DATA CENTER COOLING AUGMENTATION USING MICRO-

ENCAPSULATED PHASE CHANGE MATERIAL

by

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Abstract

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PHASE CHANGE MATERIAL

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The ever increasing information technology heat load and data center cooling energy are the main reasons to investigate the performance of microencapsulated phase change slurry over other heat transfer fluids. In recent years, more effort is being made on the development of a new technique to use the phase change materials as pump-able heat transfer fluid and as heat storage system. Thermal Energy Storage (TES) using Phase Change Materials for data centers offers a very effective method of cutting electric power costs for owners and easing demand on the power grid. Thermal storage systems have been around for decades and include various components and methods to store and retrieve pre-cooled medium. PCM storage has been popular in large commercial applications located in regions with high peak (day time) utility energy costs and a much lower off-peak (night time) cost.

Microencapsulated phase change slurry is dispersion where the phase change material, microencapsulated by a polymeric capsule, is dispersed in water. Compared to water, these new fluids have a higher heat capacity during phase change and a possible enhancement, as a result of this phase change, in the heat transfer phenomenon. The composition of phase change material used in slurry greatly affects

its efficiency, If not selected properly it can cause serious damage, e.g. agglomeration and clogging of pipes. Current available systems use microencapsulated phase change slurry with heat exchangers. The objective of this project is to design and fabricate a shell-tube, phase change material (PCM) based heat exchanger, which can act as a thermal energy storage device, to increase the energy efficiency and hence can be incorporated in data center cooling.

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Chapter 1

Introduction

1.1 Background

With ever increasing in advancement in technology, the rise in demand for the important work of data centers has created a noticeable impact on the power grid. Moreover data center dominates in almost every field these days. Data center is a facility that contains various computer related equipments most commonly known as IT equipments. In fact, data centers can be 40 times more energy intensive than a standard office building and require higher levels of power and cooling [2]. Hence, storage of that energy is a real challenge.

Energy storage not only reduces the mismatch between supply and demand but also improves the performance and reliability of energy systems and plays an important role in conserving the energy. It leads to saving of premium fuels and makes the system more cost effective by reducing the wastage of energy and capital cost. For example, storage would improve the performance of a power generation plant by load leveling and higher efficiency would lead to energy conservation and lesser generation cost. One of prospective techniques of storing thermal energy is the application of Phase Change Materials (PCMs). The use of a latent heat storage system using phase change materials (PCMs) is an effective way of storing thermal energy and has the advantages of high-energy storage density and the isothermal nature of the storage process.

PCMs have been widely used in latent heat thermal storage systems for heat pumps, solar engineering, and spacecraft thermal control applications. The uses of PCMs for heating and cooling applications for buildings have been investigated within the past decade. There are large numbers of PCMs that melt and solidify at a wide range of temperatures, making them attractive in a number of applications; here it is specifically for data center cooling.

Globally, TES (Thermal Energy Storage) is expected to grow substantially through 2020, with worldwide revenues of $3.6 billion and added capacity of 3,824 MW in that year. [2] The use of PCMs for thermal storage in buildings was one of the first applications studied, together with typical storage tanks. The first application of PCMs described in the literature was their use for heating and cooling in buildings, by Telkes in 1975 [3] and Lane in 1986[4]. Mehling et al. studied the possibility of including a PCM-module at the top of a stratified water tank. Their results showed increase of energy storage and better performance of the PCM tank. The PCM market was valued at USD 480.8 million in 2013 and is expected to reach USD 1,765.8 million by 2020, growing at CAGR of 20.7% from 2014 to 2020. [1]

1.2 Objective

The objective of this project is to design and fabricate a shell- tube, phase change material (PCM) based heat exchanger, which can act as a thermal energy storage device, and hence can be incorporated in data center cooling. The thermal energy storage device will act as a short term energy storage device.

Chapter 2

Literature Review

2.1 Thermal Energy Storage (TES)

Thermal energy storage (TES) is achieved with greatly differing technologies that collectively accommodate a wide range of needs. It allows excess thermal energy to be collected for later use, hours, days or many months later, at individual building, multi-user building, district, town or even regional scale depending on the specific technology. As examples: energy demand can be balanced between day time and night time; summer heat from solar collectors can be stored inter seasonally for use in winter; and cold obtained from winter air can be provided for summer air conditioning.

Storage mediums include: water or ice-slush tanks ranging from small to massive, masses of native earth or bedrock accessed with heat exchangers in clusters of small-diameter boreholes (sometimes quite deep); lined pits filled with gravel and water and top-insulated; and eutectic, phase-change materials. Other sources of thermal energy for storage include heat or cold produced with heat pumps from off-peak, lower cost electric power, heat from combined heat and power (CHP) power plants; heat produced by renewable electrical energy that exceeds grid demand and waste heat from industrial processes. In order to increase the heat capacity of water, micro-encapsulated phase change material (mPCM) is dispersed in it. Micro-encapsulated phase change material slurry is

mixture of microencapsulated phase change material dispersed in carrier fluid, e.g. water or oil. The mPCM slurry promise higher heat transfer capacity than other conventional heat transfer fluids.
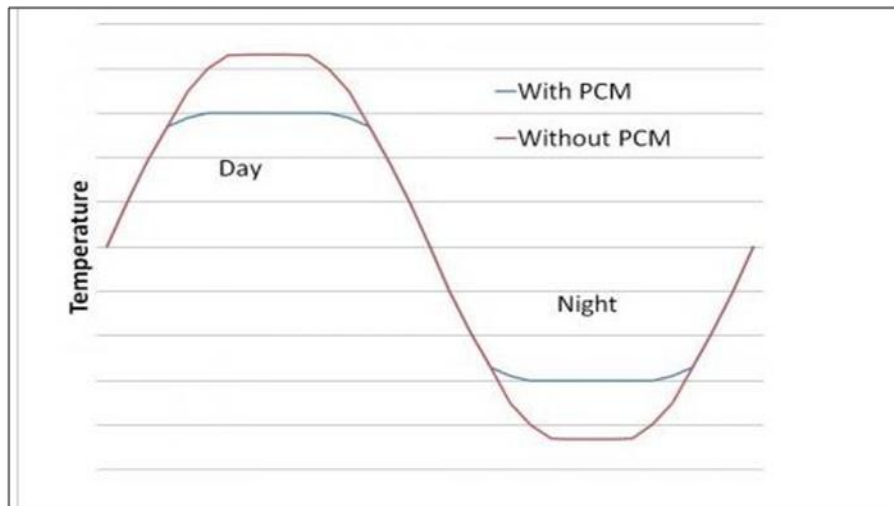
Figure 1 Working Principle of TES

2.2 Phase Change Materials (PCM)

Phase change material possesses quality to store and release large amount of thermal energy while changing its phase, for example: from solid-liquid, liquid to vapor. Best example to describe phase change material is water and ice. When ice is heated, during its phase change from solid to liquid its temperature remains constant. The temperature does not change till two phases (solid – liquid) exist simultaneously. In addition the inflowing energy is used up in the phase transition.
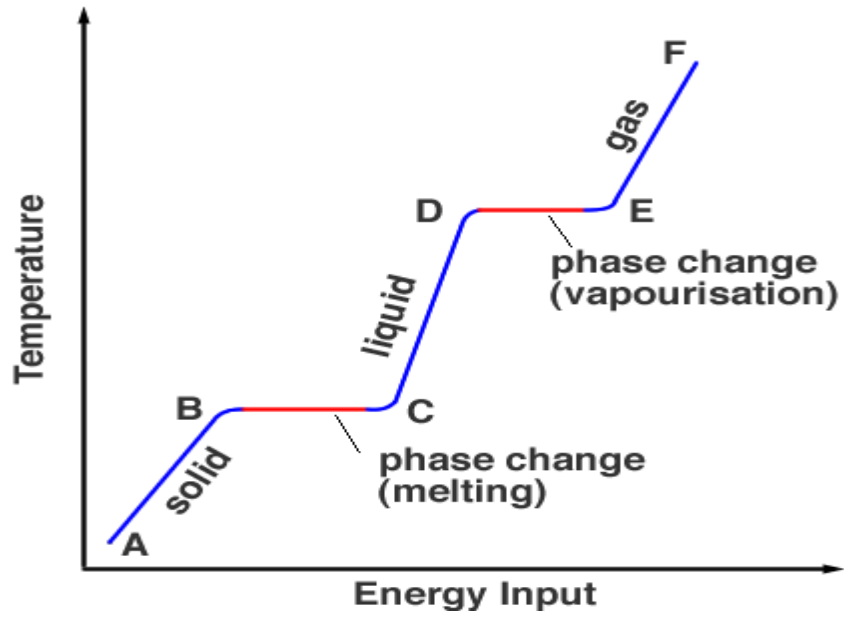
Figure 2 Phase Change Process [17]
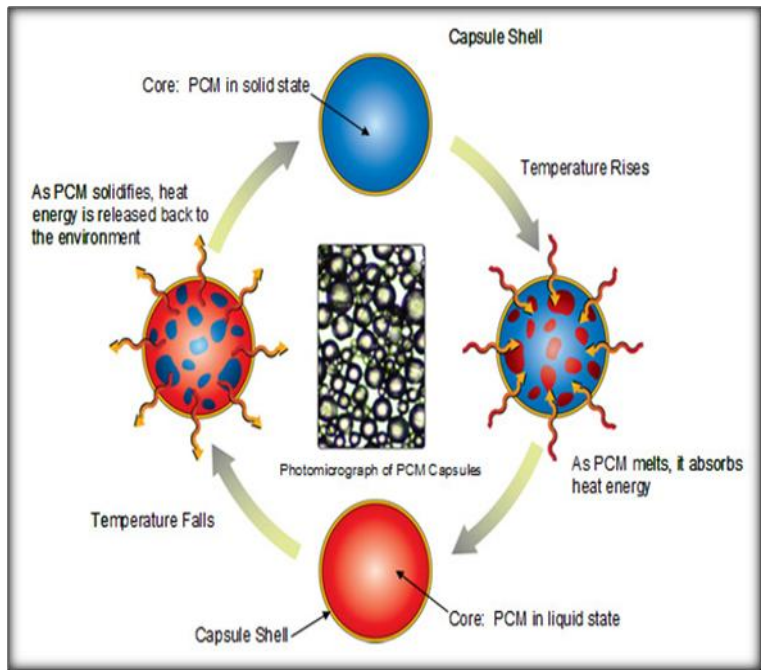
Figure 3 Working Cycle of PCM

The energy consumption in phase change is known as latest heat of fusion or melting. In contrast, water takes up or rejects heat sensibly. It takes 333 kilojoules of energy to melt one kilogram of ice at 0°C (32°F) to produce one kilogram of water. However, the same amount of energy would also be able to heat a kilogram of water from 0°C to approx. 80°C (176°F). Phase change material acts as thermal storage and they release and absorb heat at constant temperature. In addition, these materials suits very well for the thermal management as they can absorb nearly 5 times more thermal energy per unit their volume. Moreover, the flexibility of these materials to lie under varied heat of fusion makes it more compatible.

Further PCM can be mainly classified into three categories namely organic, inorganic and eutectic [18]. Following figure represents the PCM classification by Sharma et al [19]
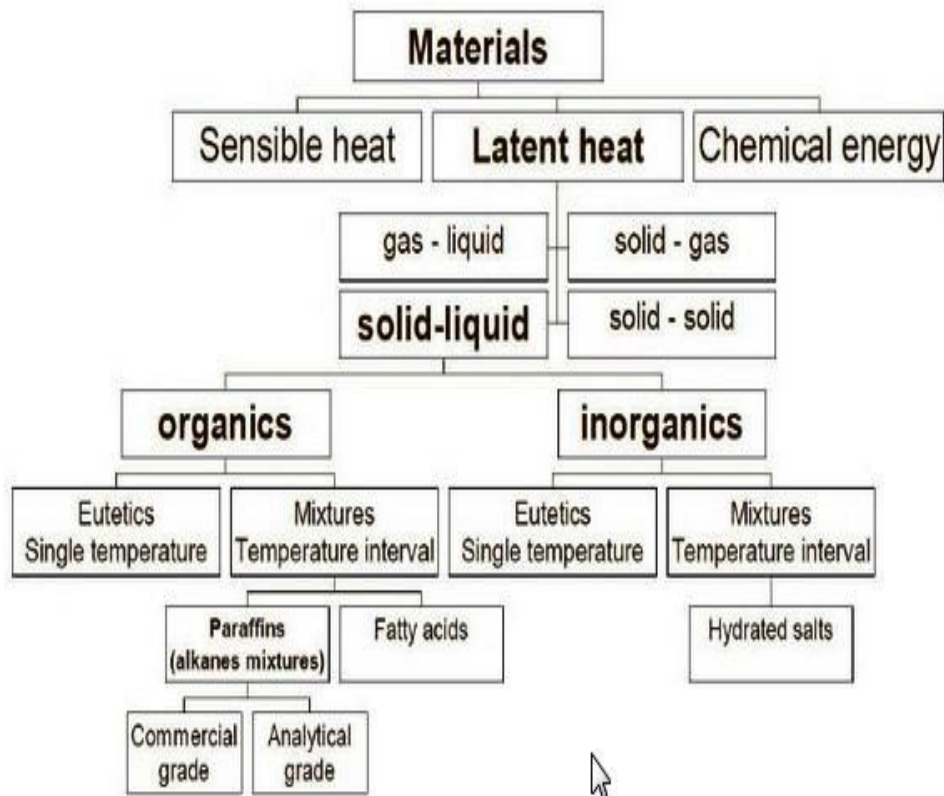
Figure 4 Classifications of Phase Change Materials [19]

Generally there are two main groups of PCMs: Organic (paraffin compounds) and Inorganic (salt hydrates). Paraffin promises more stability in terms of thermal cycling, i.e. it can undergo large number of phase changes maintaining the same characteristics. Despite, being more stable in comparison to salt hydrates they are flammable and possess lower melting enthalpy and density. The salt hydrates are corrosive in nature and their implementation needs careful examination. Also, salt hydrates undergo sub-cooling thus inhibiting the release of stored energy [20].

Table 1: Advantages and Disadvantages of PCM [20, 21]

Organic (Paraffin)	In Organic(Salt Hydrate)
Advantages not corrosive chemically and thermally stable No or little sub cooling	Advantages high melting enthalpy high density
Disadvantages lower melting enthalpy lower density flammable	Disadvantages sub cooling corrosive cycling stability
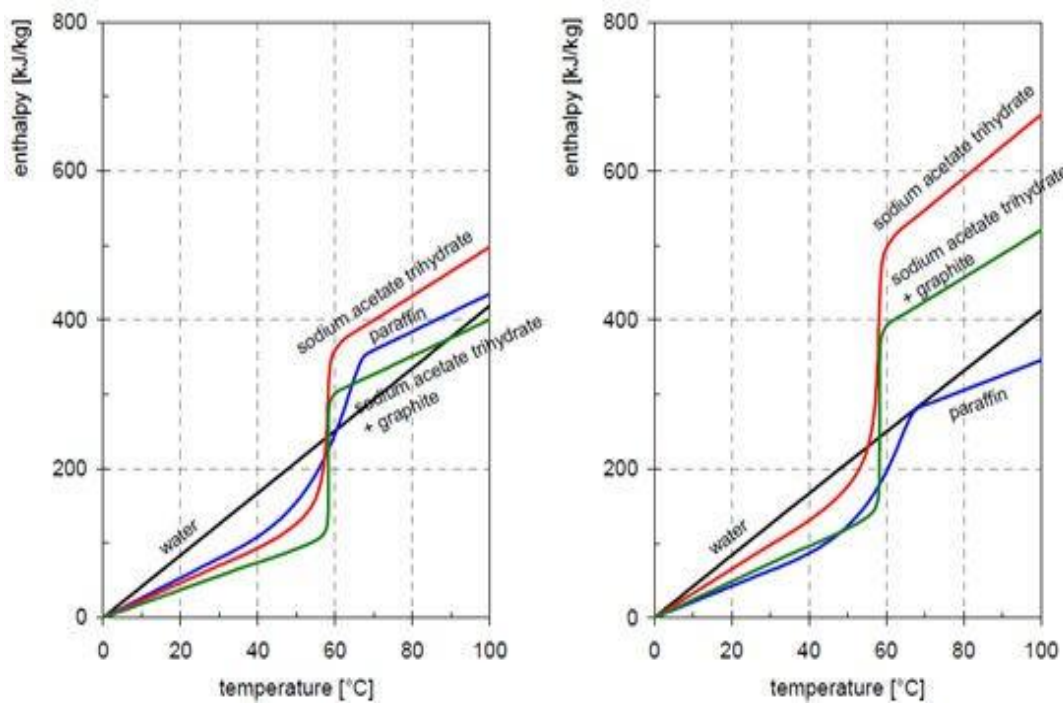
Figure 5 Specific enthalpy per mass unit [kJ/kg] (left side) and per volume unit [kJ/dm³] (right side) [20]

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2.2.1 PCM Characteristics for Heat Transfer Fluid [20]

In general PCM should meet the standard criteria to be used as heat transfer fluid:

- Suitable melting temperature

- High melting enthalpy per volume unit [kJ/m³]

- High specific heat [kJ/(kg K)]

- Low volume change due to the phase change

- High thermal conductivity

- Cycling stability

- Non-flammable, Non-poisonous, Non-corrosive

2.2.2 Microencapsulation of Phase Change Materials

PCM possess high thermal storage capacity but on the other hand they have relatively low thermal conductivity. In general there are two ways by which we can enhance the thermal conductivity of PCM :

- The heat transfer distance between PCM i.e. by conduction can be reduced: this can be achieved by microencapsulating the material into small capsules.

- Also, thermal conductivity of PCM can be increased by embedding structures of materials with high conductivity. This is done by adding graphite powders into the PCM which increases its thermal conductivity

by the factor of 10-20 (Öttinger, 2004), but also creates a kind of carrier structure that inhibits the segregation of salt hydrates and therefore improves their cycling stability segregation of salt hydrates and therefore improves their cycling stability. [20]

The concept of a carrier fluid with encapsulated particles of phase change materials was first introduced by Mehalick and Tweedie [18, 23]. Micro-encapsulation is a process in which small particles of PCMs are coated by some shell material and are produced in the form of small capsules. These capsules maintain uniform wall surface and its size ranges from few micrometers to few millimeters. The material inside the shell material is referred as core material. In addition, by micro-encapsulating the core material remains isolated from the entire system, it changes its phase inside the shell material thus preventing it from any kind of fouling or contamination problem [22].
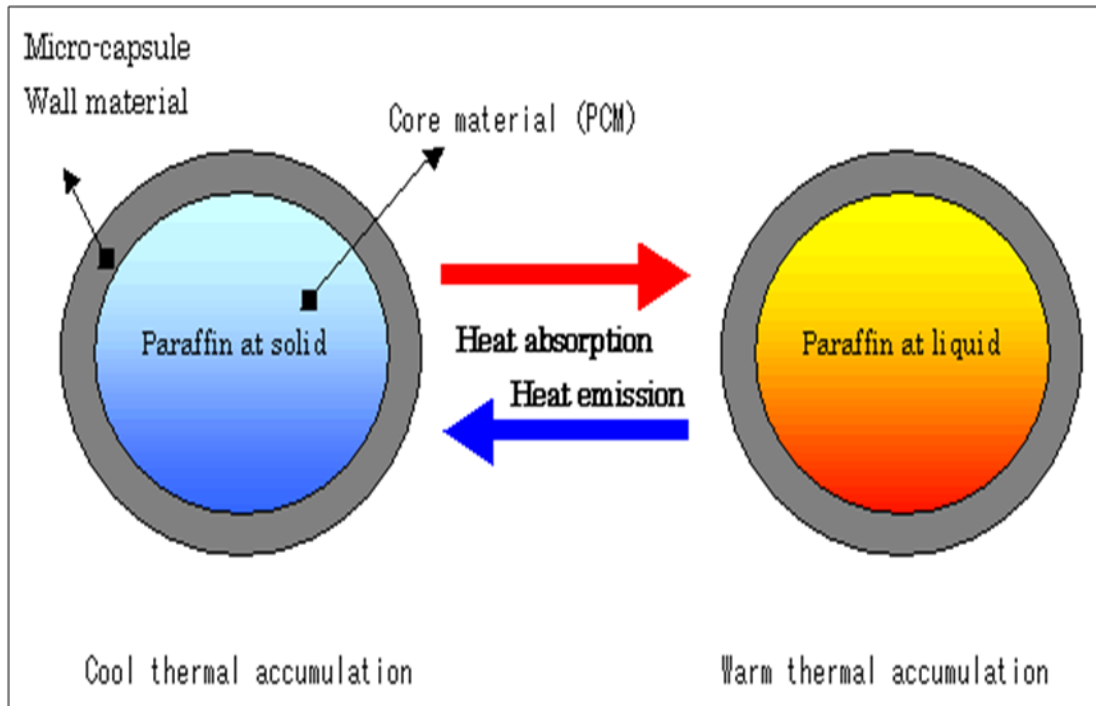
Figure 6 Microencapsulated Phase Change Material Process [21]

The shell material is generally a polymer and the particles can be either multi phase or liquid solid & gas. The two most commonly used microencapsulation techniques include, in-situ polymerization and interfacial poly-condensation. In order to obtain stable microcapsules In-situ polymerization technique is often employed. The polymerization of the paraffin microcapsules is started by changing the PH value and temperature, or by adding flocculation or coacervation agents. At last the obtained microcapsules are filtered, washed and dried. It is possible to obtain homogeneous slurry if the shell materials with hydrophilic groups like melamine resin are used. Su et al. [25] reported that the

shells of micro-encapsulated phase change materials do not have big impacts on the phase change temperature of pure paraffin.

Micro-encapsulation offers various features such as high energy storage density, low pumping power requirements, and high heat transfer rates. In comparison to liquid cooling techniques, for example: using water as a coolant, it has been seen that microencapsulated phase change slurry perform higher heat transfer rate.

Despite, its high thermal storage and high heat transfer coefficients; the major limitations with phase change material is its tendency to clog in distribution pipes and lower heat transfer rates in heat exchangers. A literature review suggests that microencapsulating the PCM can eliminate this problem while maintaining its original properties [22].

2.2.3 Required Properties of Phase Change Materials

Phase Change Material performance in heat exchange systems depends on factors such as the Stefan number, mass fraction, and the latent heat of fusion. In order for the PCM to be at optimal effectiveness, the Stefan number must be lower than 1 and defined as follows:

$$S_t = \frac{C_p\left(q_w\, \frac{R}{k}\right)}{C_m\, \lambda}$$

Where, C_p = specific heat

q_w = heat flux across the pipe wall

R = radius of pipe

k = thermal conductivity

C_m = mass fraction of PCM in suspension

λ = PCM's latent heat of fusion

I. Thermodynamic properties

Melting temperature in the desired operating temperature range should be recommended zone of ASHRAE guidelines (Fig 7).

High latent heat of fusion per unit volume

High specific heat, high density and high thermal conductivity

II. 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

III. Chemical properties

Complete reversible freeze/melt cycle

No degradation after a large number of freeze/melt cycles

Non-corrosiveness, non-toxic, non-flammable and non-explosive materials

IV. Economic properties

Low cost

Availability
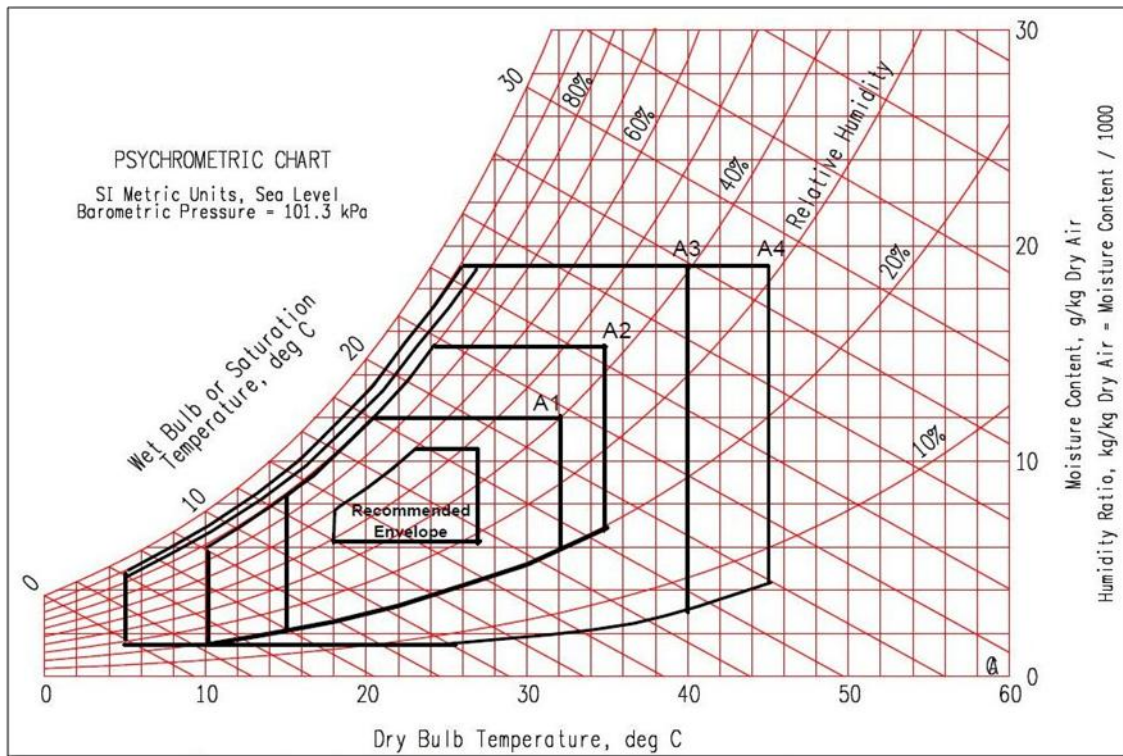
Figure 7 ASHRAE Recommended Temperature Range for Data Centers

Chapter 3

Concept of Data Center Load Leveling

3.1 Introduction

The continuous increase in the level of greenhouse gas emissions and limited resources of fossil fuels related to the climb in fuel prices are the main driving forces behind efforts to more effectively utilize various sources of renewable energy. One of the options is to develop energy storage devices, which are as important as developing new sources of energy.

The storage of energy in suitable forms, which can conventionally be converted into the required form, is a present day challenge to the technologists. Energy storage not only reduces the mismatch between supply and demand but also improves the performance, efficiency and reliability of energy systems and plays an important role in conserving the energy.
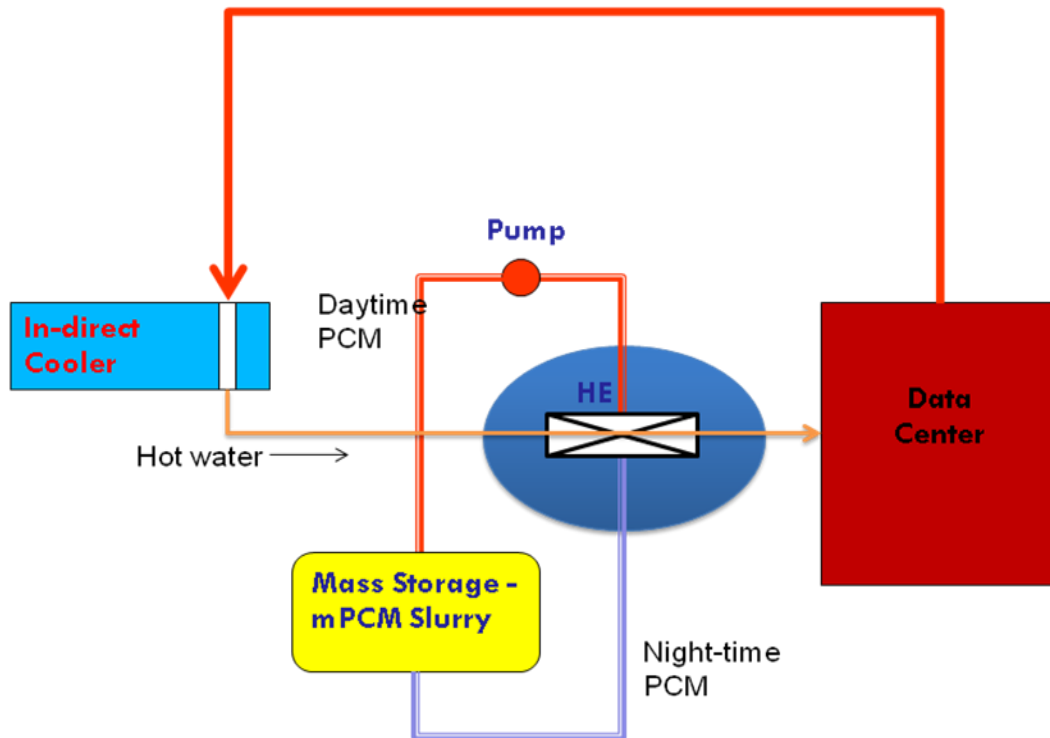
Figure 8 Schematic of Load Leveling Concept

3.1.1 Basic Components

a. Dry Cooler: An In-direct dry cooler consists, a thermal heat transfer fluid (hot water), coming out from the data center. This water is then passed through the heat-exchanger to melt PCM.

b. Storage Tank: A storage tank is used to store both cold and hot water. Cold water is extracted from below and hot water from collector is released in tank from top.

c. Pump: Since we will be using a forced circulation, we need to incorporate a pump to maintain flow in the system.

d. PCM Heat Exchanger: PCM heat exchanger is the most important component of our system and is the system which is under study.

e. Phase Change Material: PCM will be incorporated in the heat exchanger for thermal energy storage. PCM is the backbone of this project.

3.1.2 Operation

An approach for the integration of PCMs into thermal storage systems is to fill a tank directly with the PCM and to charge and discharge it via a suitable heat exchanger. In this case the effort of filling the PCM into a large number of modules is not necessary and higher PCM volume fractions can be achieved. For the heat transfer between the heat carrier fluid and the PCM for example air-to-water heat exchangers can be used. These heat exchangers are used for heating and cooling of air in air conditioning and in industry. They have a large number of thin fins, that are usually used to extend the heat exchanger surface because of the low convective heat transfer coefficient on the air side, but they can also be used to enhance the heat transfer in a PCM (Stritih, 2003).

3.1.3 Designing PCM Based Heat Exchanger

The calculation for the PCM based heat exchanger is done in the following steps

- Amount of hot water required during non-sunshine period is estimated. Accordingly, amount of energy needs to be stored is estimated.

- A suitable type of heat exchanger is selected.

- A suitable phase change material is selected.

- Dimensional parameters of heat exchanger are calculated.

3.1.4 Amount of Heat Energy to be Stored

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

Initial Temp of Water, Ti = 308 K

Final Temp of Water, Tf = 300 K

Cv of Water = 4.187 kJ/ kg (where Cv = heat carrying capacity at constant volume)

For analysis, heat exchanger with capacity (m) 10 kg water is considered.

Hence,

Q = 10 x 4.187 x 8 = 335 kJ

3.1.5 Selection of Heat-exchanger

A tube - shell type heat exchanger is the simplest choice of heat exchanger. Incorporation of phase change material is also easy in this type of exchanger. The phase change material (PCM) is incorporated in the outer shell of the heat exchanger and the heat transfer fluid (HTF), which is water in this case, flows from the inner tube.

3.1.6 Selection of suitable Phase Change Material (PCM)

- Density = 780 kg/ m3

- Transition Temperature = 22 – 26°C

- Latent heat capacity = 43 kJ/kg

PRODUCT	APPLICATION			CHARACTERISTICS							
	Summertime excessive heating protection	Stabilisation of the indoor temperature in the comfort zone Passive and active application	Surface cooling systems	Product type	Melting point [approx. in °C]	Overall storage capacity [approx. in kJ/kg]	Latent heat capacity [approx. in kJ/kg]	Solids content [approx. in %]	Density [approx. in kg/l]	Apparent density [approx. in kg/m3]	Viscosity [approx. in mPa·s]
Micronal® DS 5000	■			Dispersion	26	59	45	42 – 44	0.98		200 – 600
Micronal® DS 5001	■			Powder	26	145	110			250 – 350	
Micronal® DS 5007		■		Dispersion	23	55	43	42 – 44	0.98		200 – 600
Micronal® DS 5008		■		Powder	23	135	100			250 – 350	
Micronal® DS 5030			■	Dispersion	21	51	37	42 – 44	0.98		200 – 600
Micronal® DS 5029			■	Powder	21	125	90			250 – 350	
Micronal® DS 5037 X	■			Dispersion	26	59	45	42 – 44	0.98		200 – 600
Micronal® DS 5038 X	■			Powder	26	145	110			250 – 350	
Micronal® DS 5039 X		■		Dispersion	23	55	43	42 – 44	0.98		200 – 600
Micronal® DS 5040 X		■		Powder	23	135	100			250 – 350	

Figure 9 PCM Selection Chart

General Appearance and SEM Image of Slurry

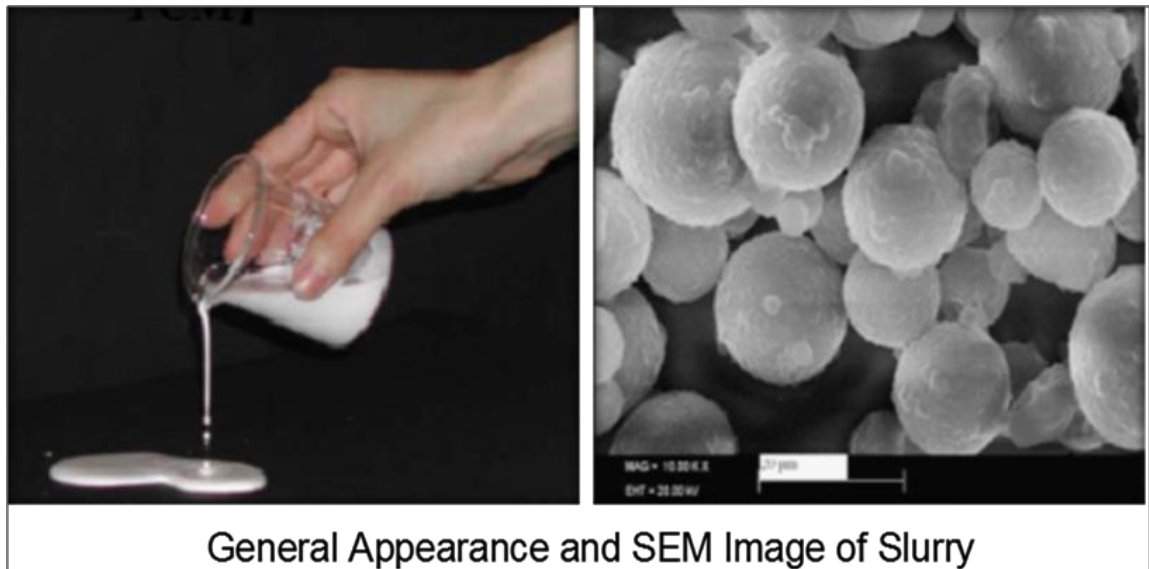Figure 10 mPCM Slurry Appearance

3.1.7 Estimation of Amount of Phase Change Material (PCM)

Amount of energy stored, Q = 10 x 4.187 x 8 = 335 kJ

Amount of PCM required, = Q / Latent heat capacity of PCM = 335/43

Hence, Amount of required PCM = 7.8 kg

Hence approximately 7.8 kg of PCM needs to be incorporated in the heat exchanger

Chapter 4

Heat Transfer Analysis inside Heat- Exchanger

4.1 Analytical Model

The latent heat 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 latent heat 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 discretised by control volume approach.

4.1.1 Mathematical Formulation of Transient Fluid Flow
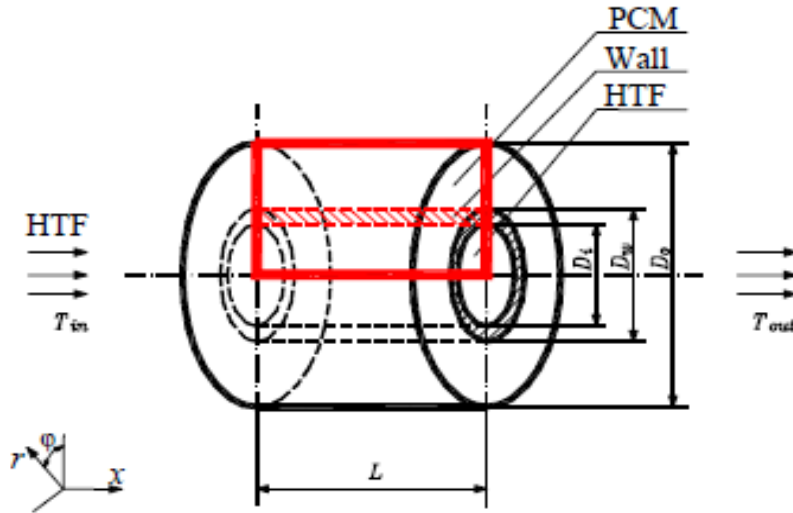
Figure 11 Two Dimensional Heat Exchanger Model

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

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

$$\frac{\partial Wx}{\partial \tau} + W_x \cdot \frac{\partial Wx}{\partial X} + W_R \cdot \frac{\partial Wx}{\partial R}$$

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

$$\frac{\partial W_R}{\partial \tau} + W_x \cdot \frac{\partial W_R}{\partial X} + W_R \cdot \frac{\partial W_R}{\partial R}$$

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

$$\frac{\partial \theta_f}{\partial \tau} + W_x \cdot \frac{\partial \theta_f}{\partial X} + W_R \cdot \frac{\partial \theta_f}{\partial R}$$

$$= \frac{1}{Re \cdot Pr} \cdot \left[\frac{\partial^2 \theta_f}{\partial X^2} + \frac{1}{R} \cdot \frac{\partial}{\partial R}\left(R \cdot \frac{\partial \theta_f}{\partial R} \right) \right] \quad (4)$$

Wall

$$\frac{\partial \theta_w}{\partial \tau} = \frac{1}{Re \cdot Pr}$$

$$\cdot \frac{a_w}{a_f} \left[\frac{1}{R} \cdot \frac{\partial}{\partial R}\left(R \cdot \frac{\partial \theta_w}{\partial R} \right) \right.$$

$$\left. + \frac{\partial^2 \theta_w}{\partial X^2} \right] \quad (5)$$

PCM

$$\frac{\partial x_p}{\partial \tau} = \frac{1}{Re \cdot Pr} \cdot \frac{a_p}{a_f} \left[\frac{1}{R} \cdot \frac{\partial}{\partial R}\left(R \cdot \frac{\partial x_p}{\partial R} \right) \right.$$

$$\left. + \frac{\partial^2 x_p}{\partial X^2} \right] \quad (6)$$

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

$$\Theta_p = A_b \cdot \chi_p + B_b$$

Where factors A_b and B_b are

$$A_b = \frac{1}{St} \cdot \frac{\rho_L \cdot c_L}{\rho_s \cdot c_s} \qquad B_b = 0 \qquad \text{for} \qquad \chi_p < 0.$$

$$A_b = 0 \qquad B_b = 0 \qquad \text{for} \qquad 0 \le \chi_p \le 1.$$

$$A_b = \frac{1}{St} \qquad B_b = \frac{1}{St} \qquad \text{for} \qquad \chi_p > 1.$$

The equations are obtained using dimensionless variable defined as:

- Dimensionless coordinates

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

- Dimensionless velocities

$$W_X = \frac{w_x}{w_{in}} \qquad \text{and } W_R = \frac{w_r}{w_{in}}$$

- Dimensionless pressure

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

- Dimensionless time

$$\tau = \frac{w_{in}}{Di} \cdot t$$

- Dimensionless temperature

$$\theta = \frac{T - T_m}{T_{in} - T_m}$$

- Dimensionless enthalpy

$$\chi = \frac{H - \rho_s \cdot c_s \cdot T_m}{\rho_L \cdot q}$$

- Reynolds, Prandtl, Stefan and Nusselt number

$$Re = \frac{w_{in} \cdot D_i}{U_f}, \qquad Pr = \frac{U_f}{a_f}, \qquad St = \frac{c_L \cdot (T_{in} - T_m)}{q}, \qquad Nu = \frac{\alpha \cdot D_i}{\lambda_f}.$$

Initial and boundary conditions are as follows:

Initial condition $\qquad \tau = 0$

$$0 < R \le 0{,}5, \quad 0 \le X \le L/Di \qquad \rightarrow \quad WX = WR = 0$$

$$0 < R \le Ro \quad 0 \le X \le L/Di \qquad \rightarrow \quad \theta f = \theta w = \theta p = \theta init$$

Initial condition $\qquad \tau > 0$

Inlet plane $\qquad X = 0$

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

$$0.5 \le R \le R_w \quad \rightarrow \quad \frac{\partial \theta_w}{\partial X} = 0$$

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

Outlet plane $X = L / D_i$

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

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

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

Axis of symmetry $R = 0$

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

Fluid – wall interface $R = 0.5$

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

Wall – PCM interface $R = Rw$

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

Outer wall $R = Ro$

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

4.2 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

4.2.1 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. Care is taken 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 centre: fine meshing

- Smoothing: high

- Size: 4.033e-005m to 8.066e-005m

- Nodes: 225993
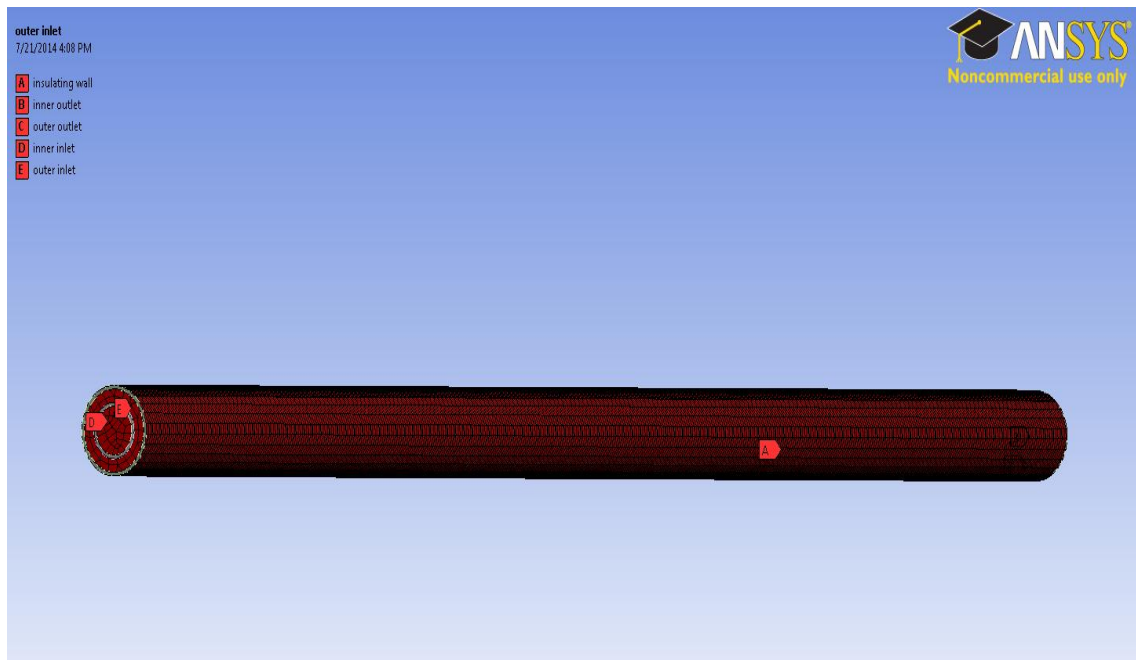
- Elements: 223865

- Average element quality = 0.817

Figure 12 Meshed Geometry of Heat Exchanger

4.2.2 Fluent Setup

4.2.2.1 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.

4.2.2.2 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:

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

ii. Energy Equation:

$$\frac{\partial}{\partial \tau}(\rho H) + \nabla.(\rho vH) = \nabla.(k\nabla T) + Sn$$

Where:

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

H=h+ΔH

ΔH = βL

β = 0 if T < Tsolidius

β = 1 if T > Tliquidus

$$\beta = \frac{T - Tsolidius}{Tliquidus - Tsolidius} \quad if \; Tsolidius < T < Tliquidus$$

Where

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

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:

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

4.2.2.3 Material Setup

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

Table 2: Reference values of mPCM

Property	mPCM reference values
Density (kg/m^3)	780 / [0.001(T-319.15) + 1]
Specific heat capacity (J/kg K)	2480
Thermal conductivity (W/m K)	0.21, T < T solidus 0.18, T > T Liquidus
Viscosity (N s/m^2)	0.001 exp(-4.25 + 1790 / T)
Latent heat (J/kg)	43000
Solidus temperature (K)	293
Liquidus temperature (K)	296

4.2.2.4 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 3: 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	-	

4.2.2.5 Reference Values

The inner inlet is selected from the drop down list of "compute from". The values

are:

- 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

4.2.2.6 Calculation Setup

- Time stepping method: Fixed

- Time step size: 0.001 s

- No. of time steps: 30000

- Max iterations/time step: 150

Chapter 5

Results and Discussion

Computational analysis of heat exchanger with mPCM showed reduction
in the temperature values of inner fluid i.e. water over a certain period of time.
The temperature plot obtained from the first computational run was as below:
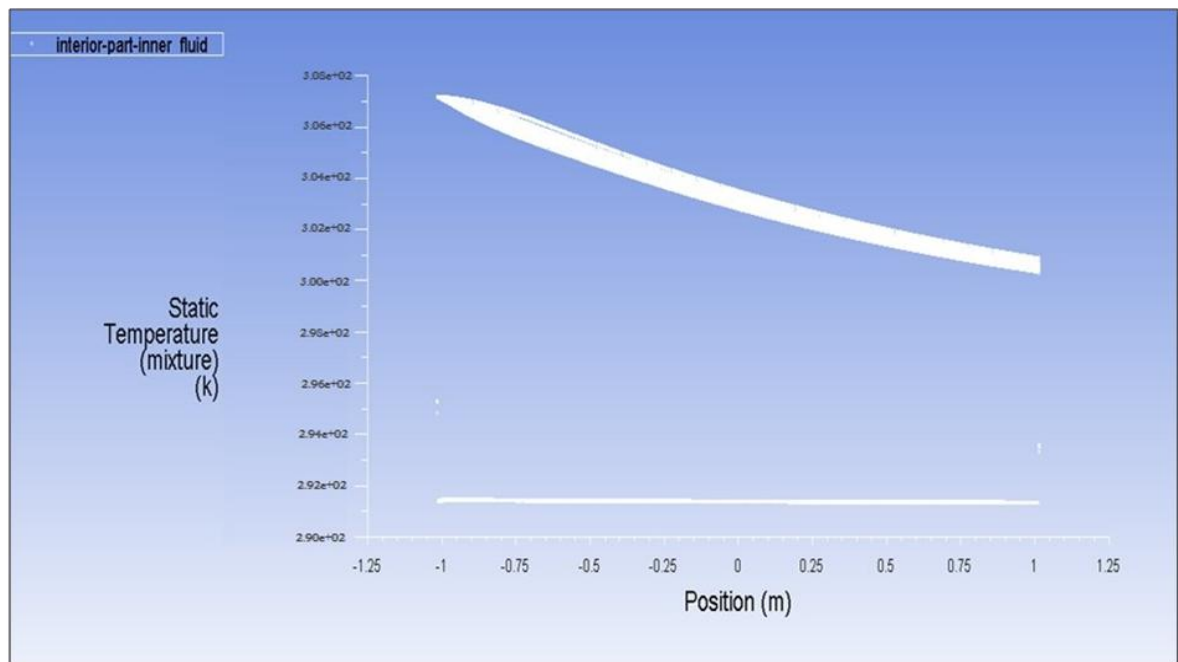

Figure 13 Temperature Plot of Inner Fluid

Contours of different study parameters are analyzed with respect to the
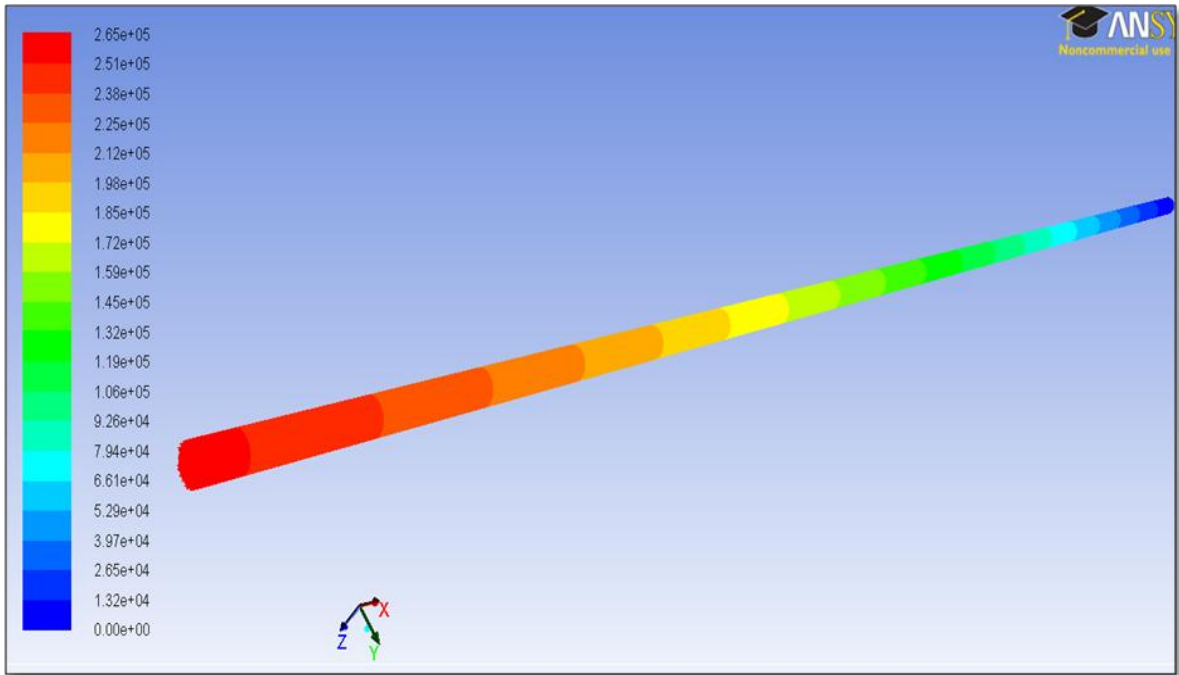time and they are showed below:

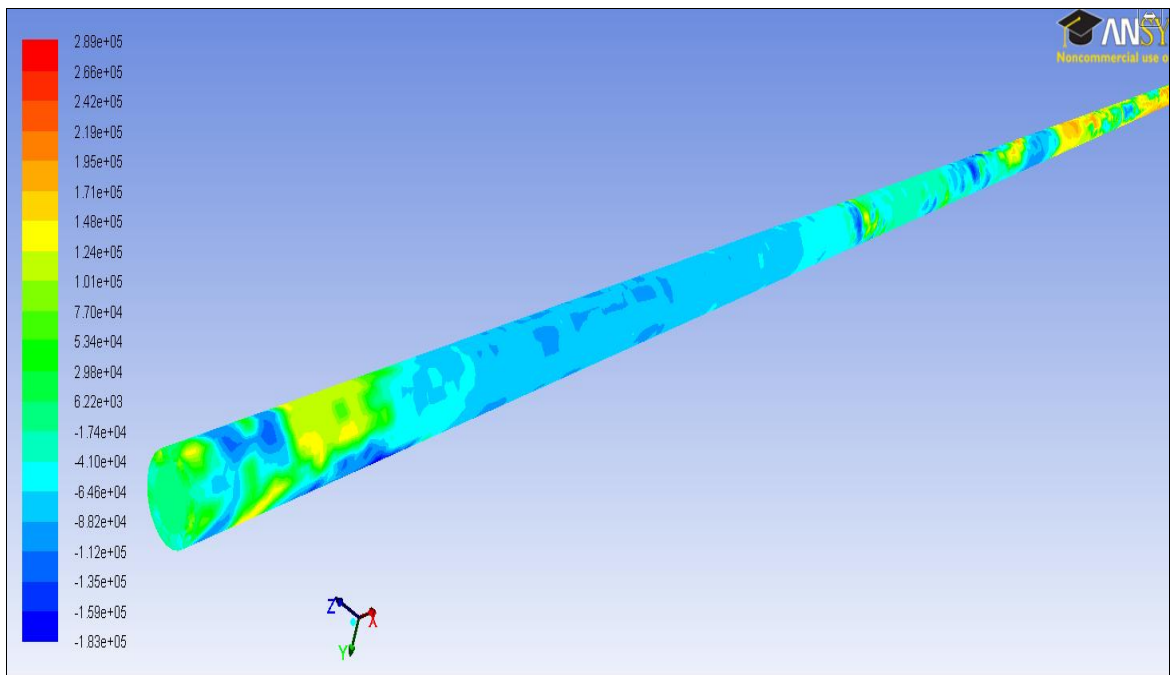Figure 14 Contours of Static Pressure (mixture) in pascal
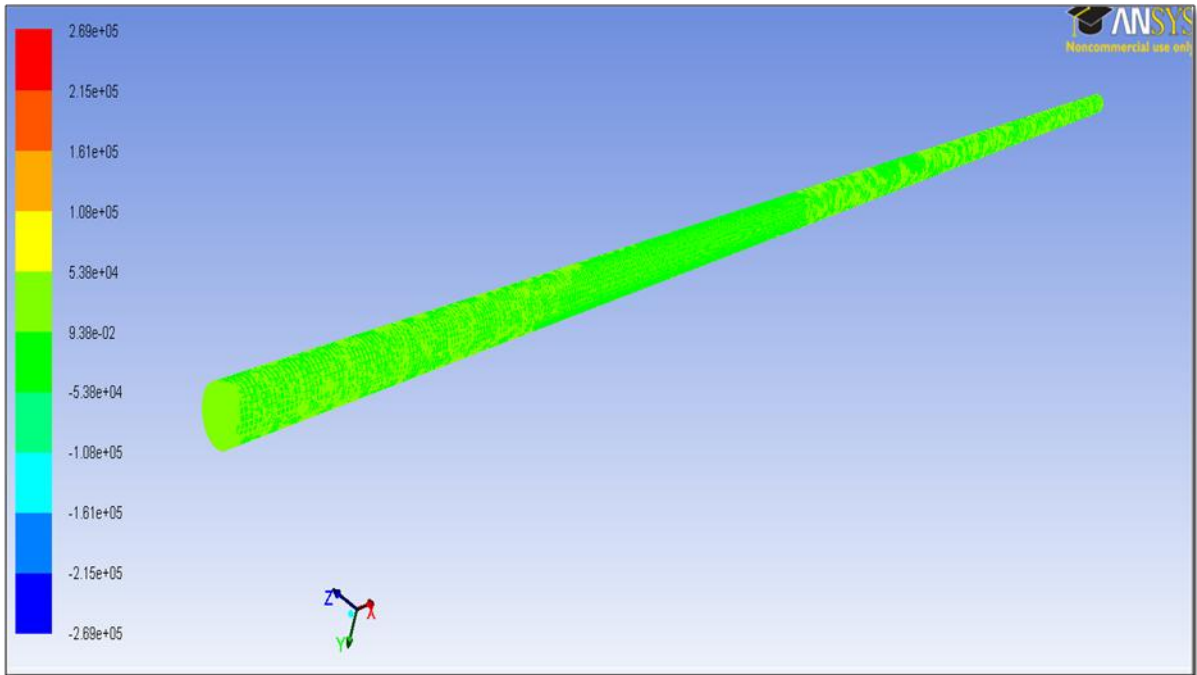

Figure 15 Contours of Enthalpy (phase-2) in j/kg

Figure 16 Contours of Total Surface Heat Flux (mixture) in w/m2
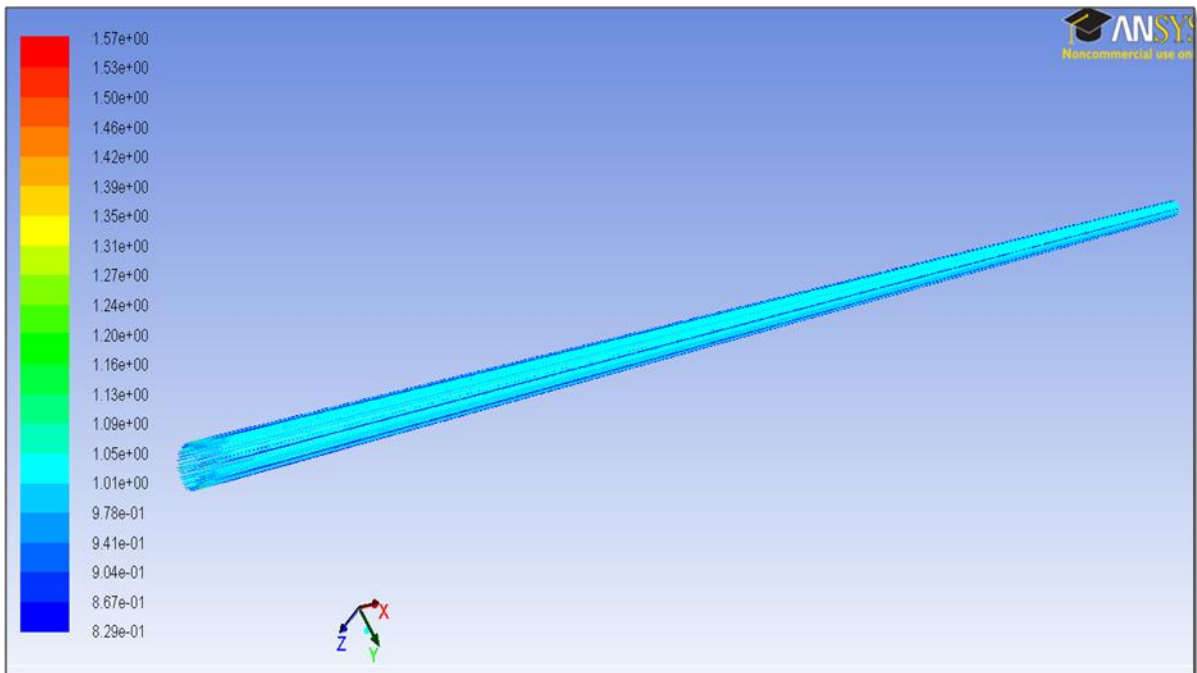

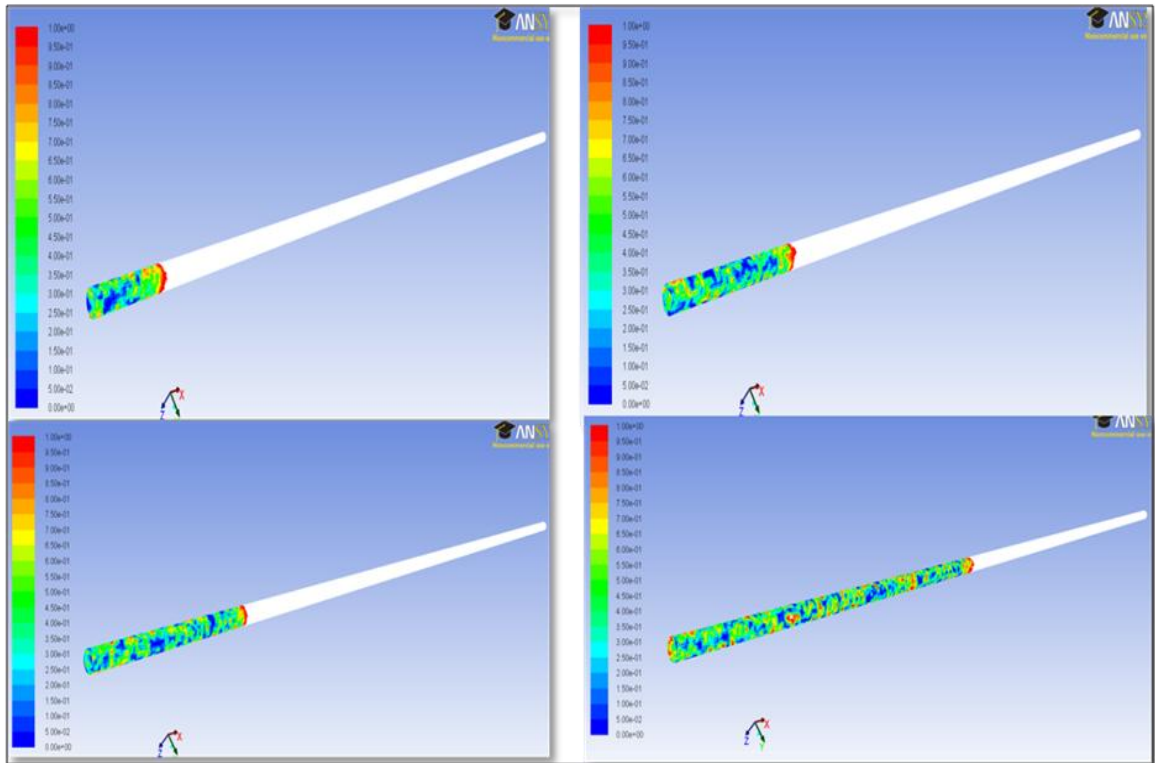Figure 17 Velocity vectors by Velocity Magnitude (mixture) in m/s

Figure 18 Contours of Liquid Fractions at Different Time Intervals

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 – tube type heat exchanger using micro-encapsulated PCM.

Chapter 6

Conclusion

BASF - Micronal DS5007 is good for energy storage in latent heat storage system. It has a suitable transition temperature range of 23 -26°C for Data Center operation and high latent heat of 43 kJ/kg. In addition, it does not exhibit any sub-cooling. A simple tube-in-tube heat exchanger system can be used for energy storage with reasonable charging and discharging times. It showed also results on cooling of water temperature, which makes the re-use of water possible in Data Center application.

For the application like data center although the investment cost is higher, it can be overcome by significant saving in electric energy. Pay back cycle can be calculated by,

$C = P/ L*E$

Where P is the price of PCM,

L is the heat to store,

E saved is the price of saved energy by system

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Biographical Information

Ruddhi Deshmukh is a graduate student at the University of Texas at Arlington. She defended her Master Thesis in summer 2014. She has completed her Bachelor's of Engineering from Pune University, India in mechanical engineering with the University Gold Medal.

Ruddhi has a special interest towards fluid and thermal engineering. She has a work experience of almost 3 years in fluid machineries. She has also worked with Professor 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. Her interest is in the field of fluid dynamics, computational fluid dynamics, thermodynamics and heat transfer.