstly reported in [16]. The study concludes that the convective heat transfer coefficients for jet impingement cooling technique is much higher than the liquid cooling technology used for micro electronic equipment. It was better in controlling the non-uniformities of temperature resulting from uneven heat dissipation in integrated circuits. Much work has been conducted to create a hybrid cooling device for high heat fluxes. Hybrid jet impingement/micro-channel modules have a higher degree of surface uniformity than other cooling schemes and their numerical analysis is studied by Barrau et al in [17].

The cooling technologies are evolving over the years to accommodate steep increase in heat flux. Fig.1 shows the plot between advancement in cooling technology and chip heat flux. The exponential curve shows the increase in the heat flux and changes in the cooling technologies. Future cooling solutions are being developed around multi-phase heat transfer technologies. The cooling technologies such as thermal vapor chamber, cold plates and jet impingement mechanisms have revolutionized the future of the thermal management landscape.

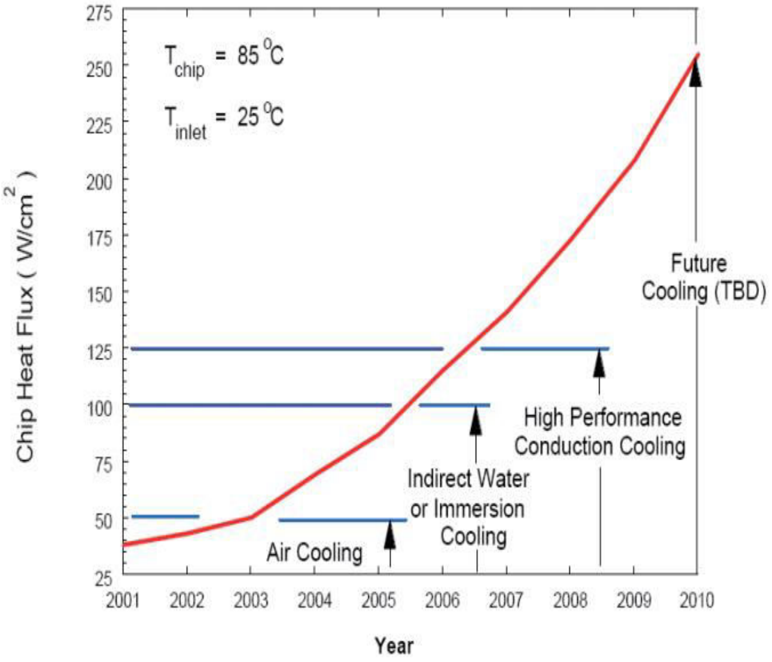

Figure 2.1 Heat flux vs. year of cooling technology development

(Source: IBM USA [3])

The solution for these difficult thermal tasks has led to unconventionality in thermal management. The development of technologies is moving from single-phase heat transfer to multi-phase heat transfer, which has led to the design of advanced cooling solutions. The latest cooling technologies leverage nanotechnology and the advancement in smart materials. Fig. 2 briefly explains the various innovative cooling solutions available in the thermal management industry.

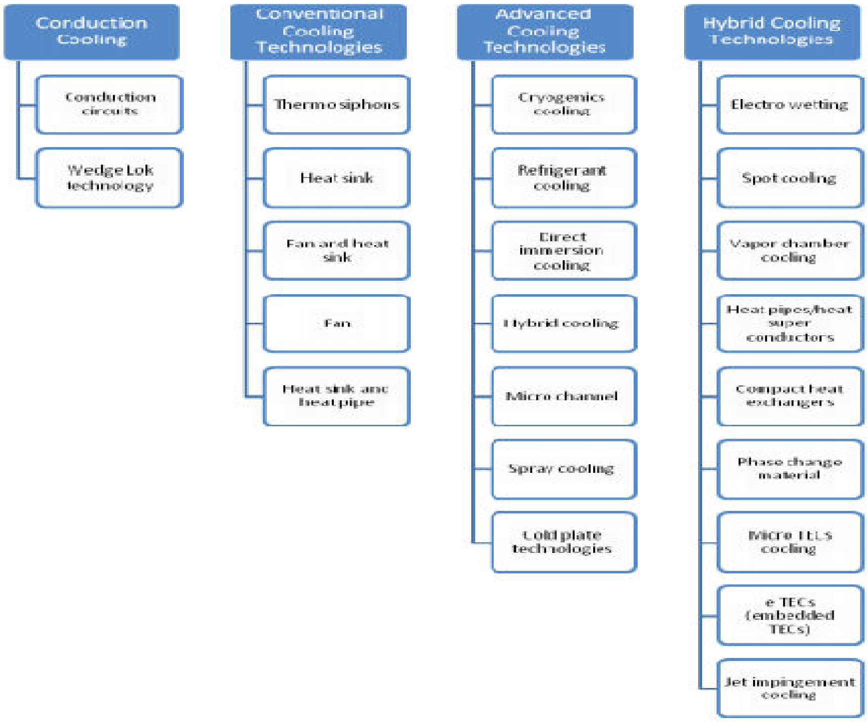

Figure 2.2 Innovative cooling solutions [4]

From a reliability and performance perspective, thermal management needs to be carried out for every electronic device which dissipates heat. This is essential for modern electronics, as they consume more power, they also generate more heat. This has led to the development of computational fluid dynamics (CFD) simulation software and advances in thermal management techniques. The increasing complexity and power density of modern electronics has challenged the traditional approach of using prototypes and testing. The modern CFD simulation software developed for challenging environments and high power dissipation devices has led to a reduction in the product development cycle.

The cooling of electronics is a competetive research area with new inventions being introduced making the system more reliable. Therefore just liquid based cooling technologies are not enough and the need of new cooling technology is neccesary to maximize heat transfer. Among the various methods of energy storage, latent heat thermal energy storage systems using phase change materials have been gaining importance. This is primarily due to their high energy storage density and their ability to provide heat at a constant temperature. The following chapter explains in details about phase change materials.

Chapter 3

Heat Transfer Improvement Techniques

3.1 Phase Change Materials and their Characteristics

A phase change material is a substance with high heat of fusion which on melting and solidifying at certain temperature, is capable of storing and releasing large amounts of energy. Heat is absorbed and released when the material changes from solid to liquid and liquid to solid respectively. PCM absorb heat behaving as conventional storage materials and then release the heat at nearly constant temperature, which is one of the major advantages of using these materials in thermal management. Apart from this, PCM store 5-14 times more heat per unit volume as compared to storage materials such as water, masonry, or rock. Many PCMs which melt with a heat of fusion in any required range, making it more compatible. Nevertheless, for their use they must exhibit desirable thermodynamic, kinetic and chemical properties with ease of availability and economic considerations.

PCMs latent heat storage can be achieved through solid–solid, solid–liquid, solid–gas and liquid– as phase change. Whereas, the only phase change used for PCMs is the solid–liquid change. Liquid-gas phase changes are not practical for use as thermal storage due to the large volumes or high pressures required to store the materials when in their gas phase. Liquid–gas transitions do have a higher heat of transformation than solid–liquid transitions. Solid–solid phase changes are typically very slow and have a rather low heat of transformation.

Primarily, the solid–liquid PCMs acts like sensible heat storage (SHS) materials and their temperature rises as they absorb heat. Compared to SHS, however, when

PCMs reach the temperature at which they change phase they absorb large amounts of heat at an almost constant temperature. The PCM continues to absorb heat without a significant rise in temperature until all the material is transformed to the liquid phase. When the ambient temperature around a liquid material falls, the PCM solidifies, releasing its stored latent heat. A large number of PCMs are available in any required temperature range from −5 up to 190 °C.

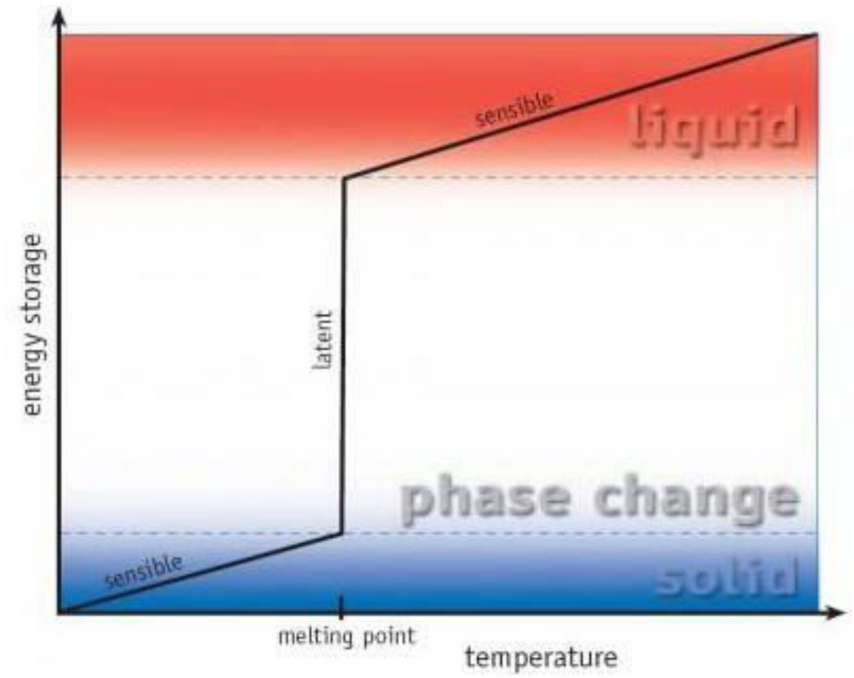

Figure 3.1 Principle of phase change material [39]

Most of PCM do not qualify for the specific use in thermal management because of the restriction applied by operating temperature range which should be in synch with melting solidification temperature range of PCM. An adequate system design has to be compensated suggesting the best PCM for use because none of the materials available are ideal. Paraffin’s are the organic phase change materials which have the ability to congruent melting without constant degradation of their latent heat of fusion. They are reliable, safe, predictable, non-corrosive and cost effective, which is exactly why they are used for thermal management.

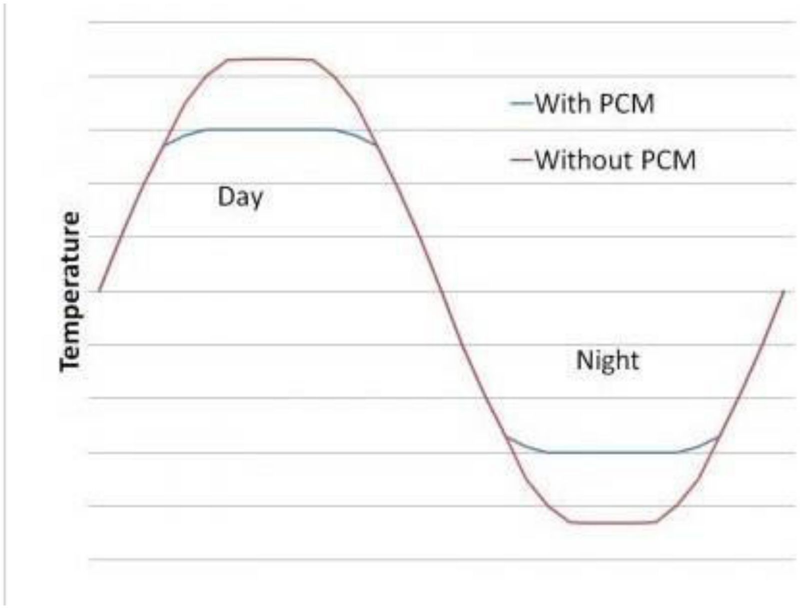

Figure 3.2 The functioning of PCM [39]

The thermal management of electronics has given huge recognition to the use of phase change material in micro-channels. Emulsions contribution and micro encapsulation methods have helped to implement the idea to micro-encapsulated phase change material slurry in micro-channels dispersed in carrier fluid. It was 1975 when Mehalick and Tweedie [18] first introduced the concept of a carrier fluid for encapsulated particles of phase change materials. A lot of work has been conducted on the PCM suspension flow due to its features as high energy storage density, low pumping power requirements and high heat transfer rate between the wall and the suspension. It was noted that when compared to liquid cooling techniques the cooling technique of using micro-encapsulated phase change material slurry shown higher rates of heat transfer coefficients indicating their ability of being more reliable in electronic cooling. The study conducted by Wang et al [19] which indicates that the heat transfer coefficient measured for PCM slurry are notably higher than those of single phase fluid flow in laminar flow conditions, but manifest more complicated circumstances at low turbulence conditions.

3.2 Classification of Phase Change Materials

A large variety of phase change materials are available in any required temperature range. There are a many number of organic and inorganic chemical materials, which can be identified as PCM from the point of view melting temperature and latent heat of fusion. Nevertheless, except for the melting point in the operating range, majority of phase change materials does not meet the conditions required for necessary storage system.

Organic PCMs: Organic materials are further described as paraffin and non-paraffin. Organic materials include congruent melting means melt and freeze repeatedly without phase segregation and consequent degradation of their latent heat of fusion, self-nucleation means they crystallize with little or no super cooling and usually non-corrosiveness.

Inorganic: Inorganic materials are further classified as salt hydrate and metallic. These phase change materials do not super cool appreciably and their heats of fusion do not degrade with cycling.

Eutectics: A eutectic is a minimum-melting composition of two or more components, each of which melts and freeze congruently forming a mixture of the component crystals during crystallization. Eutectic nearly always melts and freezes without segregation since they freeze to an intimate mixture of crystals, leaving little opportunity for the components to separate. On melting both components liquefy simultaneously, again with separation unlikely. Some segregation PCM compositions have sometimes been incorrectly called eutectics, since they are minimum melting temperature. A figure with classification of PCM is shown below,

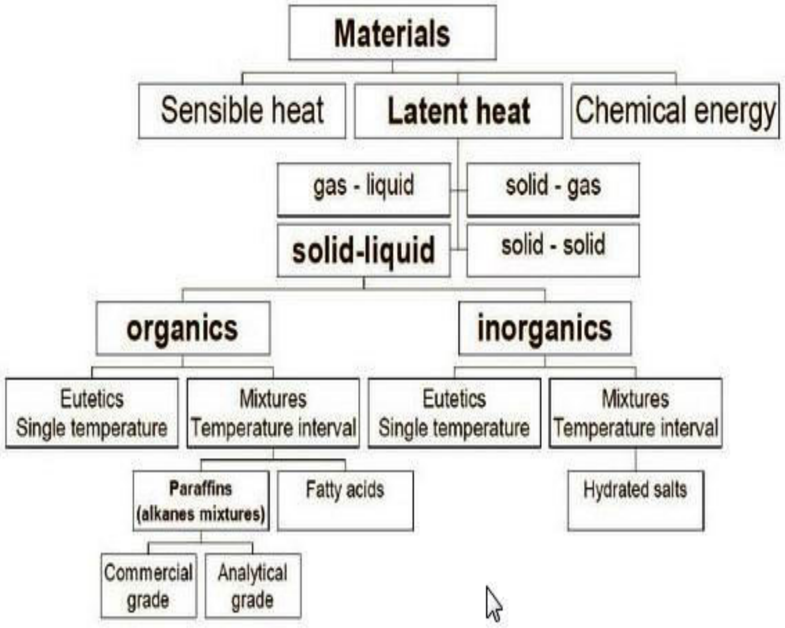

Figure 3.3 Classification of PCM [27]

3.3 Selection of Phase Change Materials

The phase change material should possess following properties:

Thermodynamic properties: Melting temperature in the desired operating temperature range, High latent heat of fusion per unit volume, High specific heat, high density and high thermal conductivity, Small volume changes on phase transformation and small vapor pressure at operating temperatures to reduce the containment problem, Congruent melting.

Kinetic properties: High nucleation rate to avoid super cooling of the liquid phase, High rate of crystal growth so that the system can meet demands of heat recovery from the storage system,

Chemical properties: Chemical stability, complete reversible freeze/melt cycle, No degradation after a large number of freeze/melt cycle, Non-corrosiveness, non-toxic, non-flammable and non-explosive materials, cost and availability.

3.4 Phase Change Process

The study by Stefan [20] of heat transfer characteristics of melting and solidification process presents the energy equation at solid-liquid interface as

$$L_{h\rho}\left(\frac{d_S}{d_t}(t)\right) = k_s\left(\frac{\delta T_S}{\delta_t}\right) - k_l\left(\frac{\delta T_L}{\delta_t}\right)$$

The above equation represents the phase change and describes the energy conversion across the interface. It is referred as moving boundary problem or Stefan which is the basic melting-solidification phenomenon. The problem referring the behavior of phase change is difficult because of following reasons 1) two phases has difficult thermo-physical quantities and 2) non-linear nature at moving interface. The moving boundary problem number is describes as the ratio of sensible heat to the latent heat [21]

$$S_{tl} = \Delta T \frac{C_l}{L_h}$$

The Stefan number characterizes the process of phase change with constant density, latent heat, melt temperature, phase wise constant specific heat and thermal conductivity. There are many techniques available to solve the moving boundary problem and much material is available for the techniques such as isothermal migration, source and sink method, periodic solution etc., but these techniques are only limited to one dimensional analysis. Numerical methods are found to be more powerful in solving this problem and among the solutions present the most feasible to solve the moving boundary problem is by enthalpy formulation. Enthalpy of the material is determined as follows [22]

$$E \ = \ E_{liq}\ (T) \ = \ L_h + \int_{Tm}^{T} c_L\ (\bar{T})\overline{dt}, for\ T \ > \ T_M$$

$$E \ = \ E_{sol}\ (T) = \ \int_{Tm}^{T} c_S\ (\bar{T})\overline{dt}, for\ T \ < \ T_M$$

Latent heat term added in enthalpy of liquid distinguishes the two enthalpies. Hence, the phases can be defined by either enthalpy or temperature. Solid phase can be characterized as:

$$Phase_{solid}: T < \ T_M\ or\ E < 0$$

Liquid phase can be characterized as:

$$Phase_{liquid}: T \ > \ T_M\ or\ E \ < \ L_h$$

When the specific heats are constant, at $T = T_M$ the enthalpy increases by magnitude L_h and the equations are reduced to:

$$E_{liq}\ (T) \ = \ L_h + \ c_L(T - \ T_M), T \geq \ T_M$$

$$E_{sol}\,(T) \;=\; c_S(T - T_M), T \leq T_M$$

The thermo physical property at certain conditions can complicate the mathematical solution one of which is when temperature reaches T_M.

3.5 Reason for enhancement of Phase Change Material

The limitation on increased application of PCM mainly because of two reasons: first being their low thermal conductivity which hurdles the most efficient heat transfer and second, the slurry form does not strongly take advantage of mixing effect. Hence, the use of PCMs is limited to high heat fluxes as the particles in the slurry melt away very quickly and the advantage of small temperature variation characteristic of phase change materials is never fully achieved. Hence the need for other alternatives to enhance the heat transfer by taking the advantage of high storage density of phase change material slurry with some high conductivity material to combat low thermal conductivity of PCM slurry is felt. The technology which is showing potential for enhancing the heat transfer rate is Nano-particle enhanced phase change material. In next chapter we will discuss the high thermal conductivity of copper nano-particle. And the effect it has on heat transfer rate and overall cooling mechanism.

3.6 Nanoparticle enhanced Phase Change Material (NEPCM)

The low thermal conductivity in PCM limits the heat transfer rates during both charging and discharging processes in the heat storage system. To overcome this problem, a wide range of investigations were carried out aiming to enhance the thermal conductivity of the organic PCMs or increase the heat transfer performance. Using nano-fluid to increase the heat transfer shows a great opportunity in storage system. The enhanced PCM is found to exhibit lengthened melt times and shortened cool-down times.

Masuda et al. [23] reported on enhanced thermal conductivity of dispersed ultrafine nanoparticles in liquids. Soon thereafter, Choi and Eastman [24] presented the benefit of using the nanoparticles dispersed in a base fluid for this new class of fluids with superior thermal properties. Rahimi et al. [25] numerically studied the natural convection of mixture of nanoparticles and water near its density maximum in a rectangular enclosure. They found that heat transfer rate considering a non-Boussinesq temperature-dependent density undergoes a nonlinear trend with changes in nanoparticle volume fraction. Khodadadi and Hosseinizadeh [26] reported a numerical solution on improvement of thermal storage energy using NEPCM. They found that the resulting nanoparticle-enhanced phase change materials exhibit enhanced thermal conductivity in comparison to the base material. In addition, their numerical results showed reduction in the overall solidification time. Ranjbar et al. [32] investigated the influence of utilizing nanoparticle on enhancement of heat transfer in a three-dimensional cavity. They showed that the suspended nanoparticles substantially increase the heat transfer rate.

Metals have high thermal conductivity; hence, they can enhance the thermal conductivity of PCMs significantly. But, metal materials oxidize, and their application to PCMs can degenerate and reduce the thermal conductivity of PCMs in the long run. Although adding metal oxides or minerals to PCMs to enhance thermal conductivity is worth considering, the thermal conductivity of such additives must be higher than that of the PCM if they are to enhance the thermal conductivity of PCMs. Moreover, a poor combination of additives to PCMs can increase interface thermal resistance and sedimentation and reduce the performance of the thermal storage without enhancing the thermal conductivity of PCMs. With the development of nanotechnology, the size of the additives can be reduced to a nanometer scale, and the reduced size can enhance the suspension performance, specific surface area, and heat transfer performance of the additives.

Hosseinizadeh et al. [35] investigated numerically unconstrained melting of nanoparticle enhanced phase change materials inside a spherical container. They used RT27 and copper particle as base material and nanoparticle that enhanced the thermal conductivity of base material. Their investigations showed that the nanoparticles cause an increase in thermal conductivity of NEPCM compared to conventional PCM. Khodadadi and Fan [34] utilized an analytic/integral approach to solve one-dimensional Stefan problem for a nano-fluid that undergoes freezing. Their model accounts for the thermal property jumps between the liquid and solid phases and showed that the freezing time decreases as the volume fraction of the nanoparticle is raised. There are only few experimental data that are addressing the use of particles in order to enhance PCMs. Wu et al. [35] developed a new sort of nano-fluid phase-change material by suspending a small amount of nanoparticles in melting paraffin.

Nanoparticles of Cu, Al, and C/Cu were added to the melting paraffin to enhance the heat transfer rate of paraffin. They concluded that Cu nanoparticles have the best performance for heat transfer. That is the reason for using Cu nanoparticle enhanced PCM for the purpose of heat transfer enhancement of liquid based data center cooling application.

Chapter 4

Designing of Heat Exchanger Based on PCM

The renewable energy is the necessity of the present day because of the increased level of carbon emission, damage to the ozone layer and rapidly increasing cost of limited fossil fuels. Hence, the need of today is develop energy storage technology which can be considered as a new source of energy. The energy that is stored in different forms, which can easily be transferred into the required form, is an exciting challenge. Energy storage reduces the difference between supply and demand it also enhances the performance, efficiency and reliability of energy systems and plays a crucial role in storing the energy.

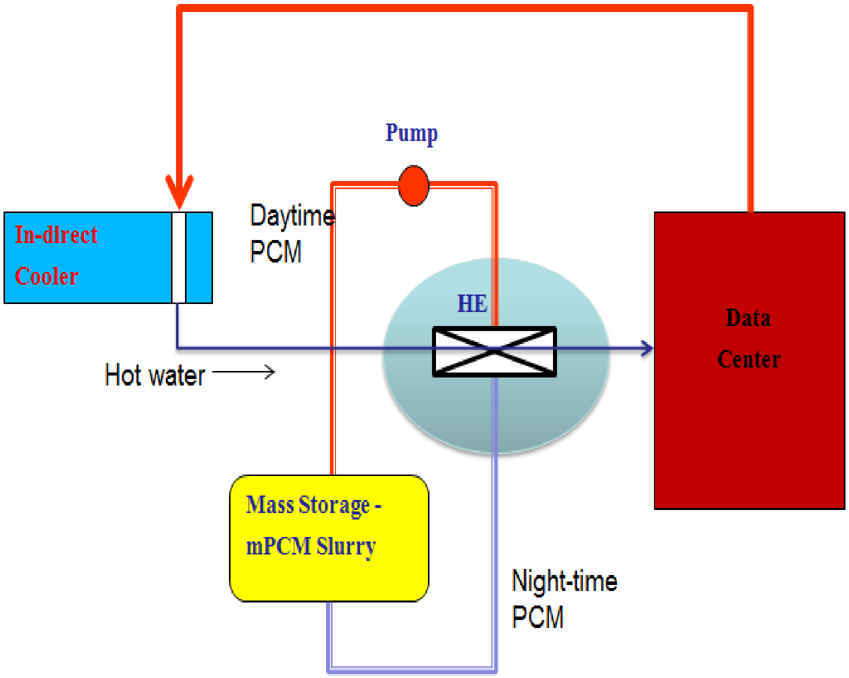

Figure 4.1 PCM based cooling system [38]

4.1 Building blocks of cooling system

Storage Tank: Its purpose is to store both cold and hot water. Cold water is taken out from below and hot water from storage is released in tank from top.

Pump: Its main function is to regulate flow in the system as we will be using forced circulation.

Dry Cooler: It consists of hot transfer fluid, coming out from the data center. This fluid is in turn used to melt PCM for energy transfer.

Phase Change Material: PCM will be circulated in the heat exchanger for thermal energy storage.

PCM Heat Exchanger: PCM heat exchanger which is part of our study is a crucial component of this system.

4.2 Heat exchanger design

Following are the parameters regarding the calculation for PCM based heat exchanger:

- A satisfactory type of heat exchanger is selected.
- An acceptable phase change material is selected.
- Quantity of water is stored based on the estimation of amount of energy stored.
- Dimensional values are calculated for the selected heat exchanger.

Amount of energy to be stored:

$$Q = m\, C_v \; (T_i - T_f)$$

Initial water temperature, T_i = 308 K

Final water temperature, T_i = 300 K

C_v Of Water = 4.187 kJ/ kg (where C_v = heat carrying capacity at constant volume)

Heat exchanger with 10 kg storage capacity is considered.

Hence,

Q = 10 x 4.187 x 8 = 335 kJ

Heat exchanger selection:

A shell and tube type heat exchanger is selected as it is easy to add phase change material in this type of exchanger. Hot transfer fluid is flowing through the inner tube and PCM is added in the outer shell of the heat exchanger.

Amount and properties of phase change material selected:

- Density = 1188.7 $^{Kg}/_{m^3}$
- Transition Temperature = 22- 26°C
- Latent heat = 142.689 $^{KJ}/_{Kg}$

Q = Amount of energy stored = 10 x 4.187 x 8 = 335 KJ

Amount of PCM = Q/ Latent heat = 335/ 142.689 = 2.4 Kg.

Therefore, 2.4kg of PCM is added on the shell side of heat exchanger.

Chapter 5

Mathematical Modeling

The thermal storage unit analyzed is a shell-and-tube type of heat exchanger with the phase change material (PCM) filling the shell side. The transient fluid flow momentum and energy equations were solved simultaneously with the tube wall and phase change material energy equations. For phase change material, the temperature transforming model was used.

A mathematical model of transient heat transfer in shell-and-tube thermal storage unit has been formulated. The dimensionless transient fluid flow continuity, momentum and energy equations were solved simultaneously with the tube wall and phase change material energy equations. The enthalpy method has been used for describing heat transfer inside the phase change material. Differential equations, with initial and boundary conditions, have been discretized by control volume approach.

5.1 Mathematical Formulation of Transient Fluid Flow

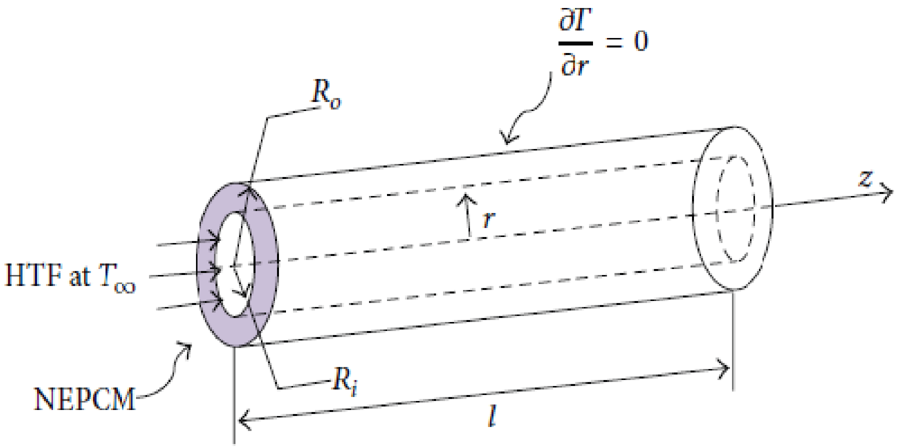

Figure 5.1 Heat Exchanger Model

A heat transfer fluid (HTF) flows through the inner tube and exchanges heat with the phase change material (PCM) on the shell side. During sunlight, i.e. active phase, hot fluid heats the PCM, the PCM melts and the heat is stored. During the eclipse phase, the PCM solidifies and the stored heat is delivered to the cold fluid.

To establish a convenient mathematical model of transient heat transfer, the following assumptions have been made:

- The heat transfer fluid is incompressible and it can be considered as a Newtonian fluid.
- Initial temperature of the latent heat storage unit is uniform and the PCM is in the solid phase.
- Inlet velocity and inlet temperature of the HTF are constant.
- Thermal losses and conduction through the outer wall of the storage unit have been ignored i.e. adiabatic outer wall is assumed.
- Fluid – wall convective heat transfer, heat conduction through the wall and phase change heat transfer can be considered as an unsteady two-dimensional problem.
- Natural convection in the liquid phase of the PCM has been ignored.

The dimensionless continuity, momentum and energy equations, governing a transient two dimensional problem of flow and heat transfer in a latent heat storage unit, for heat transfer fluid, wall and phase change material are as follows:

HTF:

$$\frac{\partial Wx}{\partial X} + \frac{1}{R} . \frac{\partial (R.Wr)}{\partial R} = 0 \qquad (1)$$

$$\frac{\partial Wx}{\partial \tau} + W_x \cdot \frac{\partial Wx}{\partial X} + W_R \cdot \frac{\partial Wx}{\partial R} = -\frac{\partial P}{\partial X} + \frac{1}{Re} \cdot \left[\frac{\partial^2 Wx}{\partial X^2} + \frac{1}{R} \cdot \frac{\partial}{\partial R} \left(R \cdot \frac{\partial Wx}{\partial R} \right) \right] \qquad (2)$$

$$\frac{\partial W_R}{\partial \tau} + Wx \cdot \frac{\partial W_R}{\partial X} + W_R \cdot \frac{\partial W_R}{\partial R} = -\frac{\partial P}{\partial R} + \frac{1}{Re} \cdot \left[\frac{\partial 2 W_R}{\partial X2} + \frac{1}{R} \cdot \frac{\partial}{\partial R} \left(R \cdot \frac{\partial W_R}{\partial R} \right) - \frac{W_R}{R2} \right] \qquad (3)$$

$$\frac{\partial \theta_{\mathrm{f}}}{\partial \tau} + W_x \cdot \frac{\partial \theta_{\mathrm{f}}}{\partial X} + W_R \cdot \frac{\partial \theta_{\mathrm{f}}}{\partial R} = \frac{1}{Re \cdot Pr} \cdot \left[\frac{\partial^2 \theta_{\mathrm{f}}}{\partial X^2} + \frac{1}{R} \cdot \frac{\partial}{\partial R} \left(R \cdot \frac{\partial \theta_{\mathrm{f}}}{\partial R} \right) \right] \qquad (4)$$

Wall:

$$\frac{\partial \theta_{\mathrm{w}}}{\partial \tau} = \frac{1}{\mathrm{Re} \cdot \mathrm{Pr}} \cdot \frac{a_{\mathrm{w}}}{a_{\mathrm{f}}} \left[\frac{1}{R} \cdot \frac{\partial}{\partial R} \left(R \cdot \frac{\partial \theta_{\mathrm{w}}}{\partial R} \right) + \frac{\partial^2 \theta_{\mathrm{w}}}{\partial X^2} \right] \qquad (5)$$

PCM:

$$\frac{\partial x_{\mathrm{p}}}{\partial \tau} = \frac{1}{\mathrm{Re} \cdot \mathrm{Pr}} \cdot \frac{a_{\mathrm{p}}}{a_{\mathrm{f}}} \left[\frac{1}{R} \cdot \frac{\partial}{\partial R} \left(R \cdot \frac{\partial x_{\mathrm{p}}}{\partial R} \right) + \frac{\partial^2 x_{\mathrm{p}}}{\partial X^2} \right] \qquad (6)$$

Where χ is the dimensionless enthalpy related to the temperature with equation

$$\Theta p = A_{\mathrm{b}} \cdot \chi_{\mathrm{p}} + B_{\mathrm{b}}$$

Where factors A_b and B_b are

$$A_{\mathrm{b}} = \frac{1}{St} \cdot \frac{\rho_{\mathrm{L}} \cdot c_{\mathrm{L}}}{\rho_{\mathrm{s}} \cdot c_{\mathrm{s}}} \qquad B_{\mathrm{b}} = 0 \qquad \text{for} \qquad \chi_{\mathrm{p}} < 0.$$

$$A_{\mathrm{b}} = 0 \qquad B_{\mathrm{b}} = 0 \qquad \text{for} \qquad 0 \leq \chi_{\mathrm{p}} \leq 1.$$

$$A_{\mathrm{b}} = \frac{1}{St} \qquad B_{\mathrm{b}} = \frac{1}{St} \qquad \text{for} \qquad \chi_{\mathrm{p}} > 1.$$

The equations are obtained using dimensionless variable defined as:

- Dimensionless coordinates

$$\mathrm{R} = \frac{r}{D_i} \qquad \text{and} \quad \mathrm{X} = \frac{x}{D_i}$$

- Dimensionless velocities

$$W_X = \frac{w_x}{w_{\mathrm{in}}} \qquad \text{and} \quad W_R = \frac{w_{\mathrm{r}}}{w_{\mathrm{in}}}$$

- Dimensionless pressure

$$\mathrm{P} = \frac{\mathrm{p} - \mathrm{p0}}{\rho_{\mathrm{f}} \cdot \mathrm{w}^2{}_{\mathrm{in}}}$$

- Dimensionless time

$$\tau = \frac{w_{\mathrm{in}}}{D\mathrm{i}} \cdot t$$

- Dimensionless temperature

$$\theta = \frac{T - T_{\mathrm{m}}}{T_{\mathrm{in}} - T_{\mathrm{m}}}$$

- Dimensionless enthalpy

$$\chi = \frac{H - \rho_{\mathrm{s}} \cdot c_{\mathrm{s}} \cdot T_{\mathrm{m}}}{\rho_{\mathrm{L}} \cdot q}$$

- Reynolds, Prandtl, Stefan and Nusselt number

$$\mathrm{Re} = \frac{w_{\mathrm{in}} \cdot D_{\mathrm{i}}}{U_{\mathrm{f}}} \ , \qquad \mathrm{Pr} = \frac{U_{\mathrm{f}}}{a_{\mathrm{f}}} \ , \qquad \mathrm{St} = \frac{c_{\mathrm{L}} \cdot (T_{\mathrm{in}} - T_{\mathrm{m}})}{q}, \quad \mathrm{Nu} = \frac{\alpha \cdot D_{\mathrm{i}}}{\lambda_{\mathrm{f}}} \ .$$

Initial and boundary conditions are as follows:

Initial condition $\tau = 0$

$$0 < \mathrm{R} \leq 0.5, \qquad 0 \leq \mathrm{X} \leq \mathrm{L}/\mathrm{Di} \quad \rightarrow \quad \mathrm{WX} = \mathrm{WR} = 0$$

$$0 < \mathrm{R} \leq \mathrm{Ro} \qquad 0 \leq \mathrm{X} \leq \mathrm{L}/\mathrm{Di} \quad \rightarrow \quad \theta_f = \theta_w = \theta_p = \theta_{int}$$

Initial condition τ > 0

Inlet plane $X = 0$

$$0 < R < 0.5 \quad \rightarrow \quad W_X = 1,\ W_R = 0,\ \theta_f = 1$$

$$0.5 \le R \le R_{\mathrm{w}} \rightarrow \frac{\partial \theta_{\mathrm{w}}}{\partial X} = 0$$

$$R_{\mathrm{w}} < R < R_{\mathrm{o}} \rightarrow \frac{\partial \theta_{\mathrm{p}}}{\partial X} = 0$$

$$R_{\mathrm{w}} < R < R_{\mathrm{o}} \rightarrow \frac{\partial \theta_{\mathrm{p}}}{\partial X} = 0$$

Outlet plane X = L / Di

$$0 < R < 0{,}5 \rightarrow \frac{\partial W_{\mathrm{x}}}{\partial X} = 0, \qquad \frac{\partial W_{\mathrm{R}}}{\partial X} = 0, \qquad \frac{\partial \theta_{\mathrm{f}}}{\partial X} = 0$$

$$0{,}5 < R < R_{\mathrm{w}} \rightarrow \frac{\partial \theta_{\mathrm{w}}}{\partial X} = 0$$

$$R_{\mathrm{w}} < R < R_{\mathrm{o}} \rightarrow \frac{\partial \theta_{\mathrm{p}}}{\partial X} = 0$$

Axis of symmetry R = 0

$$0 < X < \frac{L}{D_{\mathrm{i}}} \rightarrow W_{\mathrm{R}} = 0, \qquad \frac{\partial W_{\mathrm{x}}}{\partial R} = 0, \qquad \frac{\partial \theta_{\mathrm{f}}}{\partial R} = 0$$

Fluid – wall interface R = 0.5

$$0 < X < \frac{L}{D_{\mathrm{i}}} \rightarrow W_{\mathrm{X}} = W_{\mathrm{R}} = 0, \qquad \left(\frac{\partial \theta_{\mathrm{f}}}{\partial R}\right)_{R=0{,}5} = \frac{\lambda_{\mathrm{w}}}{\lambda_{\mathrm{f}}} \cdot \left(\frac{\partial \theta_{\mathrm{w}}}{\partial R}\right)_{R=0{,}5}$$

Wall – PCM interface R = Rw

$$0 < X < \frac{L}{D_{\mathrm{i}}} \;\rightarrow\; \left(\frac{\partial \theta_{\mathrm{w}}}{\partial R}\right)_{R=\mathrm{Rw}} = \frac{\lambda_{\mathrm{p}}}{\lambda_{\mathrm{w}}} \cdot \left(\frac{\partial \theta_{\mathrm{p}}}{\partial R}\right)_{R=\mathrm{Rw}}$$

Outer wall R = Ro

$$0 < X < \frac{L}{D_{\mathrm{i}}} \;\rightarrow\; \left(\frac{\partial \theta_{\mathrm{p}}}{\partial R}\right) = 0$$

Chapter 6

Computational Fluid Dynamics (CFD) Analysis

6.1 Introduction to CFD

CFD deals with the numerical simulation and analysis of fluid flow, heat transfer characteristics and pressure characteristics. Computational fluid dynamics uses numerical methods to predict, simulate and analyze distribution of velocity, pressure, temperature and other variables throughout the calculation domain. The calculations in CFD are based on the boundary conditions and the calculations are done in a computer. CFD is used for various applications such as data center industries, systems with high heat loads, telecommunication industry, and several more [36].

CFD is a bridge between theory and experiment. CFD represents the problem based on the numerical parameters to solve the problem. Experimental work is costlier than CFD. When compared to conducting an experiment, CFD is very fast as we can simulate many cases in specific time period. A numerical prediction is used for the generation of a mathematical model which represents the physical domain of interest to be solved and analyzed [36].

Certain locations on a server are more inclined to temperature increases than others. When stored in a data center, server hotspots may form. These hotspots are prime targets for cooling. Temperature reduction efforts focused in these regions will yield the most effective results possible. Computational fluid dynamics is a method by which the air flow of a data center can be modeled and analyzed. Using 3-D computer modeling, areas of poor airflow, increased heat and wasted cooling can be isolated and consequentially lessened or eliminated entirely, potentially saving IT owners thousands of dollars in energy costs [37]. This modeling is useful in visualizing the shortcomings and vulnerabilities in a data center server in order to create a specialized plan for reducing server temperature.

6.2 Governing Equations

The four differential equations namely conservation of mass, conservation of momentum, conservation of energy and conservation of chemical species commonly known as governing equations are used to solve the numerical solution for heat transfer and fluid flow based problems.

The conservation of mass is given by:

$$\frac{\partial_{\rho}}{\partial_{x}} + \nabla\,(\rho u) = 0$$

The conservation of momentum is given by:

$$\frac{\partial\,(\rho v)}{\partial_{\tau}} + \nabla\,.(\rho v v) = \nabla\,[\mu(\nabla v + \nabla v\,T)] - \nabla P + \rho g + S$$

The conservation of energy is given by:

$$\frac{\partial(\rho H)}{\partial_{\tau}} + \nabla\,.(\rho v H) = \nabla\,.(k \nabla T) + S_n$$

Where: $H = h + \nabla H$

$$\mathrm{h} = h_{ref + \int_{T_{ref}}^{T} C_p}\mathrm{dT}$$

$$\nabla \mathrm{H} = \beta \mathrm{L}$$

β = 0 if $T < \mathrm{T}_{Solid}$

β = 1 if $T > \mathrm{T}_{\mathrm{Liduid}}$

$$\beta = \frac{T - T_{Solid}}{T_{Liquid} - T_{Solid}} \; if \; T_{Solid} < T < T_{Liquid}$$

6.3 Computational Model

Computational Fluid Dynamics (CFD) uses different numerical methods and a number of computerized algorithms in order to solve and analyze problems that involve the flow of fluids. The calculations required simulating the interaction of fluids with surfaces defined by boundary conditions, and initial conditions are done by the ANSYS Fluent V14.0. The Navier stokes equations form the basis of all CFD problems. Two equation models are used for the simulations. To analyze the solidification/melting process, a Multi-phase model - Volume of Fluid (VOF) is used in ANSYS Fluent.

6.3.1 Meshed Geometry

Initially a relatively coarser mesh is generated. This mesh contains mixed cells (Tetra and Hexahedral cells) having both triangular and quadrilateral faces at the boundaries. It is decided to use structured hexahedral cells as much as possible. It is meant to reduce numerical diffusion as much as possible by structuring the mesh in a well manner, particularly near the wall region.

Later on, a fine mesh is generated. For this fine mesh, the edges and regions of high temperature and pressure gradients are finely meshed.

The mesh details are as follows:

- Relevance center: fine meshing
- Smoothing: high
- Size: 4.022e-005m to 8.044e-005m

- Nodes: 223993
- Elements: 225865
- Average element quality = 0.813

6.3.2 Fluent Setup

Problem Setup:

The mesh is checked and quality is obtained. The analysis type is changed to Pressure-Based type. The velocity formulation is changed to absolute and time to Transient state. Gravity is defined as y = -9.81 m/s2. In the model selection, Volume of Fluid (VOF) model is selected with keeping solidification- melting option on. It also set with pull velocities calculations.

Fluent Equations:

Fluent will solve for following equations:

i. Momentum Equation:

A single momentum equation is solved throughout the domain, and the resulting velocity field is shared among the phases. The momentum equation, shown below, is dependent on the volume fraction of all phases through the properties ρ and μ:

$$\frac{\partial \vec{V}}{\partial t} + \vec{V} \cdot \nabla \vec{V} = \frac{1}{\rho_{\mathrm{nf}}} \left(-\nabla P + \mu_{\mathrm{eff}} \nabla^2 \vec{V} + (\rho\beta)_{\mathrm{nf}} \vec{g} \left(T - T_{\mathrm{ref}} \right) \right) + \vec{S}$$

ii. Energy Equation:

$$\frac{\partial h}{\partial t} + \frac{\partial H}{\partial t} + \nabla \cdot (\vec{V} h) = \nabla \cdot \left(\frac{k_{\mathrm{eff}}}{(\rho c_p)_{\mathrm{nf}}} \nabla h \right)$$

Where:

$$\mathrm{h} = \mathrm{h}ref + \int_{Tref}^{T} Cp\, dT$$

H=h+ΔH

ΔH = βL

β = 0 if T< T_{Solid}

β = 1 if T $>$ $\mathrm{T}_{\mathrm{Liduid}}$

$$\beta = \frac{T - T_{Solid}}{T_{Liquid} - T_{Solid}} \; if\; T_{Solid} < T < T_{Liquid}$$

$$S = \frac{(1-\beta)2}{(\beta 3 + \varepsilon)} \; Amush(v - vp)$$

The momentum source term, S, contains contributions from the porosity of the mushy zone, the surface tension along the interface between the two phases, and any other external forces per unit volume. Momentum sink terms are added to the momentum equations to account for the pressure drop caused by the presence of solid material.

iii. Continuity:

$$\frac{\partial \rho}{\partial \tau} + \nabla.(\rho v) = 0$$

1. Material Setup:

Water, liquid and NEPCM materials are selected for Fluid states and Aluminum is selected as a solid state material. Properties of NEPCM are given below:

Table 6.1 Reference values of NEPCM

Property	NEPCM reference values($\varphi = 0.05$)
Density (kg/m^3)	1188.7/[0.001(T-319.15) + 1]
Specific heat capacity (J/kg K)	1584
Thermal conductivity (W/m K)	0.1742
Viscosity (N s/m^2)	0.001 $e^{(-4.25\ +\ 1690\ /\ \mathrm{T})}$
Latent heat (J/kg)	142689
Solidus temperature (K)	293
Liquid temperature (K)	296

2. Boundary Conditions:

Boundary conditions are used according to the need of the model. The inlet and outlet conditions are defined as velocity inlet and pressure outlet. As this is a parallel flow with two tubes so there are two inlets and two outlets. The walls are separately specified with respective boundary conditions. No slip condition is considered for each wall.

Table 6.2 Boundary Conditions

	Boundary Type	Velocity magnitude	Temperature
Water inlet	Velocity inlet	1.5 m/s	308 K
Water outlet	Pressure outlet	-	-
PCM inlet	Velocity inlet	1.0 m/s	293 K
PCM outlet	Pressure outlet	-	-

3. Reference Values:
    - Density = 998.2 kg/m3
    - Length = 2 m
    - Temperature = 308 K
    - Velocity = 1.5 m/s
- Viscosity = 0.001003 kg/m-s
    - Ratio of specific heats = 1.4
4. Calculation Setup:
    - Time stepping method: Fixed
    - Time step size: 0.001 s
    - No. of time steps: 30000
    - Max iterations/time step: 150

Chapter 7

Results and Discussion

Liquid Fraction shows the melting of PCM over a period and as the PCM melts, it stores energy in the form of Latent heat. These analysis results can be verified by performing experiments on shell and tube type heat exchanger using NEPCM

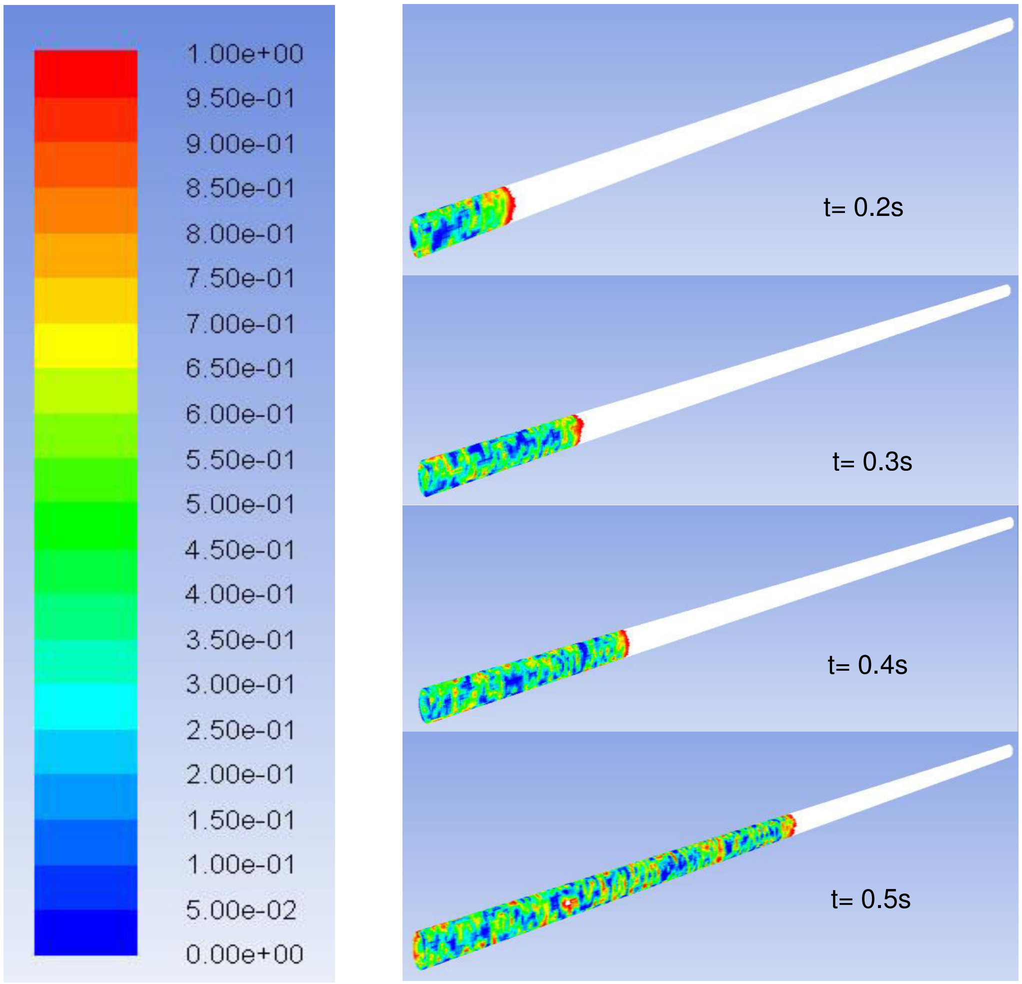

Figure 7.1 Contours of Liquid Fractions at Different Time Interval

Chapter 8

Conclusion

In this study, the effect of enhanced phase change material on the effectiveness of cooling system is analyzed using computational fluid dynamics (CFD) tool. It indicates that because of higher thermal conductivity and heat transfer rate NEPCM is a medium for better energy storage in latent heat storage system. Because of higher thermal conductivity of the phase change material the melting time is reduced. The computational analysis indicates that in the short time because of reduced melting time the liquid fraction is increased. That results in better cooling of water temperature. And this water can be used again for data center cooling application.

Considering the initial cost of data center and the electricity required for data center is high which can be compensated by saving cost on electricity. The pay back cycle can be calculated as follows:

$$C = \frac{P}{L \times E}$$

Where, P = Price of PCM, L= Latent heat, E= Cost of saved energy.

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Harshal has special interest towards fluid and thermal engineering. He has been involved in number of projects for evaporative cooling system for data center. He has also worked with Dr. Dereje Agonafer in EMNSPC (Electronics Mems & Nano-electronics Systems Packaging Center) team, at UTA on various projects focusing on the server level of data center cooling. His interest is in the field of fluid dynamics, computational fluid dynamics, thermodynamics and heat transfer.