UTILIZATION OF MICROENCAPSULATED PHASE CHANGE MATERIAL FOR THE OPTIMIZATION OF EVAPORATIVE COOLING TECHNOLOGY

By

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ABSTRACT

UTILIZATION OF MICROENCAPSULATED PHASE CHANGE MATERIAL FOR THE OPTIMIZATION OF EVAPORATIVE COOLING TECHNOLOGY

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IT equipments are the essential facet of most institutional operations of the advanced world. Modern IT equipments are far more vigorous than older equipments. With increasing density of array of servers and growth of computing power, assessing the cooling requirements has emerged as an aspect of prime importance.

Evaporative cooling is a very common cooling technology used in cooling of data centers due to low installation and power costs and simple operation. Phase change materials have been investigated over the years as thermal energy storage for cooling and heating applications. These researches have also investigated encapsulated PCM in different sizes in order to maximize its thermal properties in various heat transfer applications. However little efforts have been put to the investigation of phase change materials integrated with evaporative cooling technology.

Evaporative coolers have a limitation in humid climates or when the air reaches its saturation point. If coils with phase change material are introduced in the evaporative cooling chambers, it would sensibly cool the air from cooling pad without increasing its humidity any further. An investigation has been done to anticipate the cooling effect by microencapsulated phase change material with felicitous placement of coils to obtain significant cooling and least pressure drop with the help of experimentation. Second phase would determine the experimental evaluation to reduce water consumption in cooling pad and application of hybrid evaporative coolers in data center technology.

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EVOLUTION OF MODULAR DATA CENTERS

1.1 Introduction to Modular or Containerized Data Centers

1.1.1 Traditional Data Centers and Modular Data Centers: An Introduction

Data centers are buildings where multiple servers and communication gear are co-located because of their common environmental requirements and physical security needs, and for ease of maintenance, to store, process, manage and exchange digital data [4]. The compute servers that process the data, storage servers that store the data and network equipment, which is used for communications, are collectively called as “IT Equipment”. In addition to this IT Equipment, data center also houses power conversion equipment and environmental control equipment to maintain operating conditions [5].

With rapid advance of technology, traditional data centers bring new design challenges, some technical and some not. The technical issues include power consumption, heat density limits, communications latencies, multi-thousand-system administration costs, and efficient failure management with large server counts. The natural tendency is towards building a small number of very large data centers and this is where some of the non-technical issues come to play. These include social and political constraints on data center location, in addition to taxation and economic factors [3]. Other issues associated with traditional data centers are the shipping and delivery to the place where they need to be racked and installed. This process would require skilled labor which adds to the cost of shipping and delivery.

Modular Data Center refers to portable self-contained environment designed for rapid deployment, energy efficiency and computing density. They are portable and can be deployed much faster than a traditional data center. They are macro modules consisting of thousands or more systems. Instead of building and shipping single systems or racks of systems, the modules are built within shipping containers with all the necessary equipment, configured and shipped as a fully operational unit ready to be powered up. All that is required upon delivery is provision of power, internet connectivity and chilled water supply. Therefore, modular data centers can be deployed anywhere around the world [1].

Sun Microsystems (currently owned by Oracle Corporation) was the pioneer in the development of modular data centers. In 2007, it introduced the first ever modular data center known as Project Black box or Sun modular data center, which was a portable data center built into a standard 20 foot shipping container. It required a power supply and an external chiller to be operated. Sun Microsystems claimed that the container could house up to 280 servers. In contrast to the traditional data centers, this modular data center could be shipped and deployed to any location where it would not be possible to construct a traditional data center. Since then several companies such as Google, CommScope, Hewlett Packard, PDI, Microsoft, Amazon, etc. have contributed in the development of the containerized data centers featuring state of the art technologies [2].

Figure1.1: Sun Microsystems Modular Data Center: Project Black Box [6]

1.1.2 Significance of Modular Data Centers and Need for Cooling

Modular/Containerized data centers have gained a significant importance in the recent years for the primary reason of their simplicity and the ease with which they can be quickly deployed to expand existing IT infrastructure. When compared with traditional data centers, modular data centers are much more energy efficient and require significantly lesser maintenance.

These data centers could be located anywhere, whether it is onsite data center facilities or parking lots and garages or warehouses. Their main advantage is for providing quick expansion for rapidly growing IT infrastructure and for companies that reach their full capacity until a new one is constructed. Modular data centers gain a high interest from startup companies and companies transitioning to new data centers.

A large amount of power is utilized with capacity of these data centers to house several servers and ranging from 20 to 40 feet in dimensions. A tremendous amount of heat is generated due to this. The servers along with other electronic components generate a large amount of heat and hence it is crucial to ensure that the air temperature inside the containerized data center is within prescribed limits in order to avoid hot spots. Hot spot formation and thermal stresses account for equipment failure, short term reliability etc. Factors such as ambient temperature, humidity, location and solar loading play a major role as thermal conditions are based combined on ambient conditions as well as conditions inside the container. Reduction in chip size and high chip utilization rates have added to the heat density of chips at a rapid rate. Thus, in order to maintain optimum performance of these data centers, thermal management at the device, board, rack and room level is of utmost importance.

1.2 Evolution and Classification of Modular Data Centers

1.2.1 Benefits of Considering Modular Solutions

Modular data centers have evolved as an alternative to traditional data centers. The main benefits of using modular data centers are relative ease of shipping and deployment, lesser capitol for investment and lower operating costs when compared to traditional data centers. Maintenance and management of these containers is much simpler and thermal management of these modular data centers reduces due to comparatively low power densities than traditional data centers. Adding to that, use of free cooling techniques such as air side economizers, utilization of outside ambient air temperature etc. can be implemented and monitored in these containerized data centers which would help during the construction of traditional data centers well known as legacy data centers.

1.2.2 First Generation Modular Data Centers

First generation modular data centers refer to those units which require chilled water systems or refrigerant cooling coils as cooling infrastructure support or utilize direct expansion cooling units. Compressors and condensers are usually located outside the container for direct expansion cooling units. A number of different configurations for the cooling systems and IT infrastructure are possible for first generation configurations. The most common configuration is similar to a hot aisle/ cold aisle data center configuration where the equipment are housed in racks in a single row with aisles on either side for access and all the cooling equipment located right above, behind or to the sides of the equipment racks. These configurations provide excellent hot/cold aisle containment as they so not allow mixing of hot and cold air. However, this configuration may limit itself to serve only as a short term solution for immediate expansion of existing facilities or in locations where free cooling techniques are unfavorable. These units can be expensive as they are not very energy efficient when compared to second generation units. On the other hand, they are typically not affected by ambient air temperature and humidity.

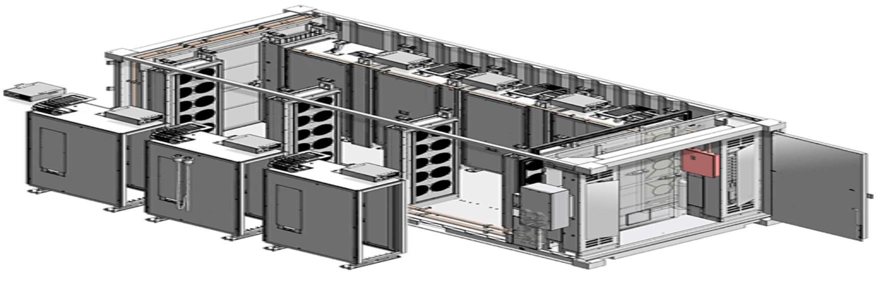

Figure 1.2: Cut View of First Generation Modular Data Center [7]

1.2.3 Second Generation Modular Data Centers

The need for chilled water supply or direct expansion cooling is eliminated for second generation data centers. These modular data centers use free cooling, chilled water or direct expansion methods. Free air cooling is paired with evaporative cooling sometimes when effective reduction of ambient air temperature in needed. As a backup, these systems may also include chilled water or direct expansion cooling units when ambient air temperature indicates the unfavorable conditions to use economizers.

SGI's ICE Cube Air is an example of a second generation modular data center unit configuration illustrated in Figure 1.3.

Figure 1.3: SGI ICE Cube Air [8]

1.2.4 Traditional Data Center vs. Modular Data Center Configurations

Table 1.1: Comparison of Primary Attributes [9]

Primary Attributes	**Traditional “Brick and Mortar” Data Center**	**First Generation Modular**	**Second Generation Modular**
Time to Deployment	Long – typically two years from design to commissioning	Potentially short – perhaps in months depending on site conditions and available infrastructure	Same as First Gen. Modular with advantage that reduced cooling infrastructure is required
Capital Cost	Highest – generally thought to range from 10- $20 million per MW of IT capacity	Lower – though there is a lack of documented deployment costs	Lowest – marginal increase in cost of unit, made up for by reduced infrastructure costs
Operating Cost	Variable, with legacy data centers having PUE’s exceeding 2.0 and best-in-class designs approaching 1.2 or lower if using outside air for cooling	Similar to traditional data center using the same cooling type. Pre-engineering and better system integration may provide some advantages.	Similar to best in class legacy data centers that use airside cooling.

1.3 Thermal Management of Data Center and Its Importance

1.3.1 Heat Generation in Data Centers

Heat is generated within the components of the device because of the flow resistance offered by the building blocks; transistors, resistors and capacitors. This heat has to be dissipated to ensure a proper and efficient working of the devices otherwise heat keeps increasing at a rate till the device fails to work or being operated [10].

Cooling allows lowering the high temperature due to the heat by transferring heat from hot fluid to the cold fluid. This is based on the first law of thermodynamics which is the law of conservation of energy. The temperature is moderated by reaching a steady state value which is acceptable for the device's operation.

The electronics cooling can be divided into various levels as shown in figure 1.4. Package at each level releases heat which has to be cooled. The power dissipation is increasing tremendously and thus thermal management is more challenging. Cooling of telecommunication systems ranges from cooling of chips, devices, cards, drawers to cabinets/racks and room.

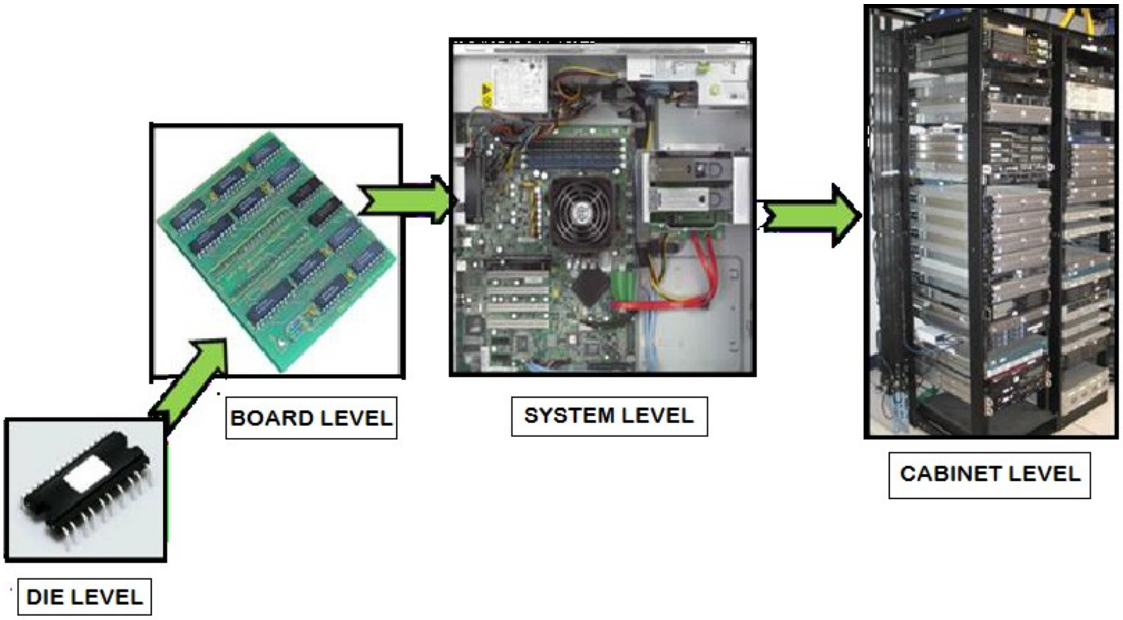

Figure 1.4: Cooling Range from Wafer Level to Cabinet Level [10]

Thermal management of Data Center is becoming more challenging on an account of the huge decrease in floor space for equipment and a tremendous increase in the power density of the servers without a drop in the energy efficiency. American Society for Heating, Refrigerating and Air conditioning Engineers (ASHRAE) sets the standards for constructing the Data Center TC9.9 [11] and also provides guidelines for the operating conditions required. Figure 1.5 shows the current trends in heat produced per foot print area.

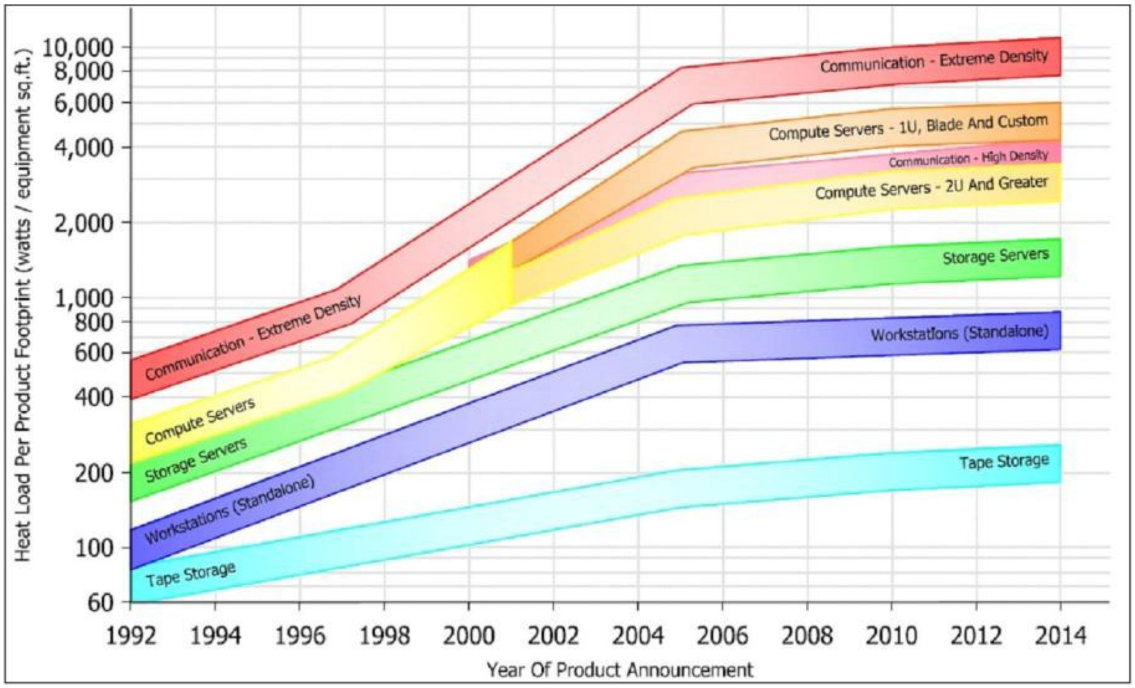

Figure 1.5 Current Trends in Heat Loads of the Data Center [10]

The current trend of increasing power in Data Centers at a warning rate leads to higher heat fluxes due to the increase in power dissipation and higher heat densities. From ASHRAE guidelines for datacom equipment [11], the predicted foot print is doubled and the heat loads for the storage servers are tripled for the same period (2000-2004). It is observed that these heat fluxes were 4000 W/ft2 in 2006 which corresponds to a heat load of 27kW in a 19 inch racks, available commercially. However, there is further increase in the coming years and it is observed that the heat loads will increase to 5000W/ft2 in 2010 and around 6000W/ft2 in 2014 for 1U blade computer servers. This corresponds to a heat load of 35 kW and 42 kW respectively. Higher heat loads in Data Centers lead to hot spots, the regions with higher heat fluxes, which increase the temperatures of Data Center causing reliability issues. Therefore, cooling of Data Centers is of high priority [10].

1.3.2 Selection of Cooling Technology

Many considerations are taken into account, depending on requirements, for the selection of modular data centers. These selections include the most energy cooling technology, IT infrastructure requirements, power requirements and several other considerations.

There are many alternatives for using cooling technology mainly depending on the location, geography, environmental conditions and availability of existing resources in the vicinity where these modular data centers are to be set up. The selection of cooling systems is primarily divided into three categories, namely air side systems, water side systems and other miscellaneous systems. Selection of air side systems is highly preferred to increase free cooling. Water side systems and miscellaneous systems such as evaporative coolers and dry coolers can be utilized when environmental conditions are not favorable for operation of air side systems. A combination of these systems can be used with conventional cooling systems such as water cooled chillers, chilled water towers and direct expansion units, depending on ambient conditions, to support IT equipments.

Apart from these factors, selection of cooling technology also depends on certain attributes such as humidity control, availability of chilled water supply, power supply for IT equipments and cooling systems and selection of filters and frequency of replacement.

CHAPTER 2

FREE AIR COOLING AND EVAPORATIVE COOLING INTRODUCTION

2.1 Free Air Cooling: An Introduction

2.1.1 What is Free Cooling?

Traditional Data Centers use mechanical cooling systems such as chilled water systems, which in turn require large and heavy mechanical systems like compressors and condensers to carry heated air by means of water which is taken to ambient atmosphere or external cooling towers. The liquid refrigerant used in these systems absorbs the heat and evaporates into vapor. The temperature of refrigerant increases due to its compression in order to release the absorbed heat to outside air. This refrigerant is allowed to expand back to its original state after all the heat has been rejected. Hence the temperature of the refrigerant reduces and it can be used again to extract heat. The entire process of using these refrigerants requires a large amount of energy.

Free cooling comes out as an alternative to the traditional cooling by using external ambient conditions and significantly reducing the use of large and heavy mechanical systems required for traditional cooling. It is a very suitable method for usage in regions having comparatively cooler climate. Even if free cooling can reduce the use of tiresome mechanical systems, it is not an ideal replacement. However, free cooling is efficient to save a large amount of energy costs.

2.1.2 Free Cooling in Data Centers

Organizations today, are inherently dependent on their information systems for smooth operations. The failure of an IT system may lead the company to deep grievances. Reliability and security of the information in the systems is always a crucial issue for companies. To overcome the difficulties of storage and security of the large volume of data, companies are prominently relying on modular data centers. The performance and processing capacity of the servers in these data centers is a significant issue with many leading companies. Presently, Moore's Law and low cost of manufacturing have relatively reduced the prices of the servers while making them more efficient and robust, but the amount of heat radiated remains the same [12].

Figure 2.1 shows the energy consumption for different systems within a data center. Apart from the critical IT load and server load, cooling of data centers utilizes a large amount of energy. Therefore, it becomes very crucial to reduce energy consumption by cooling systems to acquire an improved efficiency and hence reduce the power usage effectiveness of the entire data center.

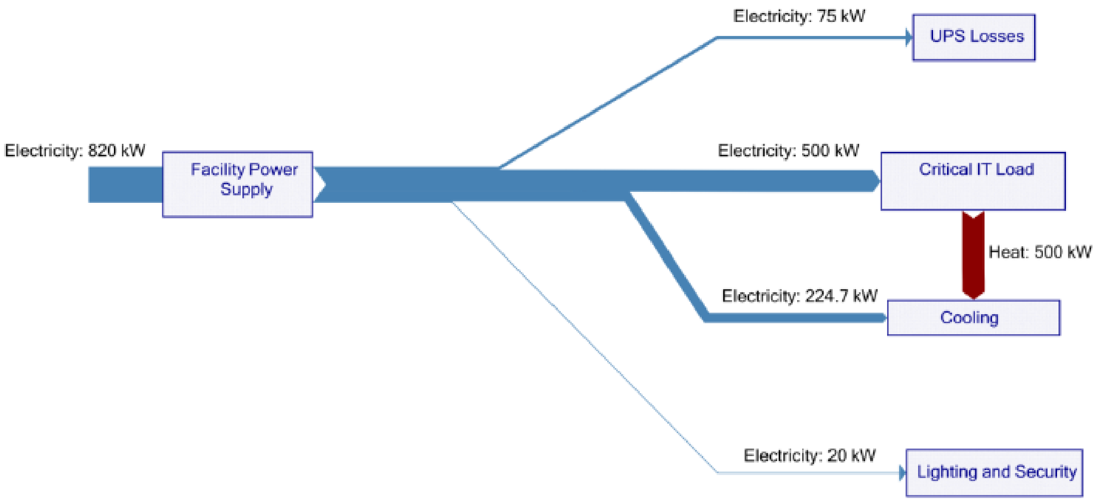

Figure 2.1: Energy Flow in Data Center [13]

2.1.3 Classification of Free Cooling Systems

Free cooling systems can be chiefly categorized in two types namely air side cooling and water side cooling. Miscellaneous cooling systems such as ground water cooling and sea-water cooling are also commonly used. In air side cooling, cold air is pulled in from outside and circulated through the servers and other electronic equipment and the heat is carried back and driven outside. However, air side cooling requires a greater volume of air to cool a data center which in turn requires larger ducts for pushing so much air. Although this cooling technique sounds very simple, it may not be practical to apply for cooling large volumes of area within a data center as pulling in so much air and filtering it is extremely difficult. Filters the size of large ducts are required to prevent entry of any contaminants such as dust, moisture etc. Additionally, large fans are needed to pull in an enormous quantity of air through the filters. Filters will have to be replaced periodically as dirty filters would cause a lot of air resistance compared to clean ones. Water side cooling is more commonly used compared to air side cooling because water is much more efficient in transferring heat than air per unit volume. Free cooling can be achieved using water side cooling systems by integrating them with centralized chilled water systems and condensers with the addition of valves. Circulating water or a glycol water mixture is used for transferring heat to outdoor cooling towers without running chillers [2].

2.2 Introduction to Evaporative Cooling Technology

Conventional cooling systems operate on a refrigeration cycle, and they can be used in any part of the world. But they have a high initial and operating cost. In desert (hot and dry) climates, we can avoid the high cost of cooling by using evaporative technique, also known as mist cooling, spray cooling or evaporative cooling. Evaporative cooling is bound to exist when there are hot and dry ambient conditions. Evaporation is a type of vaporization of a liquid that occurs only on the surface of a liquid. The other type of vaporization is boiling, which, instead, occurs on the entire mass of the liquid [14].

2.2.1 Understanding Evaporative Cooling

Evaporative cooling differs from typical air conditioning systems which use vapor-compression or absorption refrigeration cycles. For molecules of a liquid to evaporate, they must be located near the surface, be moving in the proper direction, and have sufficient kinetic energy to overcome liquid-phase intermolecular forces. Only a small proportion of the molecules meet these criteria, so the rate of evaporation is limited. Since the kinetic energy of a molecule is proportional to its temperature, evaporation proceeds more quickly at higher temperatures. As the faster-moving molecules escape, the remaining molecules have lower average kinetic energy, and the temperature of the liquid, thus, decreases. This phenomenon is also called evaporative cooling [15].

Evaporation is the conversion of a liquid substance into the gaseous state. When water evaporates from the surface of something, that surface becomes much cooler because it requires heat to change the liquid into a vapor. When air moves over a surface of water it causes some of the water to evaporate. This evaporation results in a reduced temperature and an increased vapor content in the air. The bigger the area of contact between the air and water the more evaporation occurs, resulting in more cooling and the addition of moisture. In order for water to evaporate, heat is required [16].

In simple words evaporative cooling means evaporation of water when it comes in contact with air. This phenomenon occurs due to the tendency of air to equalize temperature and vapor pressure. When the water molecules evaporate, they absorb heat from the surroundings and lower the temperature of dry air by converting water into water vapor, which utilizes much less energy than refrigeration. This phenomenon of absorbing heat in form of vapor is called adiabatic cooling. Evaporative cooling efficiency can be measured by considering wet-bulb temperature of air as compared to its dry-bulb temperature. The effectiveness of evaporative cooling depends on the wet bulb temperature of air. When both the temperatures are same, there is no significant cooling effect.

2.2.2 Benefits of using Evaporative Cooling

The benefits listed below indicate why evaporative cooling is cheap and requires less energy than other forms of air cooling [16].

- Evaporative coolers use a supply fan and a fractional horsepower sump pump. They do not use an energy intensive refrigerant compressor, so they require 1/5 to 1/2 as much electricity to operate as refrigerated cooling.
- Maintenance requirements are simpler for evaporative air cooling equipments than for refrigerated air conditioning equipment.
- The life-cycle cost of using evaporative cooling is less than a comparable refrigerated air unit.
- Evaporative cooling does not directly use any chemical substances that are known to be detrimental to the earth’s ozone layer.
- Improved indoor air quality from evaporative air coolers is due to their use of 100% outside air rather than recirculated air.

2.2.3 Types of Cooling Systems Used in Evaporative Cooling

Evaporative cooling systems chiefly have two type of systems; direct evaporative cooling and indirect evaporative cooling. They can be used individually or by combining both the systems.

2.2.3.1 Direct Evaporative Cooling

In traditional direct evaporative cooling systems, ambient air blows through a water-saturated medium and is cooled by the evaporation principle discussed earlier. The air continues to carry moisture until it reaches close to its saturation point. This decreases the dry bulb temperature while keeping the wet bulb temperature of air constant. This cooled air is than circulated by a blower where cooling is required. As these systems are simple and cheap, they are widely used for the cooling of residential houses and industrial warehouses. Direct evaporative cooling systems generally use much lesser energy.

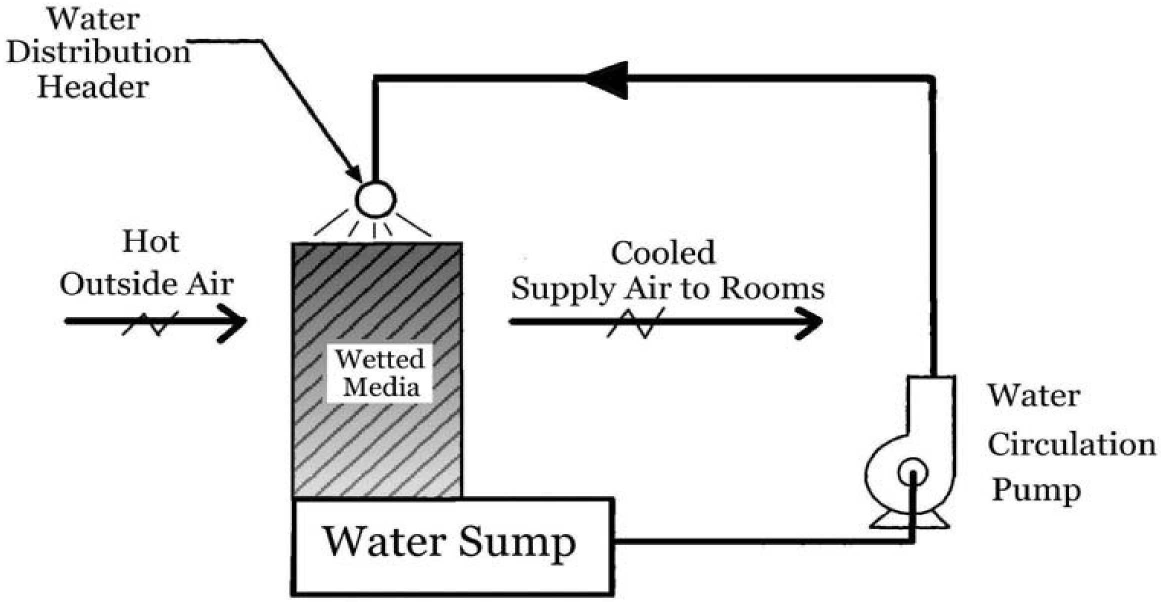

Figure 2.2: Direct Evaporative Cooling Schematic [16]

The presence of a media type evaporative cooler inherently creates a pressure drop and this will create a drop in blower output. Increase in inlet duct differential pressure will cause a reduction of blower mass flow and also operating pressure. This factor is important when considering the application of any inlet technology such as evaporative cooling systems [17].

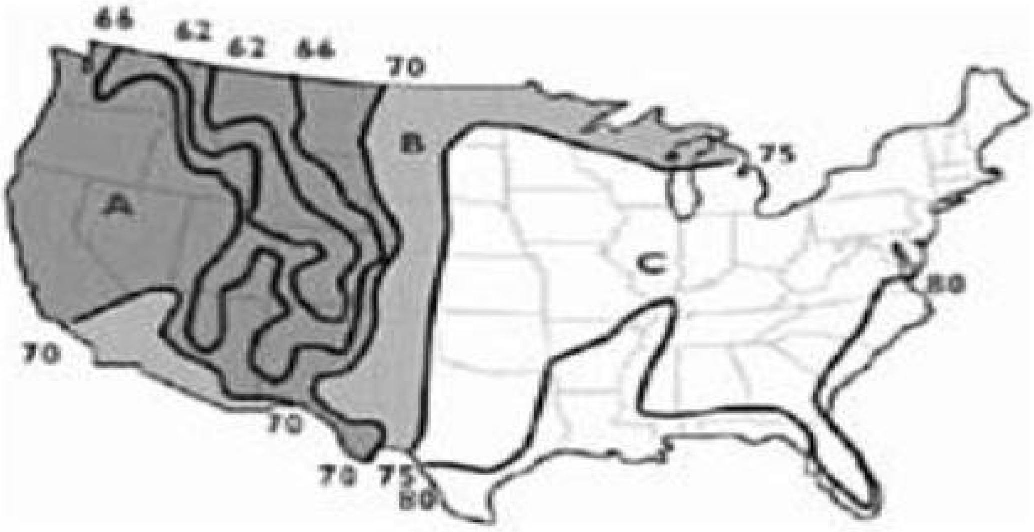

Figure 2.3 U.S. Geological Survey Map [18]

Figure 2.3 shows U.S. geological survey map of areas where use of direct evaporative cooling is suitable. Evaporative coolers work efficiently in areas marked A whereas the efficiency decreases in areas marked B. However, use of direct evaporative coolers is not recommended in areas marked C. This map is based upon wet bulb temperature at 1% design conditions.

One of the more effective methods to use direct evaporative cooling is called direct inlet fogging. Water is injected through special atomizing nozzles producing a fog of very fine droplets which evaporate almost instantaneously. The evaporation process results in a cooling effect on the inlet air feeding the compressor. The air can nominally be cooled to the corresponding wet bulb temperature [19]. This method of direct evaporative cooling has a advantage of getting 100% effectiveness when it comes to attaining relative humidity at blower inlet. Hence it gives the lowest temperature possible without using refrigeration.

Figure 2.4: Direct Inlet Fogging [19]

Table 2.1 shows a descriptive comparison between traditional evaporative cooling and direct inlet fogging.

Table 2.1: Qualitative Comparison between Traditional Evaporative Cooling and Inlet Fogging [2]

	Traditional Evaporative Cooling	Direct Inlet Fogging
Need for high quality water	Not required any particular kind of water	Demineralized water is required
Incremental Inlet Pressure drop	High	Low-practically nil
Size foot print	Large	Small
Effectiveness	0.85 to 0.9	0.97 to 1.0
Maintenance	High	Comparatively low
Aux power consumption	Requires Pump	High pressure pump required
Sensitivity to relative humidity	High	Lower
Installation down time	Extended outage	Can be done in 2-3 days

2.2.3.2 Indirect Evaporative Cooling

Indirect evaporative cooling works on same principle as direct evaporative cooling i.e. lowering air temperature by evaporation of water. Indirect evaporative coolers have been in use for over 20 years, but have gained recent acceptance because of better manufacturing techniques that have lowered their cost and improved performance. These systems use a heat exchanger, and do not add moisture to the room air stream also known as sensible cooling [16].

Contrasting to direct evaporative coolers, indirect evaporative coolers reduce both dry bulb and wet bulb temperature. The main difference in using indirect evaporative cooling is that a heat exchanger is required to cool the air.

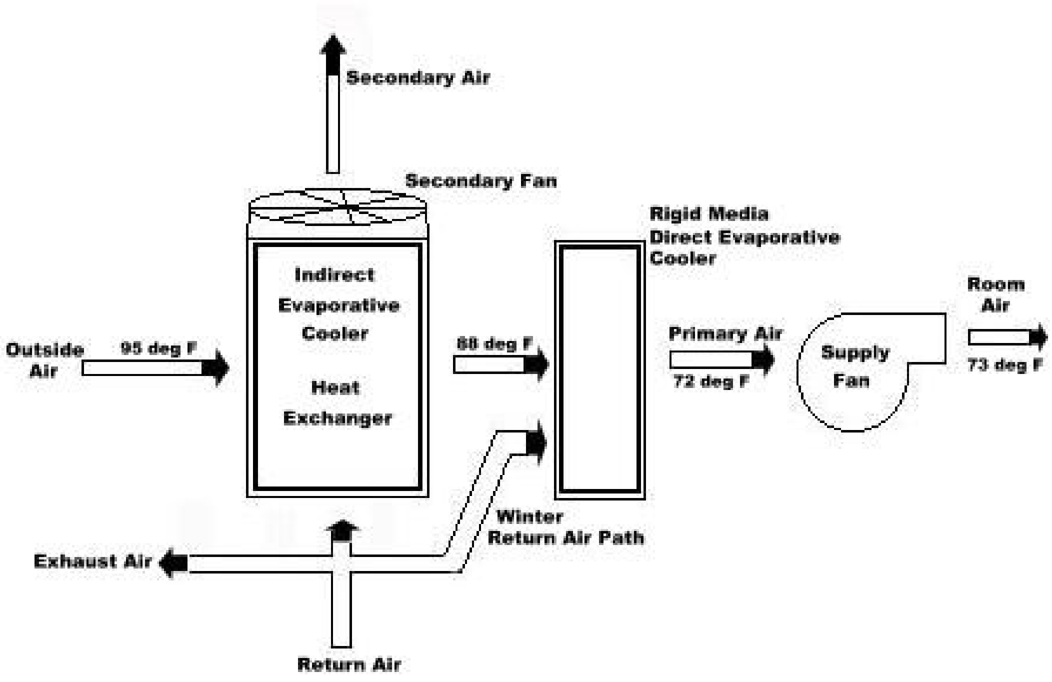

Figure 2.5: Indirect Evaporative Cooler Used with Direct Evaporative Cooler [16]

Figure 2.5 shows indirect evaporative cooling system installed upstream of the rigid cooling media. Hot ambient air is blown through indirect evaporative cooler or heat exchanger which is supplied with water. A simple heat exchanger consists of a series of metal tubes in which cold water keeps running. When hot air passes through these tubes, evaporation takes place and the hot air is cooled. This cooled air is further processed through evaporative coolers if needed or is blown to the space to be cooled.

Indirect evaporative cooling provides cool air without raising its moisture content as much as direct evaporative cooling. This cooling method is more appropriate for areas marked C in figure 2.3. Indirect coolers utilize more energy as they use electricity for the supply fan motor, a sump pump, and a smaller secondary fan motor used for the heat exchanger’s airflow.

CHAPTER 3

ENVIRONMENTAL INFLUENCE AND UNDERSTANDING PSYCHOMETRIC CHARTS

3.1 Environmental Influence

Usage of different alternative cooling technologies is highly determined on the basis of ambient conditions of a particular place. Consider that the ambient air temperature of a place is between 18°C to 27°C. In such cases the use of refrigeration unit or evaporative cooling system would not be required and it would just be a waste of resources. Contradicting to this, if the ambient air temperature is higher than 27°C, using only air-side economizer would not be appropriate. Hence the study of the temperature profile and its history for a particular site is of prime importance in the selection of cooling technology [2].

This chapter shall concentrate on the generally accepted environmental classes for datacom facilities according to ASHRAE Datacom Series [17]. The impact of ambient conditions on different categories of datacom energy use would be discussed.

3.2 Environmental Categories

Telecommunication environments are categorized mainly into three main divisions, namely [17] [2]:

- 1st Category: This category comprises of a datacom facility which has controlled environmental parameters and mission critical operations that include types of products typically designed for these environments namely enterprise servers and storage products.
- 2nd Category: This category comprises of a datacom space or lab environment with limited control of environmental parameters. Small servers, storage products, personal computer and workstations are some products designed for these criteria.

- 3rd Category: NEBS (Network Equipment Building System): Per Telcordia GR-63-CORE and GR-3028-CORE, includes typically a telecommunications central office with limited control of environmental parameters. Switches, transport equipments and routers are some products designed for these criteria.

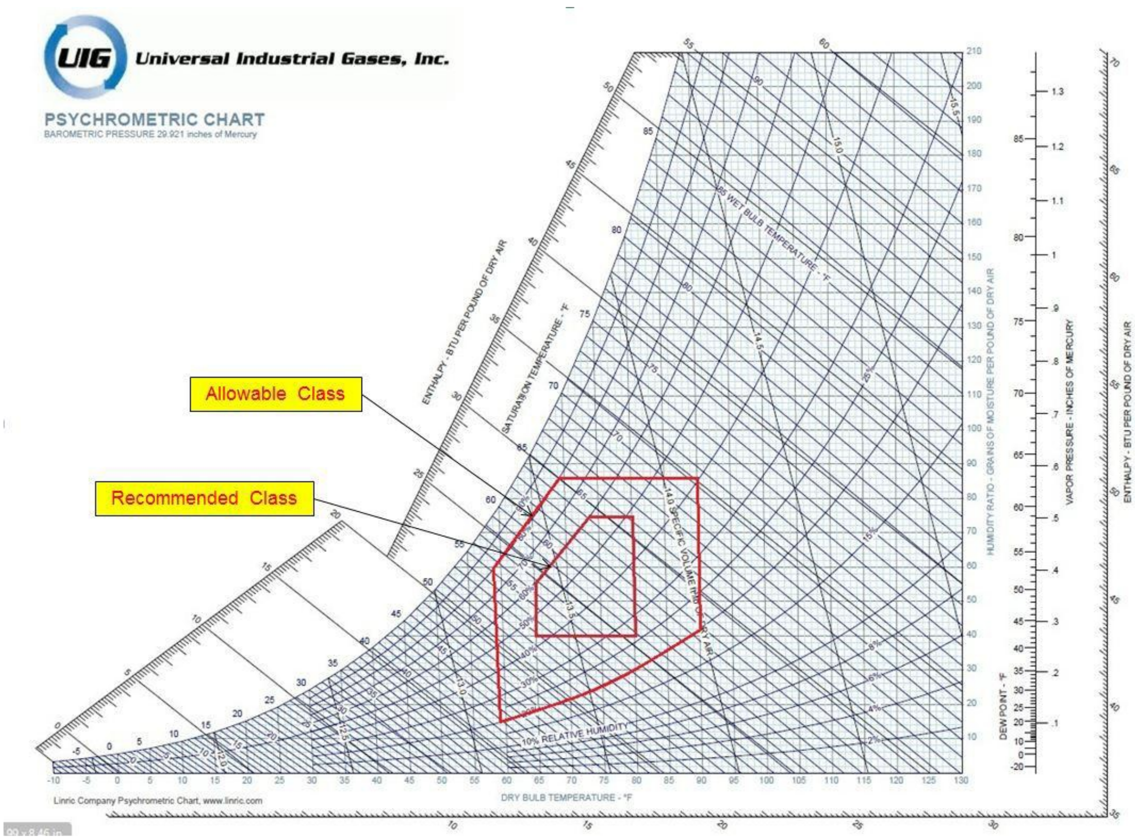

Figure 3.1: Recommended Operating Conditions for Data Centers of 1st Category and 2nd Category According to ASHRAE [30]

Most of the network devices needed for containerized data center is classified in 1st category and 2nd category. Recommended temperature and humidity conditions for 1st and 2nd category are shown in Figure 3.1 [17].

Table 3.1 distinguishes the allowable temperature and humidity conditions for the above categories. Relative temperature as well as dew-point temperature range is also listed in the table. These conditions are corresponds to inlet at datacom equipment, not to conditions at the return to the air-conditioning equipments. Temperature in datacom spaces, such as hot aisles e.g. can exceed the recommended conditions. Battery storage, switch gear rooms e.g. do not necessarily need these environmental conditions [2].

Table 3.1 Category 1 and Category 2 Design Conditions [2] [17]

Condition	1st / 2nd Category	
	Allowable Level	Recommended Level
Temperature Control Range	59°F - 90°F (1st Category) 50°F - 95°F (2nd Category)	64.4°F – 80.6°F
RH Control Range	20% - 80% 63°F. Max dew point (1st Category) 70°F Max dew point (2nd category)	41.9°F dew point – 60% RH and 59°F dew point
Filtration Quality	65%, Min 30% (MERV11, min MERV8)	

Recommended operating conditions for direct evaporative cooling, published by ASHRAE are shown in Figure 3.2 [30]. It shows mainly four separate regions with different environmental conditions. First region encompasses temperature range below 64.4°F dry bulb temperature when both cooling and humidification are needed. This condition can be achieved by mixing of ambient air and exhaust hot air. Second region indicates the conditions where cooling is possible without refrigeration. Only mechanical cooling and humidification is required in this region. Third region shows temperature range between 58°F wet bulb and 64°F wet bulb. In this region direct evaporative cooling minimizes the need of mechanical cooling. Region IIIA needs a dehumidification system. Fourth system requires refrigeration system with humidity control [2].

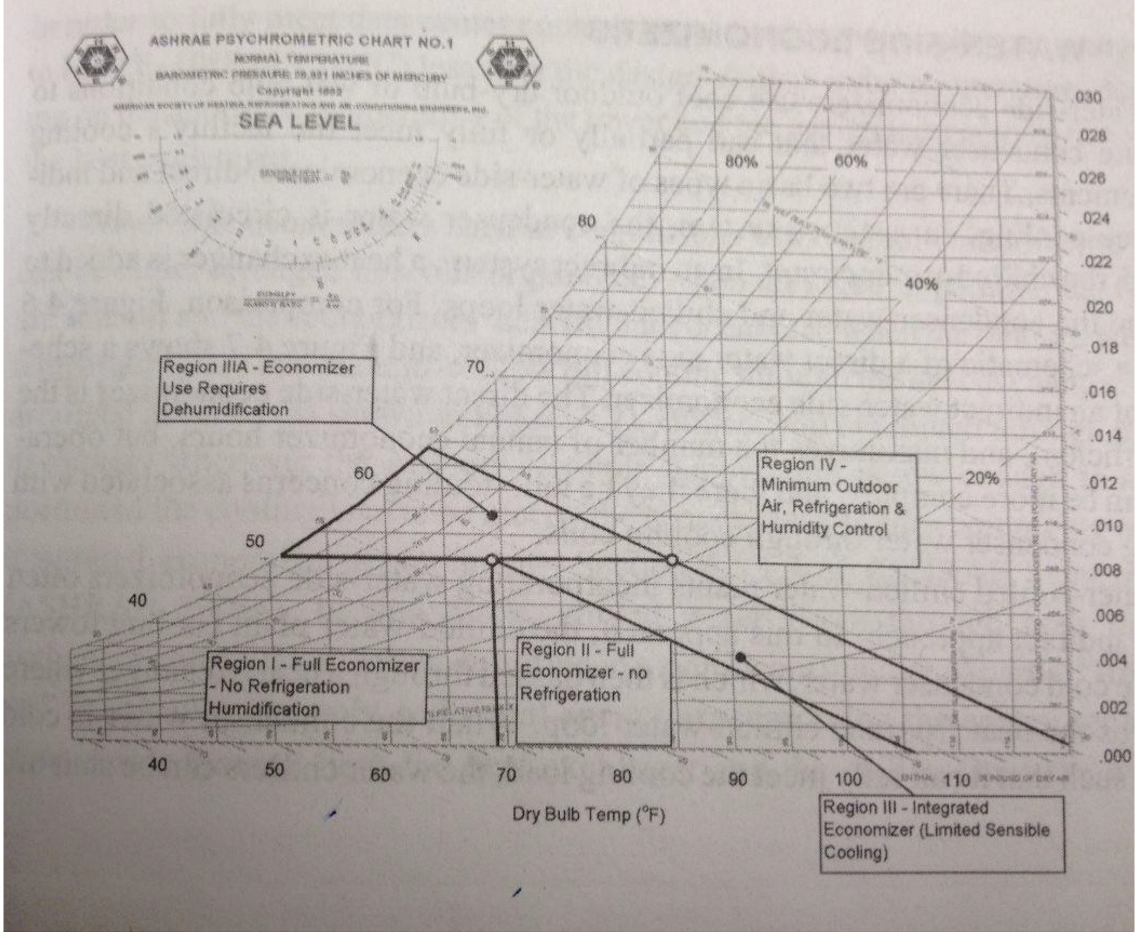

Figure 3.2: Recommended Operating Conditions for Direct Evaporative Cooling Air-Side Economizer [31]

Figure 3.3 shows operating conditions for inlet-fogging system with air-side economizer. There two regions in this psychometric chart in which first region is recommended for inlet operating conditions for air side economizers and second zone indicate conditions between 50°F wet bulb and 66°F wet bulb temperature, where direct evaporative cooling can attain ASHRAE recommended envelope.

3.3 Understanding Psychometric Chart

The principles of psychometrics apply to any physical system consisting of gas-vapor mixtures; the most common system of interest is the mixture of water vapor and air, because of its application in heating, ventilating and air-conditioning. Psychometric chart is a representation of all air properties, calculated at standard atmospheric pressure. It is one of the most important tools to figure out heat load and cooling calculations and to find solutions to air conditioning problems [2].

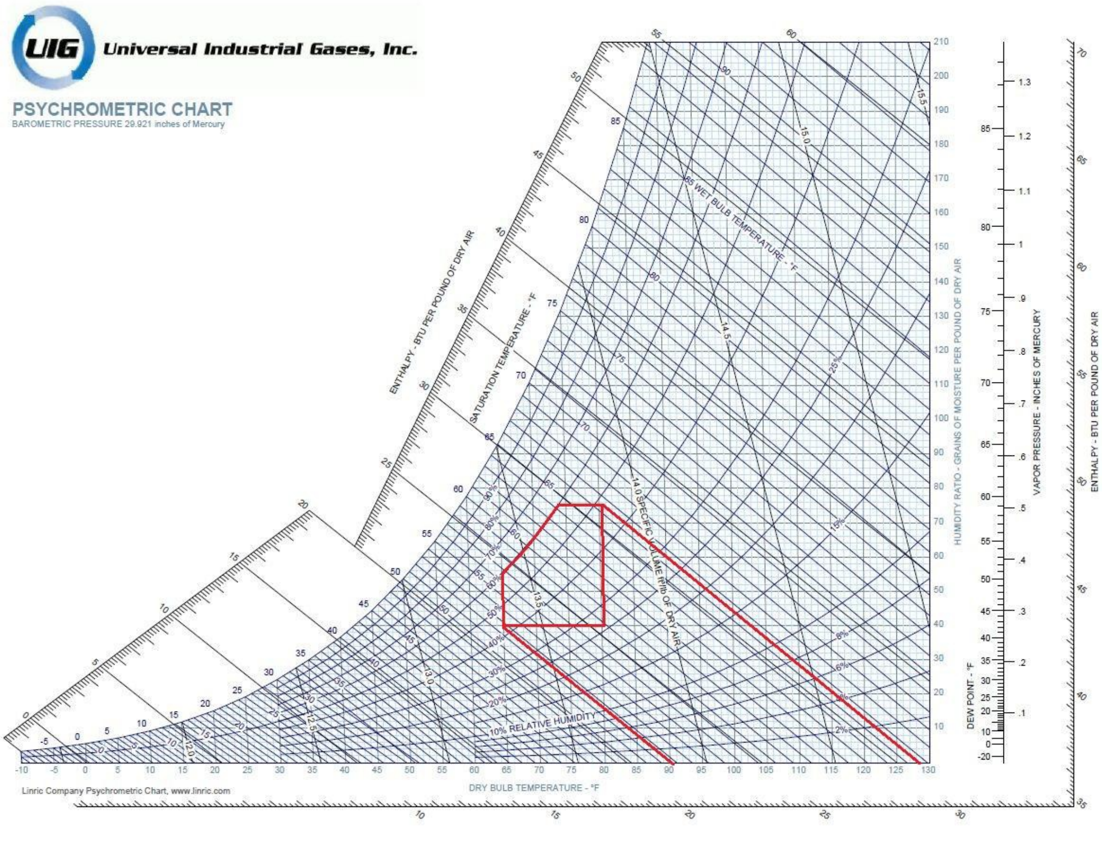

Figure 3.3 Operating Conditions for Direct Evaporative Cooling [2] [30]

An example is illustrated in Figure 3.4 [2] [30] to calculate the amount of water needed for inlet fogging system, considering ambient conditions for Dallas, TX [31]. Ambient air temperature is 100°F (15% relative humidity) and we need to achieve 80°F (49% relative humidity) at a flow rate of 9500 CFM. First step to solve this problem would be finding ambient condition on the chart, which shows that moisture content for given condition is 43 grains/lb for dry air. Now follow the constant wet bulb temperature till we reach the temperature we want to achieve which shows moisture content 75 grains/lb. Hence we know that 32 grains/lb moisture is added. Hence the required amount of water for cooling is 0.0512 lb/sec (9500CFM x 32 grains/lb).

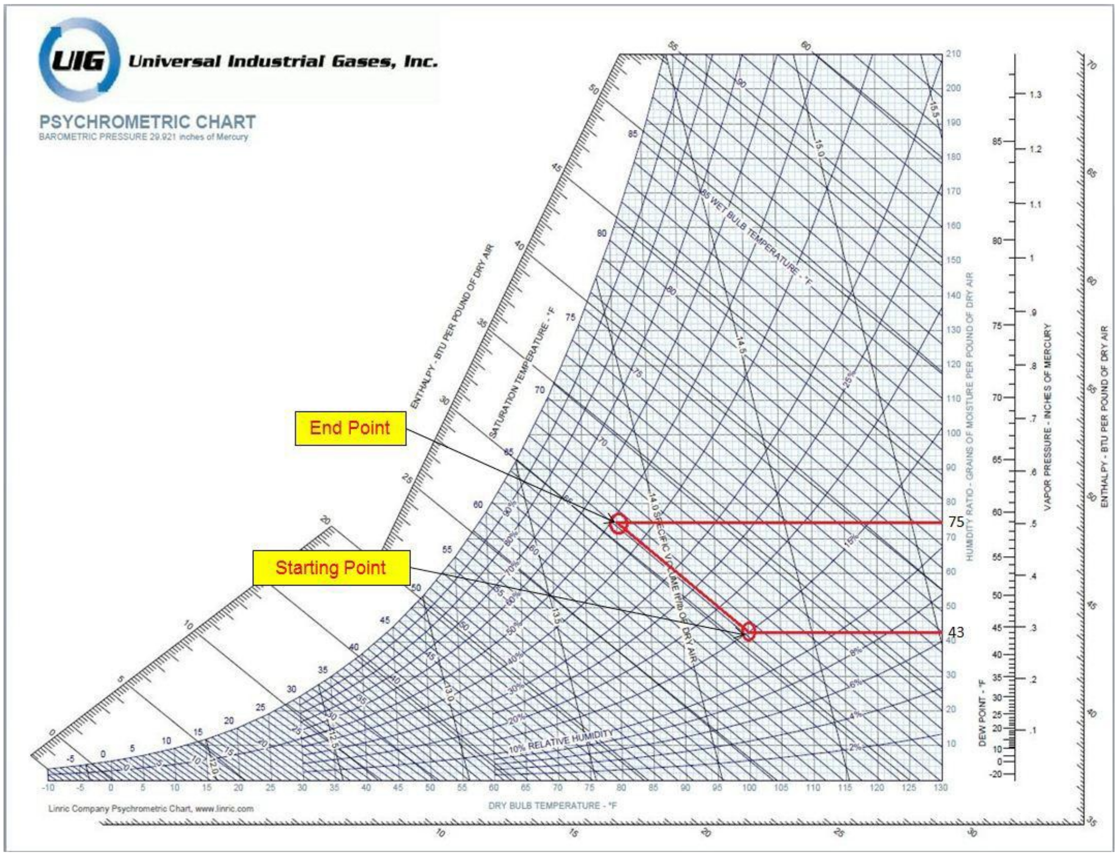

Figure 3.4: Initial and Final Conditions for the Given Illustration [2] [30]

CHAPTER 4

PHASE CHANGE MATERIALS

4.1 Introduction to Phase Change Materials

Thermal energy storage relates to storing of energy in reservoirs for future use. Thermal energy storage systems are often used to balance the energy requirements between day time and night time. The temperature of thermal reservoir is kept either higher or lower, when compared to the ambient temperature depending on the energy requirement at specific period of time.

4.1.1 Phase Change Material Definition

A phase change material (PCM) is a substance which has high heat of fusion which when melted and solidified at a fixed temperature, tends to store or release large amounts of heat. PCM behaves like traditional sensible heat storage materials until it reaches its melting or crystallization point by absorbing heat. As soon as it reaches its phase change temperature, it starts absorbing heat at constant temperature. It continues to absorb heat until all the material has changed its phase. These materials absorb heat behaving as conventional storage materials and then release the heat at nearly constant temperature, which is one of the biggest advantages of using these materials in thermal management. Another advantage of using these materials over storage materials such as water, masonry, or rock is their capability to store 5-14 times more heat per unit volume. There are a large number of PCMs which are known to melt with a heat of fusion in any required range, making it again more compatible. However, for their employment they must exhibit desirable thermodynamic, kinetic and chemical properties with ease of availability and economic considerations [20]. Figure 4.1 shows a general temperature vs. energy curve for phase change materials compared to water.

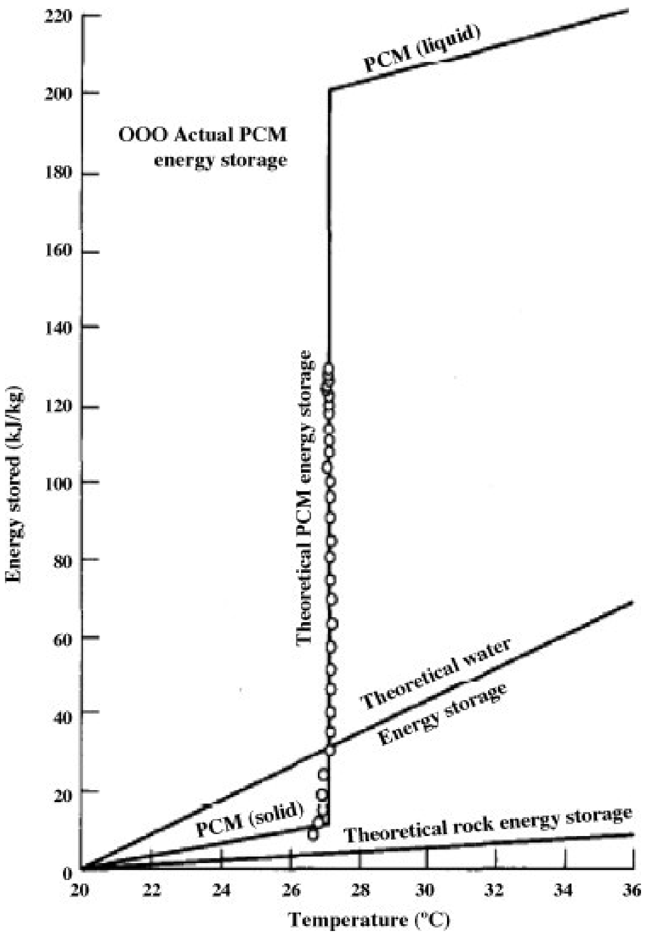

Figure 4.1: Temperature vs. Energy Curve Showing High Energy Storage Phase Change Materials [21]

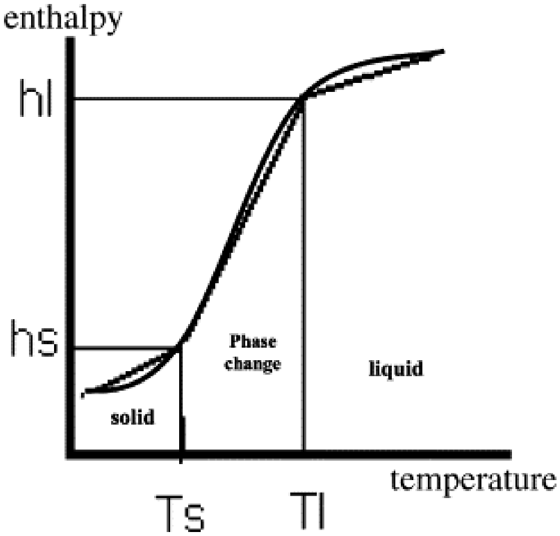

Figure 4.2: General Temperature vs. Enthalpy curve for PCM [23]

4.1.2 Classification of PCM

The latent heat storage of phase change materials can be achieved by a variety of phenomena: solid to liquid phase, solid to solid phase and liquid to gas phase. Solid to solid phase change is a typically slow process which has very low heat of transformation. Liquid to gas phase has the highest energy of transformation. However, it is not feasible to use them as they require high pressure storage and occupy large volume. Hence the solid to liquid phase change is accepted to be used widely. Figure 4.2 shows a discrete classification of solid-liquid phase change materials.

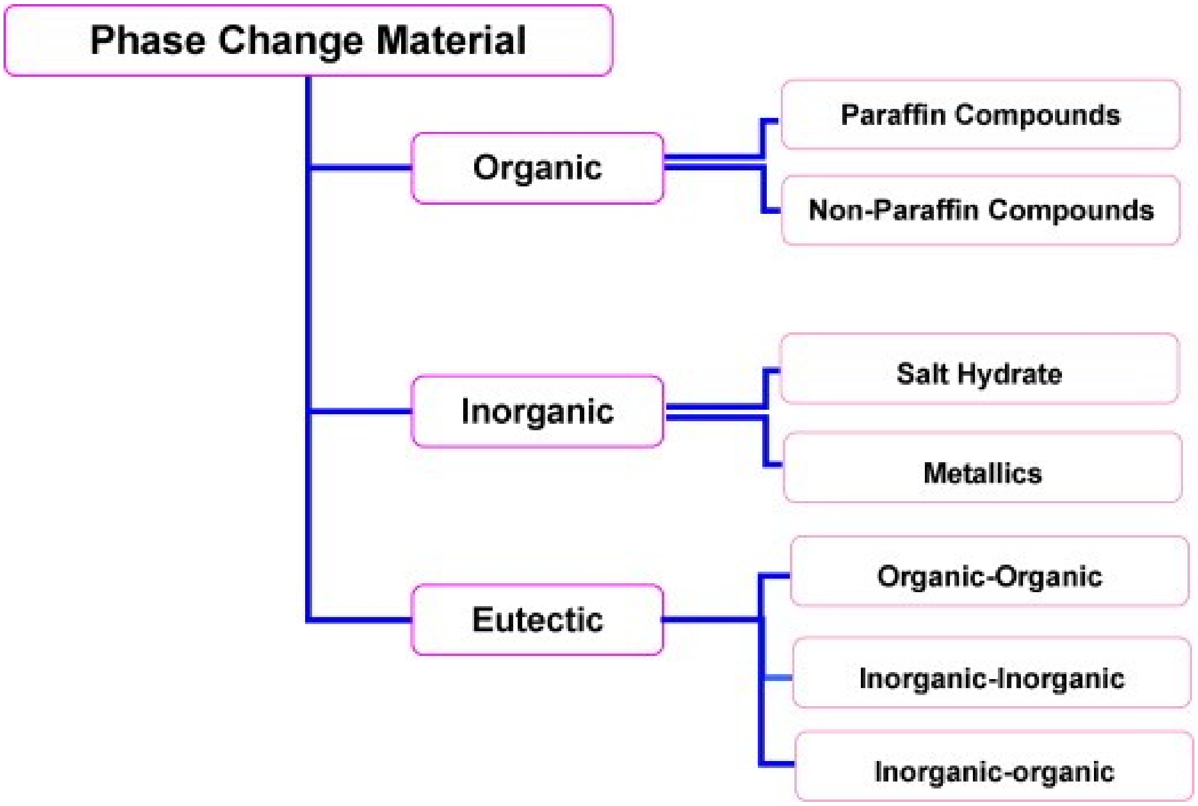

Figure 4.3: Classification of PCMs [21]

Phase change materials are chiefly classified into organic, inorganic and eutectic materials. Paraffin has a very high thermal stability which means it can undergo a number of phase change cycles without changing its material properties. On the contrary they are flammable and have relatively low enthalpy and density when compared to salt hydrates. Salt hydrates are corrosive and low cycling stability. Salt hydrates sometimes tend to crystallize at a much lower temperature than its melting point which is known as sub-cooling [22]. Table 4.1 shows some advantages and disadvantages of organic and inorganic PCMs.

Table 4.1: Comparison between Organic and Inorganic PCMs [21]

Organic (Paraffin and Fatty Acids)	Inorganic (Salt Hydrates)
Advantages • Freeze without super cooling • Chemically stable • High heat of fusion • Self nucleating properties • No segregation • Recyclable	Advantages • High latent heat storage capacity • High thermal conductivity • High heat of fusion • Sharp melting point • Non flammable • Low cost
Disadvantages • Low thermal conductivity • Low latent heat storage capacity • Flammable	Disadvantages • High change in volume • Super cooling • Low stability

4.1.3 Selection Criteria for PCMs

Selection of PCMs depends on a vast number of factors. Some key factors that decide the selection criteria are: desired melting temperature, high specific heat and high thermal conductivity, high latent heat of fusion, high density etc. Some other factors include high nucleation rate, chemical stability, non-corrosiveness and non-toxic, non-flammable, low cost and high availability.

4.2 PCM: Properties and Applications

4.2.1 Phase Change Materials Properties

Efficiency of phase change materials in heat exchange systems depends on factors such as the thermal conductivity of material, Stefan number, mass fraction, and the latent heat of fusion. The thermal conductivity of phase change material is defined as [24]:

Thermal conductivity = heat flow rate/ (area × temperature gradient)

It is measured in watts per meter-Kelvin, W·m-1·K-1.

Heat Capacity of a material is defined as the capacity to store heat by the material:

Heat capacity = V * p * Cp

Where:

V = volume (m3)

p = density (kg/m3)

Cp = specific heat (J/kg*K)

It is measured in joules per Kelvin (J/K).

The ratio of thermal conductivity to heat capacity is called thermal diffusivity of the material. Materials which have high thermal diffusivity tend to adjust their temperature rapidly with their ambient temperature, because they conduct heat quickly in comparison to their thermal bulk. It is defined as [24]:

$$\alpha = \kappa/\rho C p$$

Where:

α = thermal diffusivity

κ = thermal conductivity

ρ = density

Cp = heat capacity

The units are m^2/s (meter^2/second).

The optimal effectiveness of phase change material is obtained when its Stefan number is lower than 1. A higher heat capacity is obtainable by having high mass fraction and high latent heat of fusion. Stefan number is defined as [24]:

$$St = \frac{c_p\left(q_w \frac{R}{k}\right)}{c_m \lambda}$$

Where:

c_p = suspension’s specific heat

q_w = heat flux across the pipe wall

R = radius of pipe

k = suspension’s thermal conductivity

c_m = mass fraction of PCM in suspension λ = PCM's latent heat of fusion

4.2.2 Microencapsulation of Phase Change Materials

As discussed in earlier part of this chapter, most of organic PCMs are non-corrosive and chemically stable, performance little or no sub-cooling, are compatible with most building materials and have a high latent heat per unit weight and low vapor pressure. They have disadvantages in low thermal conductivities, high changes in volume on phase change and flammability, though extensive investigations are carried out to enhance their heat transfer rate. In contrast, inorganic materials (salt hydrate and metallic) have a high latent heat per unit volume and high thermal conductivities, and are non-flammable and low in cost in comparison to organic materials. However, they are corrosive to most metals and suffer from decomposition and sub-cooling, which can affect their phase change properties. Therefore, In order to overcome these problems, a new technique of utilizing microencapsulated phase change material (MEPCM) in thermal energy storage system has been developed [25].

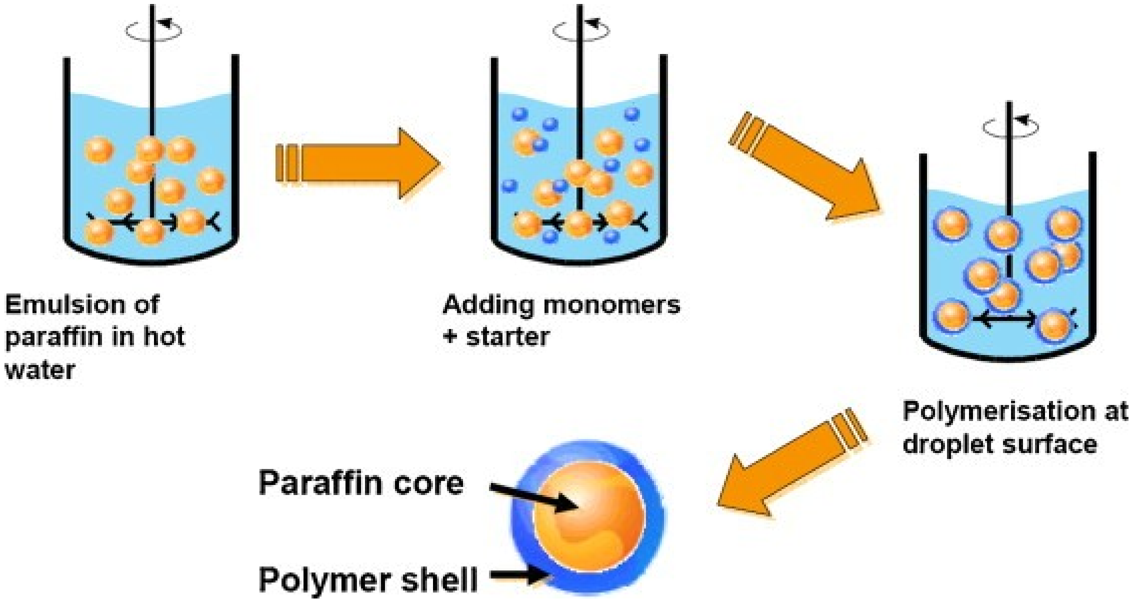

Figure 4.4 Microencapsulation process of BASF [28]

In general, microencapsulation is a process in which minute particles or droplets are surrounded by a coating, or embedded in a homogeneous or heterogeneous matrix, to give small capsules with many beneficial properties [26]. Due to microencapsulation, liquid and gas phase change materials can be handled in similar way to solids and it provides a physical boundary between the core material and the shell material [25]. The microencapsulated phase change material is defined as mixing of phase change materials core and a polymer or inorganic shell to maintain the shape and prevent PCM from leakage during the phase change process [27]. Microencapsulation allows the PCMs to be usable into construction materials, such as concrete, easily and economically. They also provide a portable heat storage system. By coating a microscopic sized PCM with a protective coating, the particles can be suspended within a continuous phase such as water. The heat transfer distance between PCM particles by conduction can be reduced by microencapsulating the material into small capsules [22]. These microencapsulated particles can be in dispersed medium or can be converted into powder form as shown in Figure 4.5 [29], depending on the application.

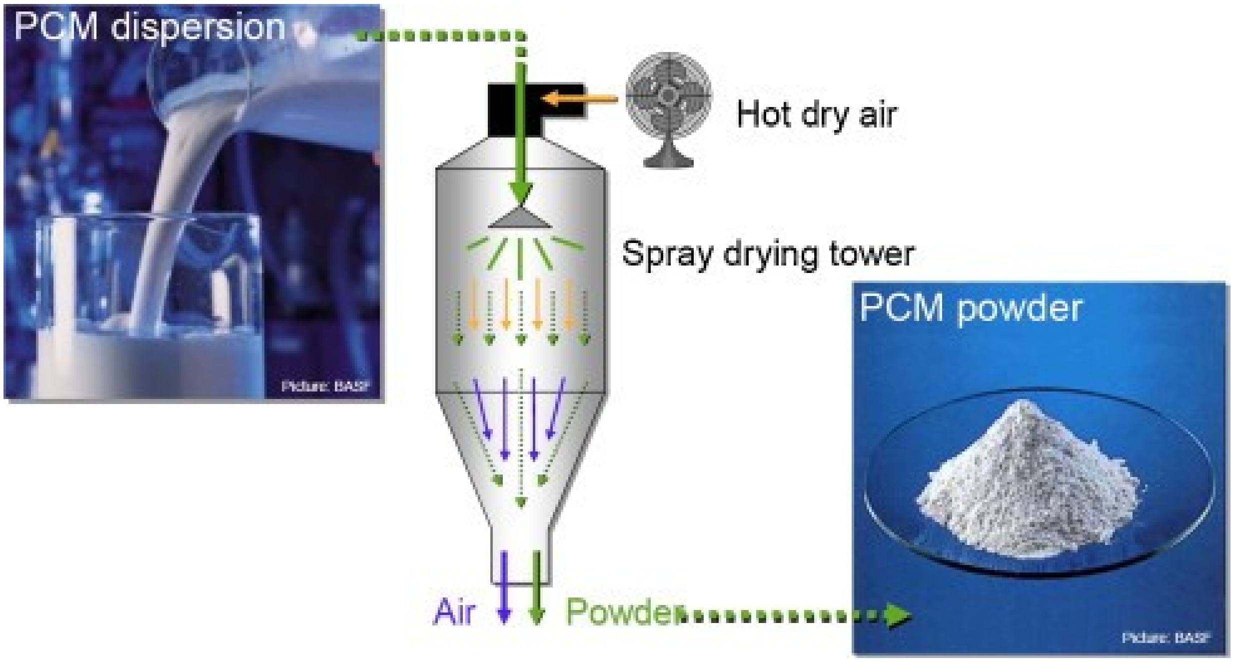

Figure 4.5: Drying Process Used by BASF [29]

4.2.3 General Applications of Phase Change Materials

Phase change materials have been investigated over the years as thermal energy storage for cooling and heating applications. Investigative research has been done to use microencapsulated PCM in different sizes in order to maximize its thermal properties in various heat transfer applications. Some of the fields in which phase change materials have been largely incorporated are: textile industry, cooling of buildings, heat exchanger systems, solar power plants etc.

CHAPTER 5

EVAPORATIVE COOLING UNIT WITH MICROENCAPSULATED PHASE CHANGE MATERIAL

5.1 Objective and Approach

The usage of high amounts of data center energy for the purpose of cooling has leaded us to think of alternative cheap and efficient cooling techniques. Direct evaporative cooling units have a limitation with certain ambient conditions. It uses water in form of vapor to cool the ambient air. The ambient air, after a certain point cannot carry anymore water vapor which is known as its saturation point. This means that the air cannot be cooled any further once it reaches its saturation point. Thus the efficiency of evaporative cooler decreases considerably when the climate is more humid and the relative humidity of ambient air is high.

Many attempts have been done to use microencapsulated phase change slurry as a working fluid in indirect evaporative cooling units. Previous experiments have resulted into clogging and agglomeration into the system because of breaking down of the carrier shells or capsules of phase change materials present in the slurry mixture due to the induction of high stress when pumped. Moreover usage of mPCM slurry follows with the increase in pumping power costs due to high viscosity of mPCM slurry. Constructing an appropriate cooling circuit for the slurry has also added to the initial costs.

Hence the above limitations of direct evaporative cooling systems and microencapsulated phase change slurry have inspired us to think of an innovative technique of introducing microencapsulated phase change material inside the direct evaporative cooling system. This research hence highlights the effects on the cooling performance, when microencapsulated phase change material is added on the downstream of cooling pad in a direct evaporative cooling system.

5.2: Initial Developments and Hybrid Evaporative Cooler

5.2.1 Robust Cooling Pad

The initial idea behind this research was to develop a robust evaporative cooling pad by integrating micro-encapsulated phase change material in the conventional evaporative cooling pad. It would have potential to provide sustainable cool air for wide range of commercial and industrial applications. Current direct and indirect evaporative cooling technology requires continuous water circulation over the pads to achieve effective cooling. This contributes in increase water consumption and pumping cost. Also, vapor compression refrigeration systems are found to be more expensive than evaporative cooling technology. Moreover, this would also help in downsizing facilities, reducing cost, use of refrigerant and energy requirement in vapor compression refrigeration system. The presence of phase change material would significantly reduce water consumption and pumping cost in comparison to conventional evaporative cooling systems. Further, it would add to enhancing the efficiency of traditional evaporative cooling pad and ensures cost savings.

This idea was further given hopes by a thought of inserting copper coils containing mPCM powder into traditional cooling pad in three different ways as shown in Figure 5.1, Figure 5.2 and Figure 5.3. With such cooling pad, the incoming air would melt the phase change material while water flowing over the cooling pad would crystallize it. Yet this system was not acceptable due to following flaws:

- Manufacturing of such cooling pads with coils is a tedious work which would add to the initial cost.
- Moreover with this system a question arises, if the phase change material has the ability to switch phase continuously while heating and cooling simultaneously.

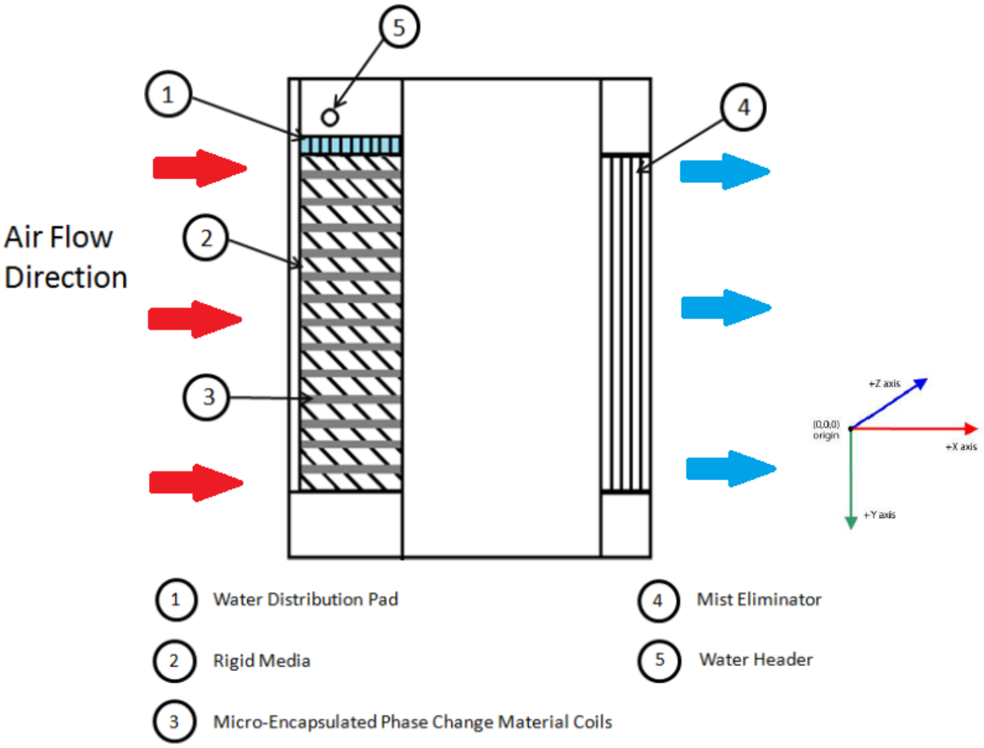

Figure 5.1: Evaporative Cooling Pad with mPCM coils arranged in X axis

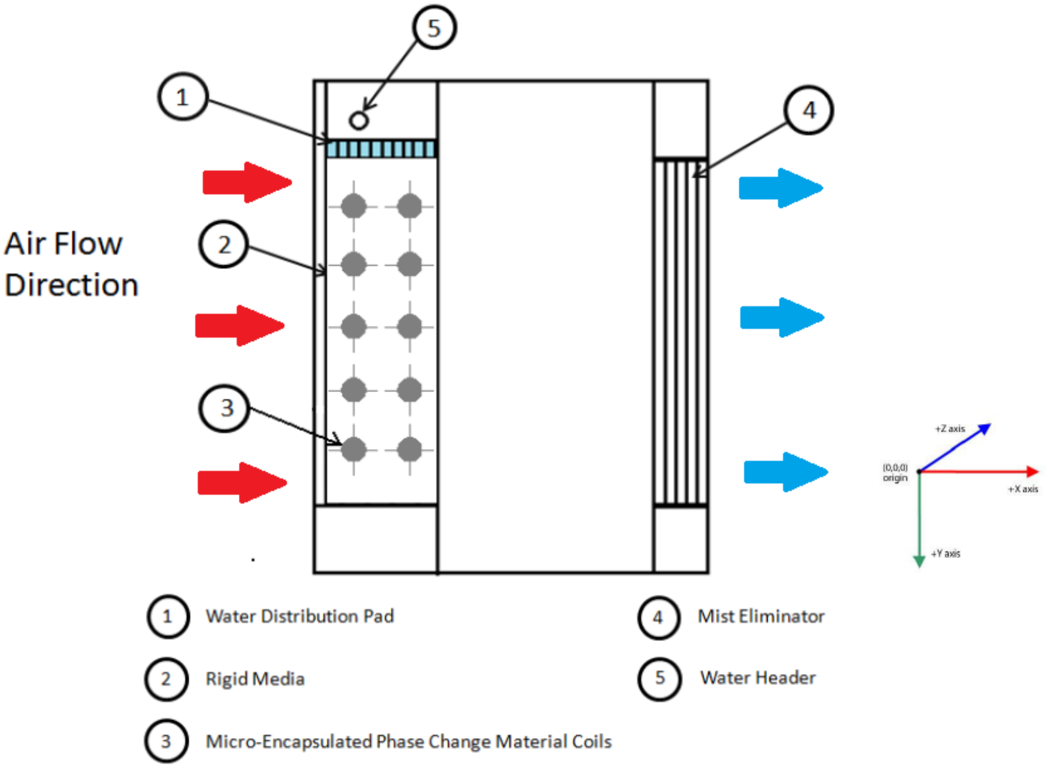

Figure 5.2: Evaporative Cooling Pad with mPCM coils arranged in Z axis

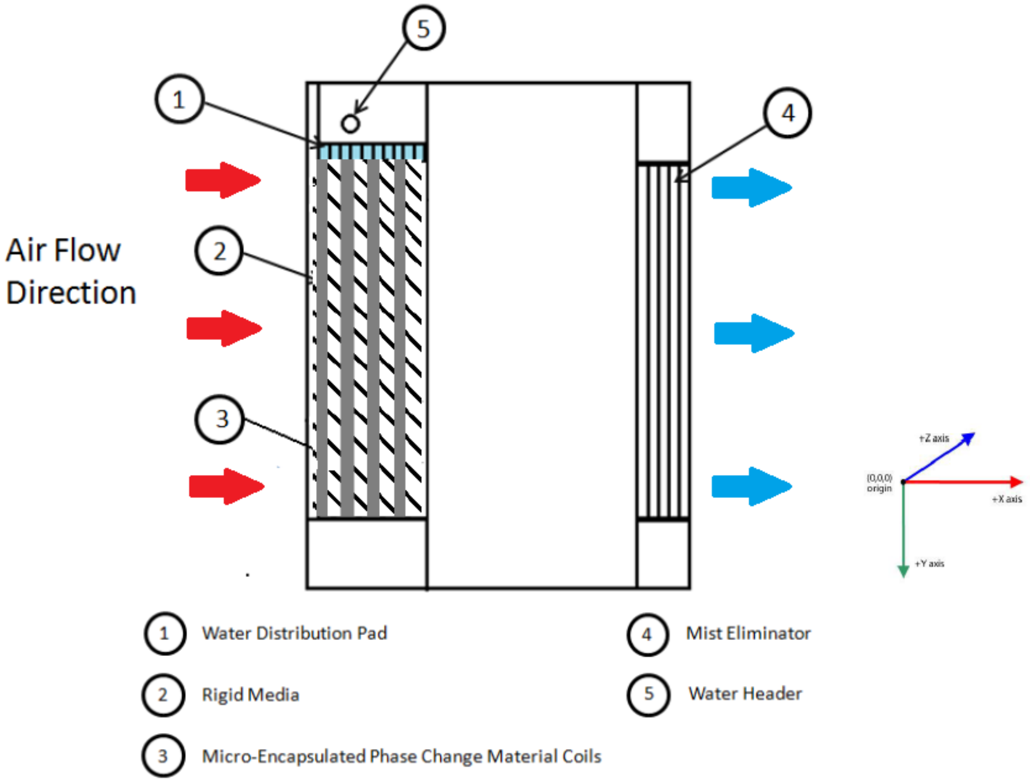

Figure 5.3: Evaporative Cooling Pad with mPCM coils arranged in Y axis

5.2.2 Experimental Test-Rig Considerations for Hybrid Evaporative Cooler

An evaporative cooler test rig was made from iron material with a plexi glass on the top as covering shown in Figure 5.4. The system was built to accomplish two major tasks:

- To obtain the cooling capacity of microencapsulated phase change material for the air coming through the cooling media.
- To find experimentally, the time taken for a certain amount of mPCM material to melt giving an unknown delta T.

In addition to these, pressure drop across the mPCM containing coils is also an important aspect of this experiment. Figure 5.5 shows cut-view of the rig. The experiment shall be conducted with same boundary conditions with and without microencapsulated PCM in the test rig.

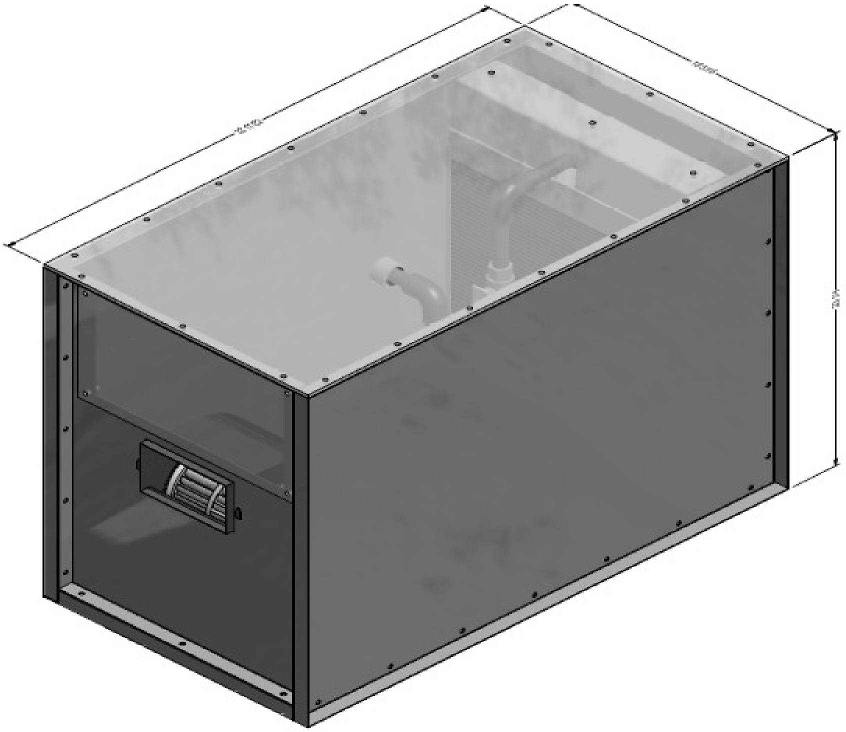

Figure 5.4 Outer View of Experimental Test-Rig

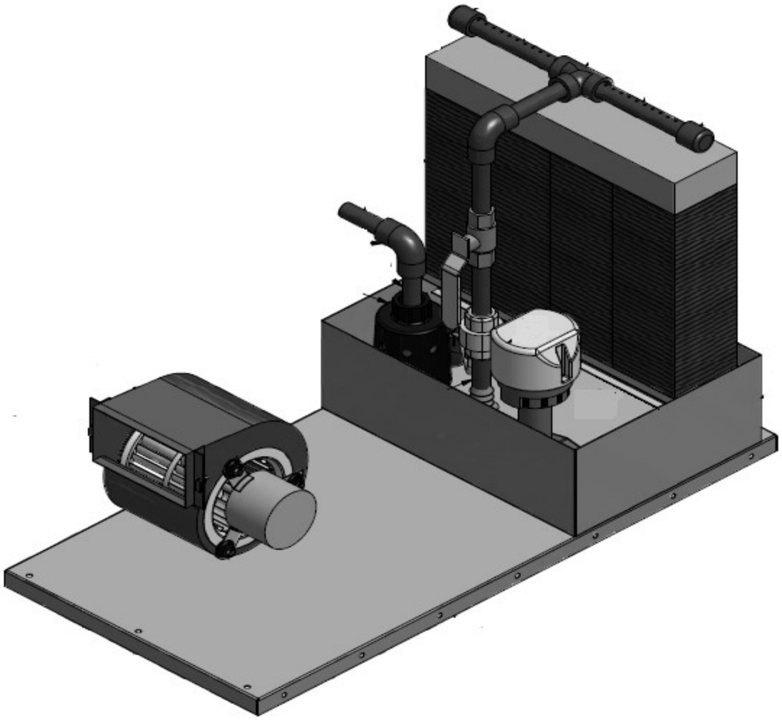

Figure 5.5: Cut-View of the Experimental Test-Rig

A close and specific approach was taken for designing and building of the experimental test rig. Following are the considerations that were taken care of while building the rig:

5.2.2.1 Panel Walls and Glass Covering

The outer panel was made up of iron material with length 33-11/32 inches, width 18-5/16 inches and height 23-1/4 inches. A ¼ inch plexi-glass top was used to cover the top of the panel as shown in Figure 5.4. Drain sump pan was made of same material.

5.2.2.2 Selection of Cooling Technology and Cooling Media

There are mainly two types cooling technology used in direct evaporative cooling: wet media cooling and spray cooling. Wet pad cooling was selected for this experiment as it has a higher evaporation rate when compared to spray cooling as shown in Figure 5.6.

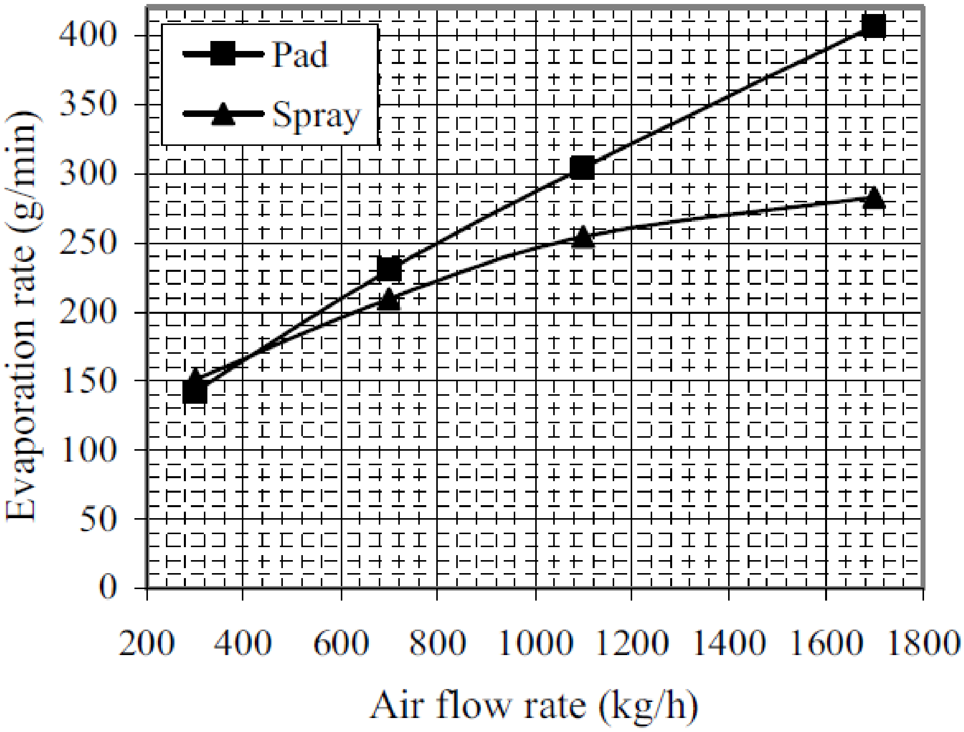

Figure 5.6: Evaporation Rate: Wet Pad Cooling vs. Spray Cooling [32]

There are many factors that affect selection of wet cooling pads are: pad material, form factor: pad thickness and flute angle, evaporative efficiency, pressure drop across cooling pads, life of cooling pad, cost and water availability. A cellulose cooling pad of height 12 inch, thickness 4 inch and width 16 inch was selected as cellulose has high cooling capacity, lesser pressure drop and is readily available.

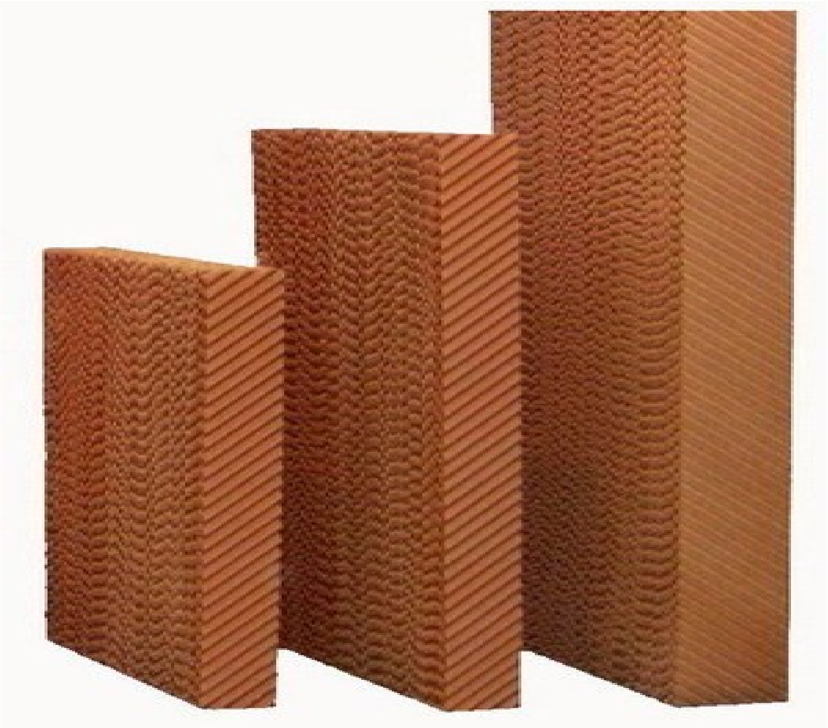

Figure 5.7: Cellulose Wet Cooling Pad [33]

5.2.2.3 Selection of Phase Change Material and Coils containing mPCM

Figure 5.8: Micronal Powdered mPCM [34]

Selection of phase change materials varies on many factors like desired melting temperature, high specific heat, high thermal conductivity, high latent heat of fusion, high density etc.

Micronal DS 5008 X was selected for as appropriate mPCM for this experiment. It consists of microscopically small polymer beads which contain a core of high purity paraffinic waxes. One of the benefits of using it is that it is pre-tested under varying thermal loads. It is very much suitable for active cooling systems as it does not have abrupt temperature rise [34]. Table 5.1 shows some properties of Micronal DS 5008 X.

Table 5.1: Properties of Micronal DS 5008 X [34]

Product Form	Powder
Particle Size	0.1 – 0.3 mm
Approximate Melting Temperature	23°C
Approximate Solidification Temperature	19°C
Overall Heat Capacity	135 kJ/kg
Latent Heat Capacity	100 kJ/kg
Apparent Density	250 – 350 kg / m^3

Copper tubes of 5/8” inner diameter and 12” length were used to contain mPCM material. Each coil had aluminum fins of size 2” x 1.5” mounted on it to enhance heat transfer and air flow over the coils. Fins were mounted at a rate of 11 fins per inch. A total of twenty four such coils with fins mounted on a base plate (eight in each row and three such rows) were used for testing. 18.4 gram of microencapsulated phase change material was

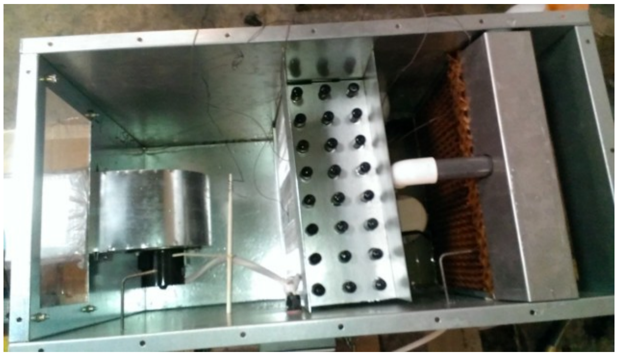

Figure 5.9: Placement of mPCM Coils in Evaporative Cooler

filled in each tube keeping 10 percent of the volume space empty for thermal expansion of mPCM. Hence a total of 441.6 gram of mPCM was used for testing.

Figure 5.10: Coils with Fins

5.2.2.4 Sump Pump and Blower Panel

Generally water sump pumps are used in evaporative coolers. A Little Giant CP3-115 evaporative cooler pump was selected for this experiment, specifications of which are given in Table 5.2.

Table 5.2: Specifications of Evaporative Cooling Pump [35]

Type	Evaporative Cooler
Body Material	Polystyrene
GPM of Water @ 1 Ft. of Head	9.3
Motor Type	Shaded Pole
Width	4-1/4 inches
Length	4-1/4 inches
Height	9 inches
RPM	3000
Voltage	115
CFM	15,000-21,000
Max. Temp	120 F

Figure 5.11 Evaporative Cooling Pump

Revcor 2-2651 blower fan having specifications: clockwise rotation, 0.3125” bore, disc centered between the wheel ends, aluminum construction with plated steel hub, single plane balance was used in the test rig.

5.2.2.5 Temperature and Pressure Measurement

As a thermocouple measures in wide temperature ranges, selection of type of thermocouple may become a difficult task. Some of the criteria used in selecting a thermocouple are temperature range, chemical resistance of the thermocouple or sheath material, abrasion and vibration resistance, installation requirements etc [36]. Omega type T thermocouples were used in this experiment specifications of which are listed below:

Table 5.3: Technical Specifications of Omega Type T Thermocouples [36]

Type	Omega Type T
Material	Copper-Constantan
Temperature range	-250°C-350°C
Limits of Error	1.0°C or 0.75%

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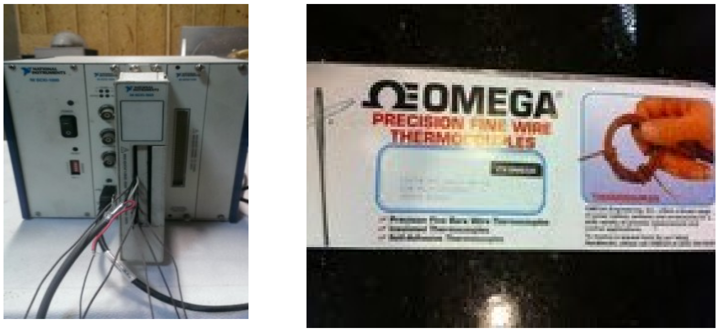

Figure 5.12: Data Logger & Thermocouples Used In Experiment

In all six thermocouples were installed; one each in center coil containing mPCM in every row, one each on upstream and downstream of cooling media and one downstream of the mPCM coils. Thermocouples placed in mPCM coils would enable us to observe the heat transfer across each row. National Instruments NI SCKI 1000 data logger was used to collect data from these thermocouples

Static pressure tips with manometer as shown in Figure 5.13 were used to measure differential pressure drop.

Figure 5.13 Manometer

5.3: Results, Conclusion and Future Work

5.3.1 Results and Discussion

As shown in Figure 5.9, mPCM containing copper coils were placed on the downstream side of cooling pad. The volume of air coming in the system was set at 350 cubic feet per minute. The relative humidity of ambient air was measured to be 43.4%. Initially, dry bulb temperature and wet bulb temperatures of ambient air were measured to be 89.3^{0}F and 69.7^{0}F respectively.

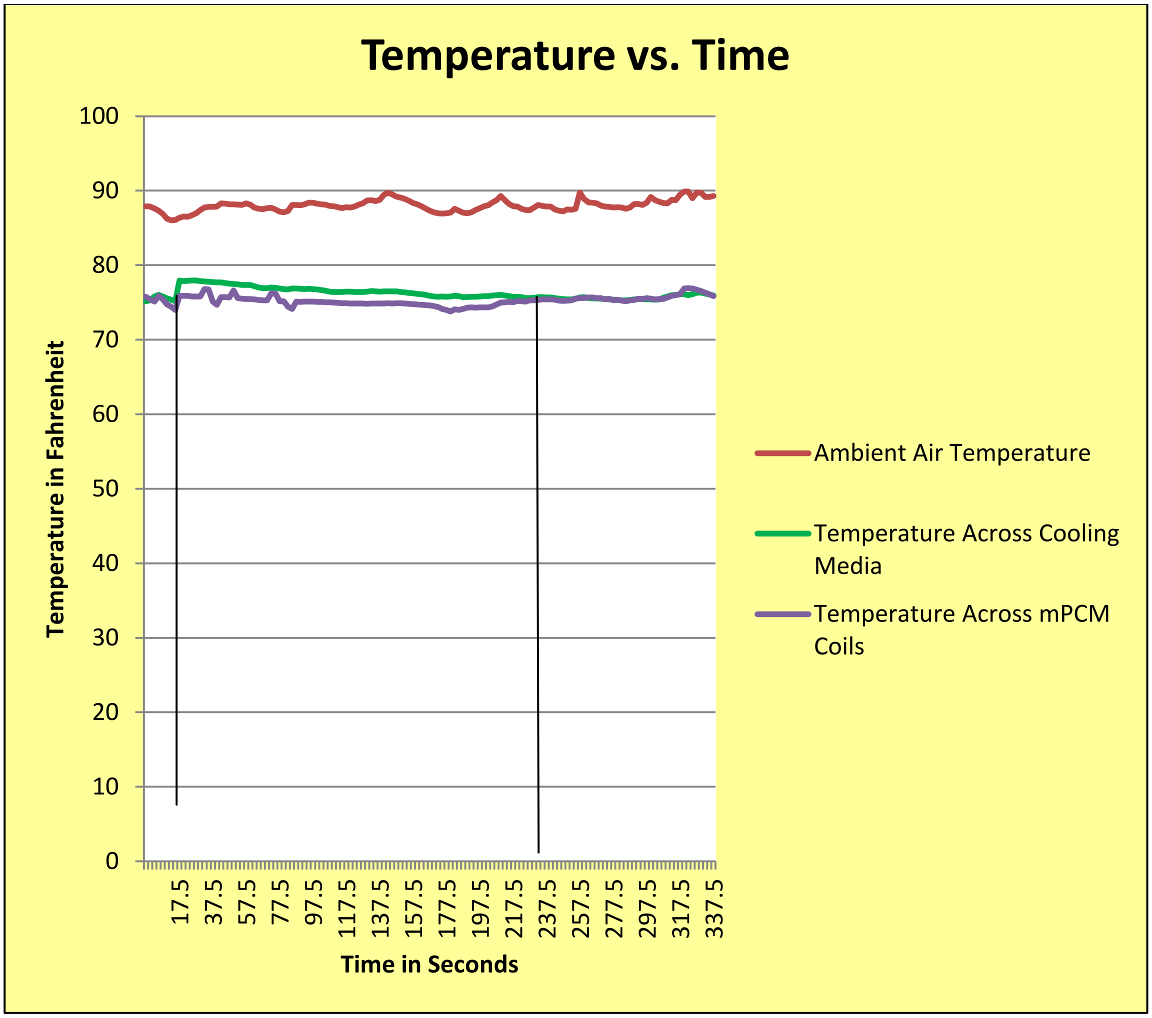

Figure 5.14: Temperature vs. Time Graph for Evaporative Cooler with mPCM Coils

Figure 5.14 shows the ambient temperature, temperature across cooling pad and temperature across mPCM coils with respect to time. The two vertical lines indicate the starting and ending points of cooling due to mPCM coils. It can be seen that initially the cooling effect due to mPCM coils took some time and the rise was abrupt. But the cooling effect gradually decreased with respect to time.

Figure 5.15 shows the temperature drop across cooling pad compared to temperature drop across mPCM coils. It is seen that an average temperature drop of 1.5^{0}F was achieved. The temperature drop line is very unstable at the beginning but it becomes stable after sometime confirming to the result discussed above. The gradual decrease in cooling indicates the melting of mPCM and the null cooling effect indicates that all the mPCM in the system has melted.

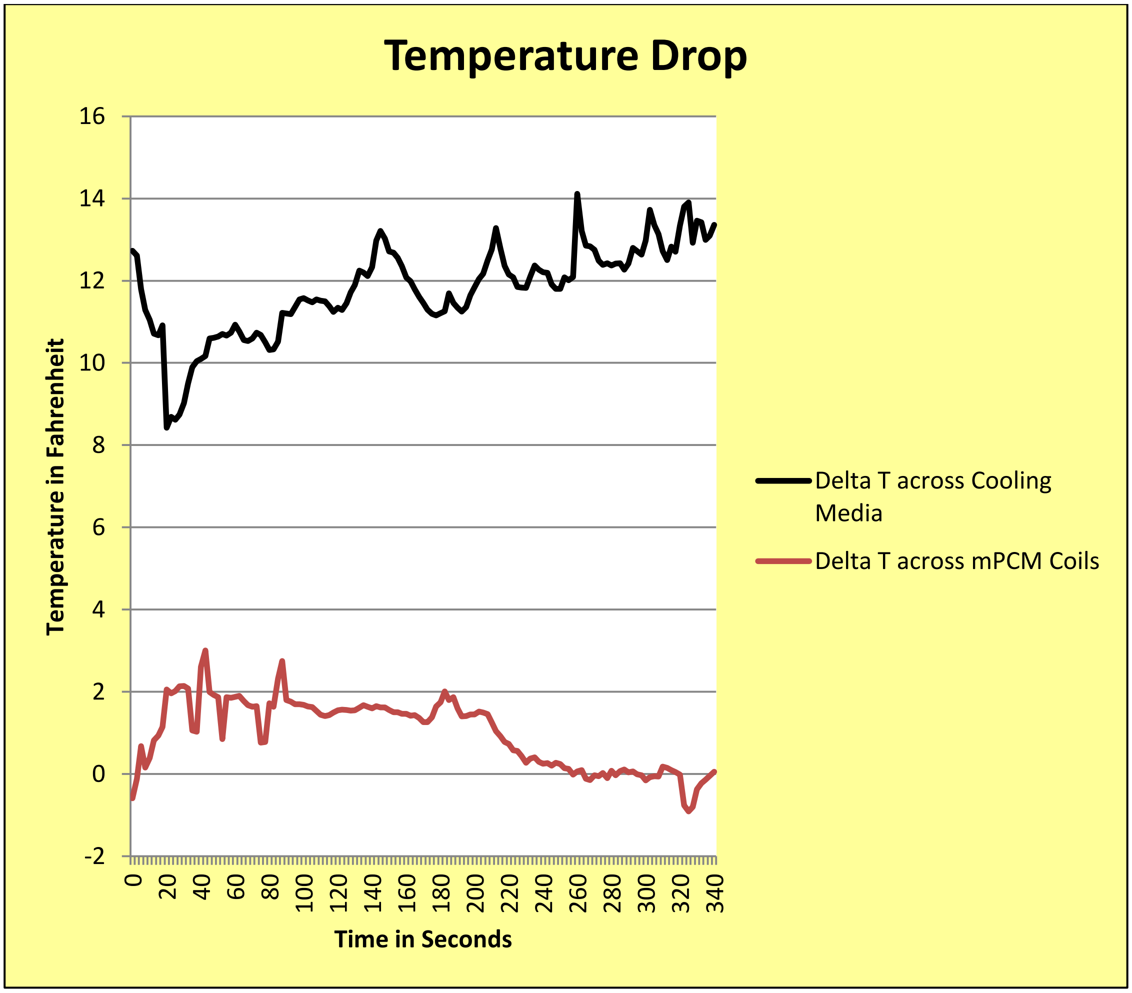

Figure 5.15: Comparison of Temperature Drop across Cooling Pad and mPCM Coils

Figure 5.16 shows the heat transfer across mPCM coils. It is observed from the figure that heat transfer across the first row i.e. the row facing cooling media was a bit higher when compared to other two rows. The reason for this is that it directly faces the air blown from the cooling media while the other two rows get heat transfer once the heat has passed the first row of coils.

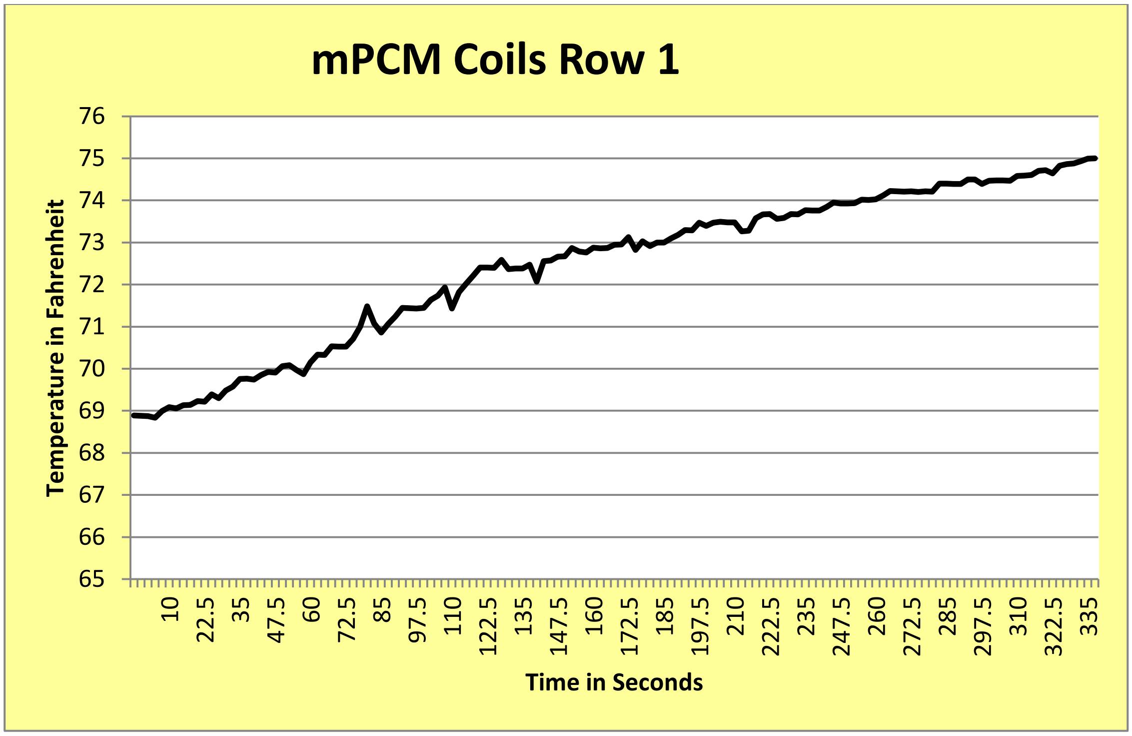

Figure 5.16(a): Heat Transfer in Row 1

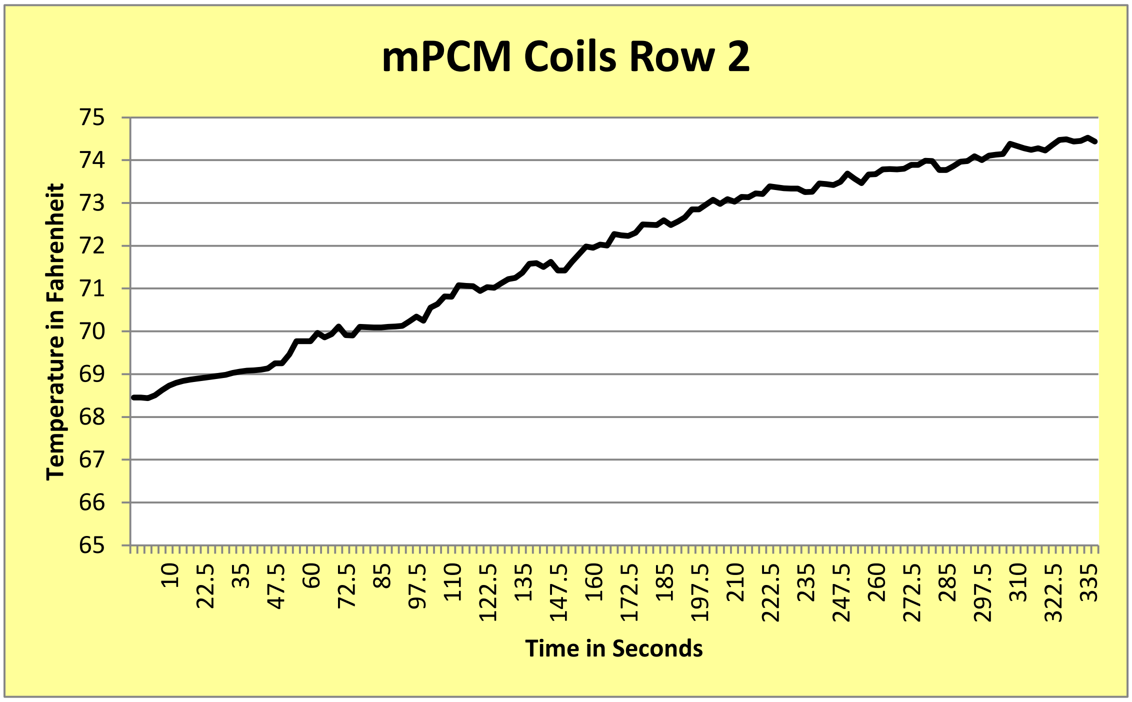

Figure 5.16(b): Heat Transfer in Row 2

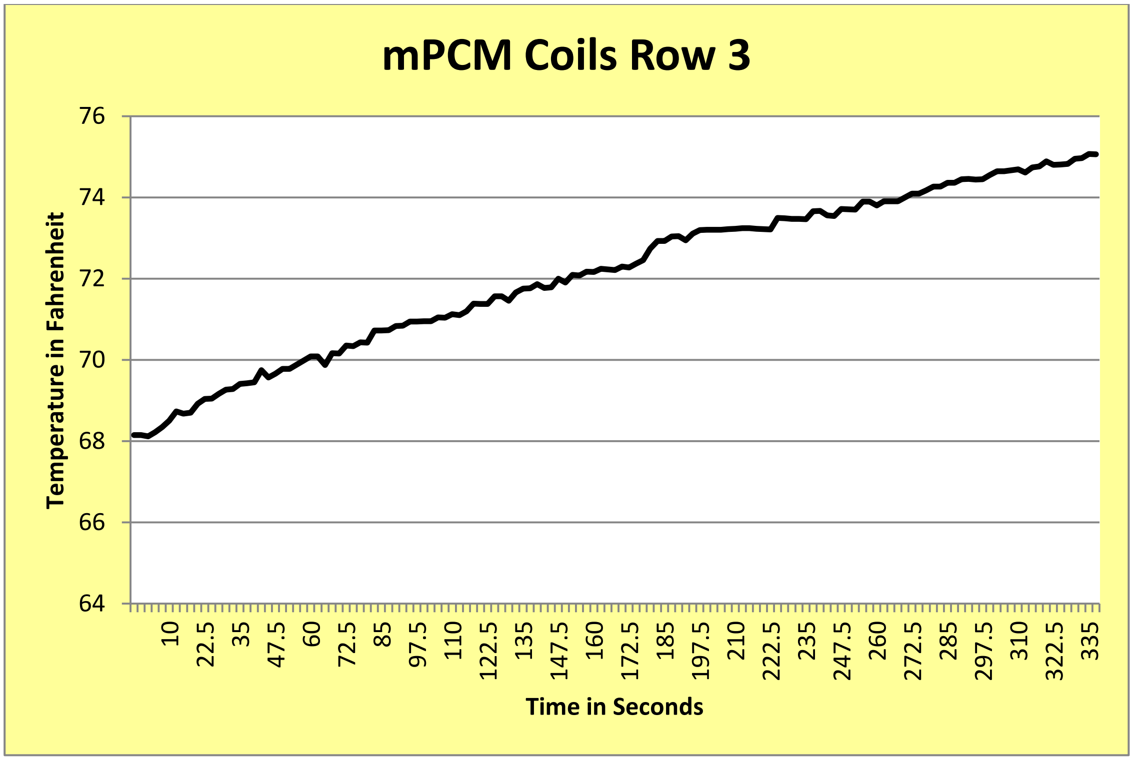

Figure 5.16(c): Heat Transfer in Row 3

5.3.2 Conclusion

It is concluded that mPCM coils in evaporative systems can decrease the temperature of air coming from cooling media without increasing its humidity any further. A small temperature drop was found for approximately four minutes by adding mPCM coils to the evaporative cooling rig. The temperature increase was swift in the mPCM coils facing the cooling pads when compared with other coils. Pressure drop across cooling pad was 0.05 inches of water (12.44 Pascal) whereas pressure drop across mPCM coils was 0.06 inches of water (14.93 Pascal) which are almost equal. Hence it can be it can be concluded that the pressure drop got doubled when mPCM coils were added to the system. A larger temperature drop could be achieved by adding more amount of mPCM to the system. Cooling period of mPCM can be increased by adding a cooling circuit to cool mPCM in the system. However, pressure drop would be an aspect to think of while designing cooling circuit

5.3.3 Future Work

MPCM shall be used in dispersion form instead of powder form as dispersion form provides a greater heat transfer surface area than powder form. Dual wall pipe coils are proposed to be used to serve the purpose of cooling circuit for mPCM.

Figure 5.17: Double Wall Pipes [37]

The outer tubes would be filled with mPCM and water shall be used as coolant in inner tubes. Water shall be flown through these pipes at regular intervals. Research has shown that cooling pad continues to cool at same efficiency even if water is not distributed over it for certain time. This water shall be used for mPCM cooling tubes by inserting a stop valve in the water distribution circuit. Hence, a higher cooling efficiency would be achieved without increasing pumping cost and water usage of evaporative cooling system.

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BIOGRAPHICAL INFORMATION

Jeet Shah received his Bachelor's Degree in Mechanical Engineering from Hemchandracharya North Gujarat University, Patan, India in June 2011. He completed his Master of Science degree in Mechanical Engineering at the University of Texas at Arlington in May 2013. He has received scholarships during his under graduation and graduation.

He has been involved in a number of projects in Electronics, MEMS and Nanoelectronics Systems Packaging Center at The University of Texas at Arlington, USA. His research areas include using microencapsulated phase change materials and slurry for active cooling applications. He has worked on industry projects for Mestex, A Division of Mestek, Inc. during his research at the UTA.

Jeet also worked as a Manufacturing Engineer Intern FILL PACK PHARMA MACHINERIES in 2010. He is an Auto CAD 2011 Certified Associate and has knowledge of Pro E and ANSYS. He has also worked with scanning electron microscope and sputter coating machines. He is associated with American Society of Mechanical Engineers (ASME) and Institute of Electrical and Electronics Engineers (IEEE)