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PHASE CHANGE MATERIAL BASED PASSIVE COOLING SYSTEMS DESIGN PRINCIPAL AND GLOBAL APPLICATION EXAMPLES

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ABSTRACT

Thermal Energy Storage (TES) technologies may be considered as a useful tool in reducing the cooling load requirement of modern engineering systems. This is achieved by means of spreading the day time work loads over an entire 24 hour period, in order to utilise the earths naturally occurring ambient temperature differences.

*The night-time cooler ambient can be used to charge the latent heat capacity of various " Positive Temperature Eutectic" solutions between **+4 °C** and **+117 °C** without the use of any refrigeration machinery by simply allowing the surrounding air to freeze these solutions. It is then possible later for the stored energy by the Positive Eutectic Thermal Energy Storage "PETES", to be released back to the occupied space during daytime to handle the heat gains.*

This technique is generally called Passive Cooling and it may enable the charging process to take place by means of free cooling, i.e. without running the chillers and as a result becomes a very economical and environmentally friendly system. Furthermore, PETES opens new opportunities to explore heat balance for the existing and new systems, which could offer significant overall system efficiency improvements.

Privatisation has created a new kind of energy market whereby the period of energy usage and the type of energy used is becoming the main criteria for price structuring rather than overall energy consumption. Hence, cooling systems must be designed to provide sufficient flexibility for load shifting and a PETES Thermal Energy Storage technique can be considered as a useful tool to achieve this aim.

This paper is extended to investigate the Passive Cooling TES systems in the form if Eutectic PlusICE Solutions. The results of performance tests for various temperature ranges as well as the practical application guidance are also incorporated as part of this paper.

KEYWORDS: *Phase Change Material, PCM, Passive Cooling, Free Cooling*

1.0 - BACKGROUND

Energy usage, economical and environmental issues are becoming the focal points for both end-users and the public at large. Current trends towards privatisation and an open market approach for utility companies has created a new kind of energy market whereby the period of energy usage and the type of energy used is becoming the main criteria for price structuring (1) rather than overall energy consumption.

Hence, current building services must be designed to provide sufficient flexibility for load shifting and energy usage control in order to achieve the most economical operation. A Thermal Energy Storage technique whereby **" Storing High or Low Temperature energy for later use in order to bridge the time gap between energy availability and energy use "** can be considered as a useful tool to achieve this aim.

Unfortunately **HVAC & Refrigeration TES** applications utilise water ice which can only be produced with low temperature chillers. As a result, the benefits of night-time low ambient temperature, existing water chillers and possibly free ambient cooling options cannot be fully utilised. If we can offer designers ICE which freezes and melts above 0 °C, this product will open new horizons for environmentally friendly and economical systems for both New and Retrofit type process cooling / heating load shifting applications.

This paper investigates Positive Temperature Eutectic Solutions for long term TES usage to achieve the above aim. Relevant application guidance along with typical application examples are also incorporated within this paper.

2.0 - THERMAL ENERGY STORAGE:

Thermal Energy Storage bridges the time gap between energy requirement and energy use. A thermal storage application may involve a 24-hour or alternatively a weekly or seasonal storage cycle depending on the system design requirements. Whilst the output is always thermal, the input energy may be either thermal or electrical.

In full storage systems, the entire design load for the design day is generated off peak and stored for use during the following peak period. In partial storage systems, only a portion of the daily load is generated during the previous off peak period and put into storage. During the peak period, the load is satisfied by a simultaneous balancing operation of the installed machinery and stored energy in order to satisfy the overall daily design duty.

2.1 - Storage Medium:

For HVAC and refrigeration application purposes, water and phase change materials (PCM) constitute the principal storage media. Water has the advantage of universal availability, low cost and transport ability through other system components.
However, a conventional water based TES system for air conditioning applications require low temperature chillers and therefore standard water chillers must be replaced with low temperature glycol chillers which operate at lower evaporation temperatures (2).

2.2 Current Ice Production Technology :

Ice production techniques can be divided into two main groups namely ***Dynamic*** and ***Static*** systems (3) as shown in Table 2.2.1. The ice produced can be used either ***directly*** to chill products such as fish, vegetables, meat, poultry etc. or ***indirectly*** as a secondary coolant for a latent heat cooling effect for process cooling such as ice storage, TES systems for air conditioning and process cooling as a secondary cooling medium.

STATIC ICE PRODUCTION	DYNAMIC ICE PRODUCTION
1 - Ice Builders **2 - Ice Banks** **3- Encapsulated Ice Modules** **a) Balls** **b) Flat Containers**	**1 - Plate Harvester** **2 - Tube Harvester** **3 - Flake Ice Machines** **4 - Binary Ice Machines**

Table 2.2.1 - Current Ice Production Technology

3.0 - POSITIVE TEMPERATURE EUTECTIC TES SYSTEMS :

Positive Temperature Eutectic Solutions (PlusICE) are mixtures of two or more chemicals which, when mixed in a particular ratio, have a freezing / melting point above water freezing temperature of 0°C and they offer a thermal energy storage facility between **+4 °C** and **+117 °C**.

Although the term "Eutectic" is widely used to describe the materials we are interested in, a better description would be "Phase Change Materials" ("PCMs"). Unfortunately, very few of the documented PCMs (a number of which are listed in Table 3.1) [5] are true Eutectics and so many have to be modified to obtain a material suitable for long term use.

Material	**Melting Point (°C)**	**Heat of Fusion (kJ/kg)**	**Latent Heat (MJ/m^3)**
$MgCl_2.6H_2O$	117	169	242
$Mg(NO_3)_2.6H_2O$	89	163	252
$CH_3COONa.3H_2O$	58	226	287
$MgCl_2.6H_2O$/ $Mg(NO_3)_2.6H_2O$	58	132	201
$Na_2HPO_4.12H_2O$	34	265	379
$Na_2SO_4.10H_2O$	32	251	335
$Na_2CO_3.10H_2O$	32	233	340
Waxes	28 to 4	220 to 245	170 to 195
Polyethylene glycols	28 to -15	146 to 155	165 to 175
$CaCl_2.6H_2O$	27	191	298
Glauber's salt + additives	24 to 4	wide range	wide range
$CaCl_2.6H_2O$/ $CaBr_2.6H_2O$	15	140	249
Water	0	335	335
Range of water/salt Eutectics	0 to -64	Wider range	wide range

Table 3.1 - Range of commonly used PCMs

Eutectics are well known and in fact early applications date back to the late 18th century. However the separation and the life expectancy of these mixtures were unpredictable and therefore their wide spread usage was limited. The disadvantages of a conventional HVAC chiller and ice (water ice) storage system can be overcome by utilising the latent heat capacity of various "Eutectic" mixtures without the need for minus circulation temperatures. Positive temperature thermal energy storage **"*Plus*ICE"** not only enables the designer to utilise existing chiller technology but also enables charging by means of free cooling [4], i.e. without running the chillers

PCMs can be broadly grouped into two categories; ***"Organic Compounds"*** (such as polyethylene glycol) and ***"Salt-based Products"*** (such as Glauber's salt). Each group of PCMs comes with advantages and disadvantages some of which are listed in Table 3.2 [4].

	Advantages	**Disadvantages**
ORGANIC	Simple to use Non-corrosive No supercooling No nucleating agent	Generally more expensive Lower latent heat/density Often give quite broad melting range Can be combustible
SALT-BASED	Generally cheap Good latent heat/density Well defined phase change temperature Non-flammable	Need careful preparation Need additives to stabilise for long term use Prone to supercooling Can be corrosive to some metals

Table 3.2 - Characteristics of PCMs

4.0 - PlusICE APPLICATIONS ;

Positive Temperature Eutectic Solutions (PlusICE) between **+4 °C** and **+117 °C** can be charged using free cooling or conventional water chillers and therefore offers many cost effective energy management concepts for both New and Retrofit type process cooling / heating load shifting applications [6]. The purpose of this paper is to look into the passive cooling options in more detail and to this end a number of applications are investigated in details.

4.1.- Office Air Conditioning;

A small scale 10.8 m2 (27 m3) standard UK office complete with all the conventional internal heat gain is selected near Nottingham, UK and this office is fitted with Passive Cooling heat pipe beams as illustrated in Figure 4.1.1 filled with 21 °C PCM Eutectic solutions. The relevant freezing and melting curves for this specific PCM solution is shown in Figure 4.1.2.

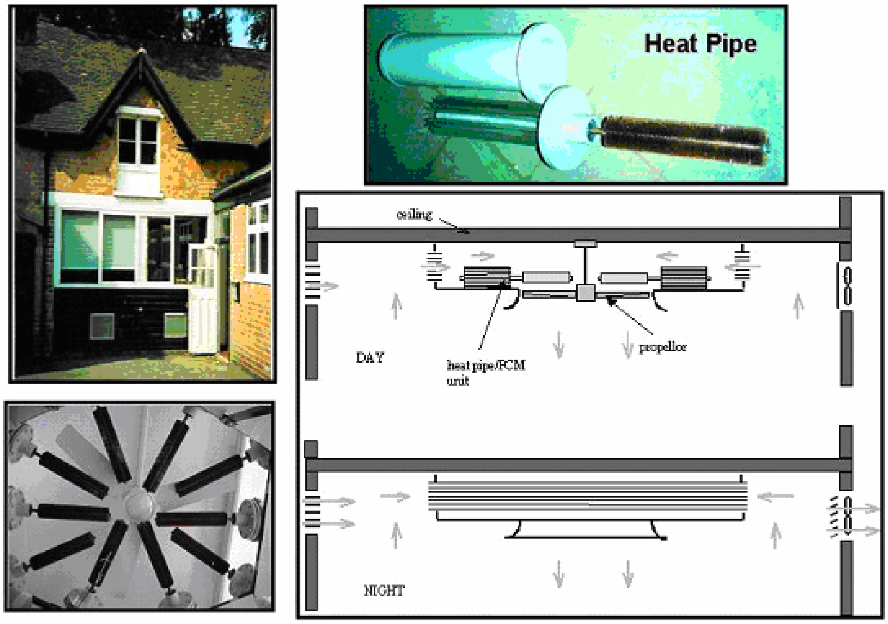


Figure 4.1.1- Test Office Passive Cooling Heat Pipe Design

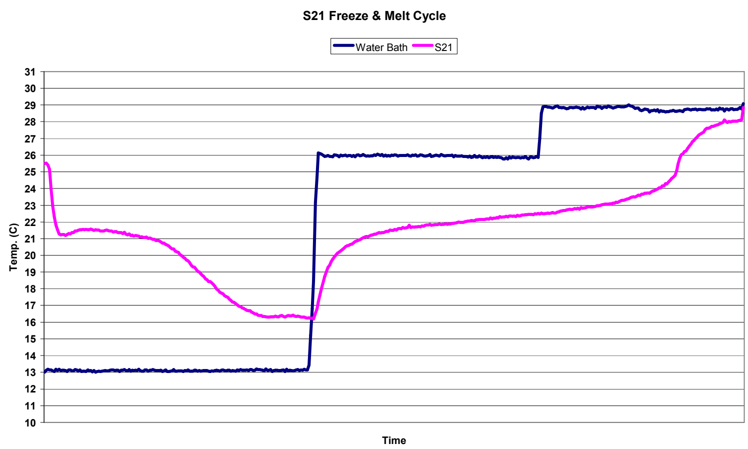


Figure 4.1.2- 21C PCM Freezing and Melting Curve

This test site at Nottingham, UK operated for a whole year with full data logging and a typical peak daily operational data recorded as illustrated in Figure 4.1.3. The recorded data proved that the system coped well with the average office internal gains throughout the year without running a single refrigeration machinery by simple utilising colder night-time air to charge these beams and release back the stored energy during peak day periods.

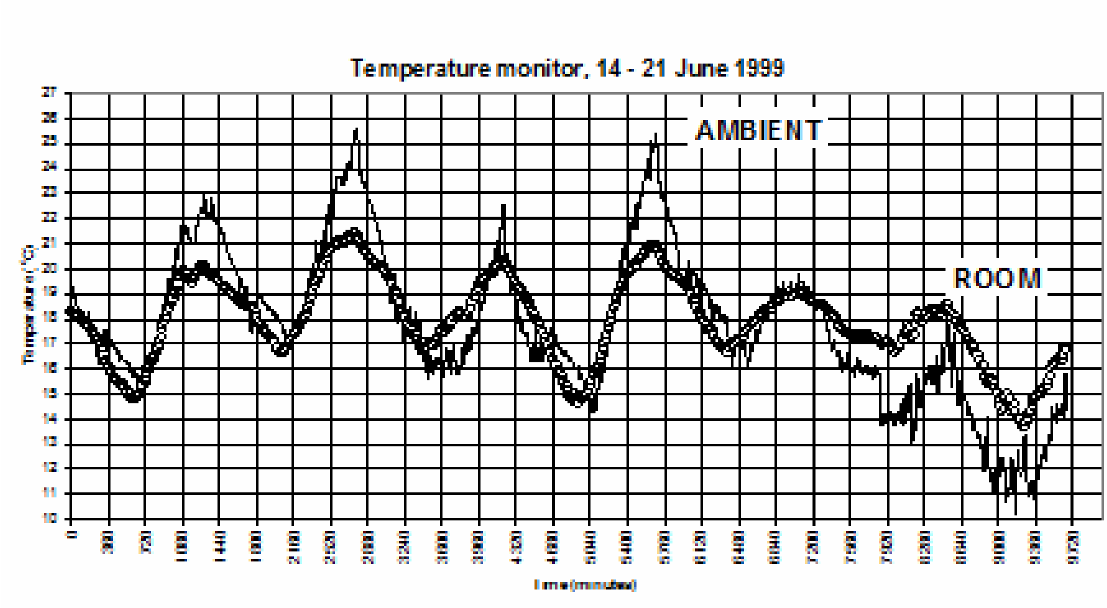


Figure 4.1.3- Peak Passive Cooling System Daily Operational Data

Another application in Stevenage, UK phase change material is permanently sealed inside an Aluminium profile beam which enables the heat transfer via natural convention as illustrated in Figure 4.1.4. This office area is partially cooled during the summer months by using cool air at night to cool the structure of the building, which is used to reduce the daytime temperature.

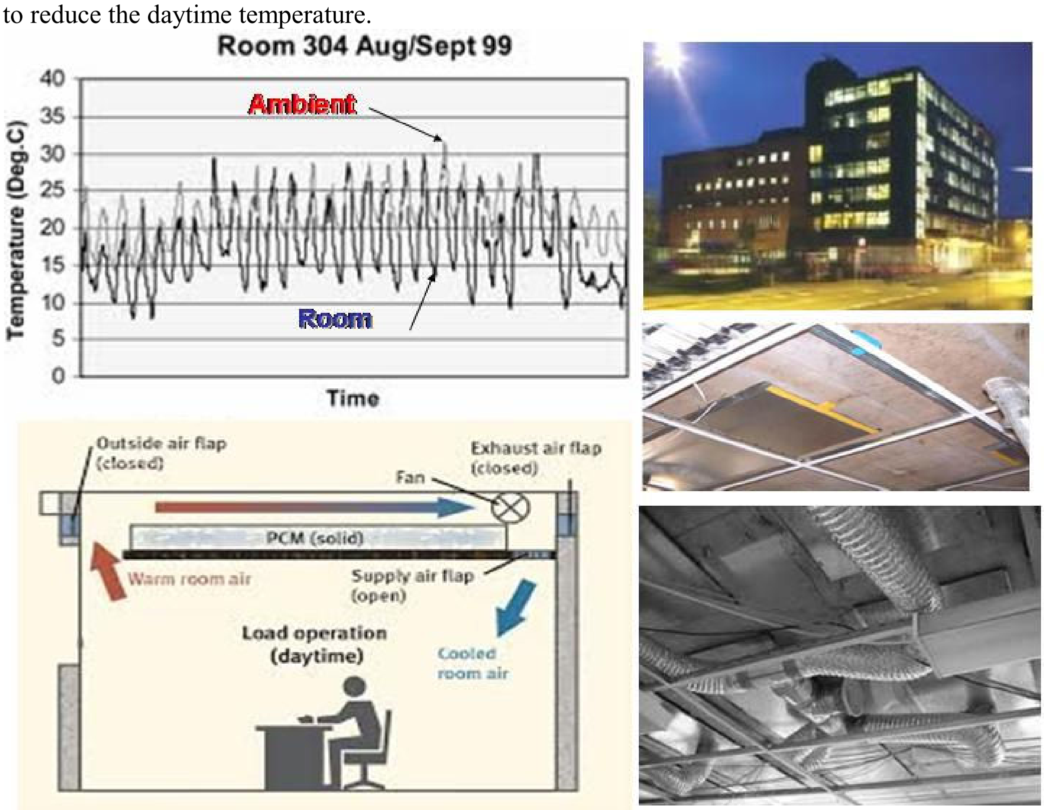


Figure 4.1.4- Daneshill House, Stevenage, UK passive cooling application

The cooling capacity of the structure has been enhanced with the innovative use of a Passive Cooling Cell filled with 'Phase Change Material' which changes state at a predetermined temperature, is fitted to 48 steel plates which are positioned close to the concrete slab in the ceiling void.

Air from the room is delivered via ceiling fans and flexible ducting to the centre of the plates and discharges back into the room via the ceiling void. The operating cycle of the system is arranged to bring cool air from the east side of the building during night-time and discharge warm air to the west elevation. Later ceiling fans operate at high speed to cool the structure and PCM panels.

These cells are manufactured using pouches in a multiple cell arrangement with varying length to suit the site, operating temperature and space dimensional requirements. However, it is reported that pouches are very delicate to handle and easily damaged on site.

The latest product addition to the passive cooling concept is the PCM filled tubes as illustrated in Figure 4.1.5.

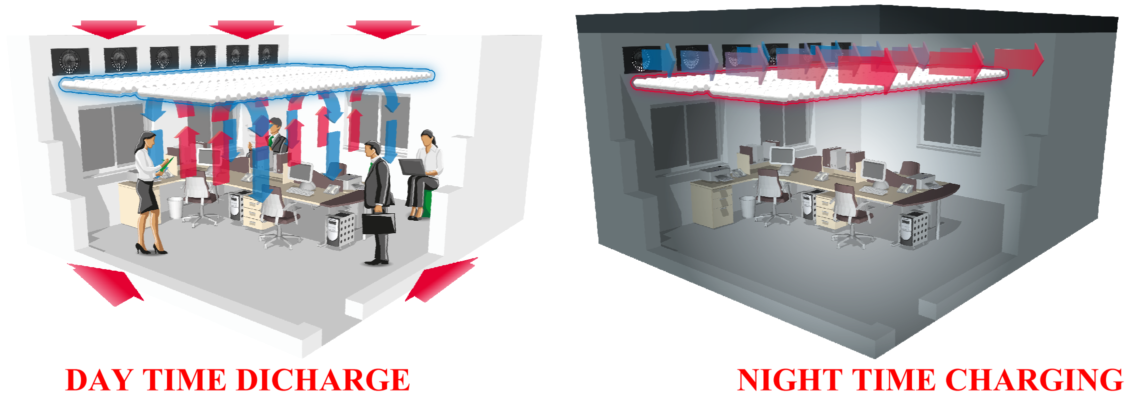


Figure 4.1.5- Passive Cooling Office Application

When the surrounding air temperature is less than the PCM solution generally during night tubes freeze naturally by the cooler night ambient and later this stored energy in the form of latent heat can be released back to the system during day-time to absorb the internal heat gains.

As the heat tends to rise and using the temperature strafication within the room rising heat melts the tubes and cooler air drops back to occupied space and the PCM filled tubes acts like a heat sponge and soak up the heat during day time.

As long as sufficient number of tubes are placed facing the room to match the daily heat gains and if the rising heat does not build up and increase the temperature stratification layer temperature, the comfort zone (~1.5m levels) within the room remains well below the upper comfort level limits and as such a PCM based passive cooling system may offer an energy free cooling solution.

Some of the typical application examples are illustrated in Figure 4.1.6 for class room and school communal areas such as lecture theatre and halls and Figure 4.1.7 for commercial applications.

Figure 4.1.6- PCM based passive cooing for school applications

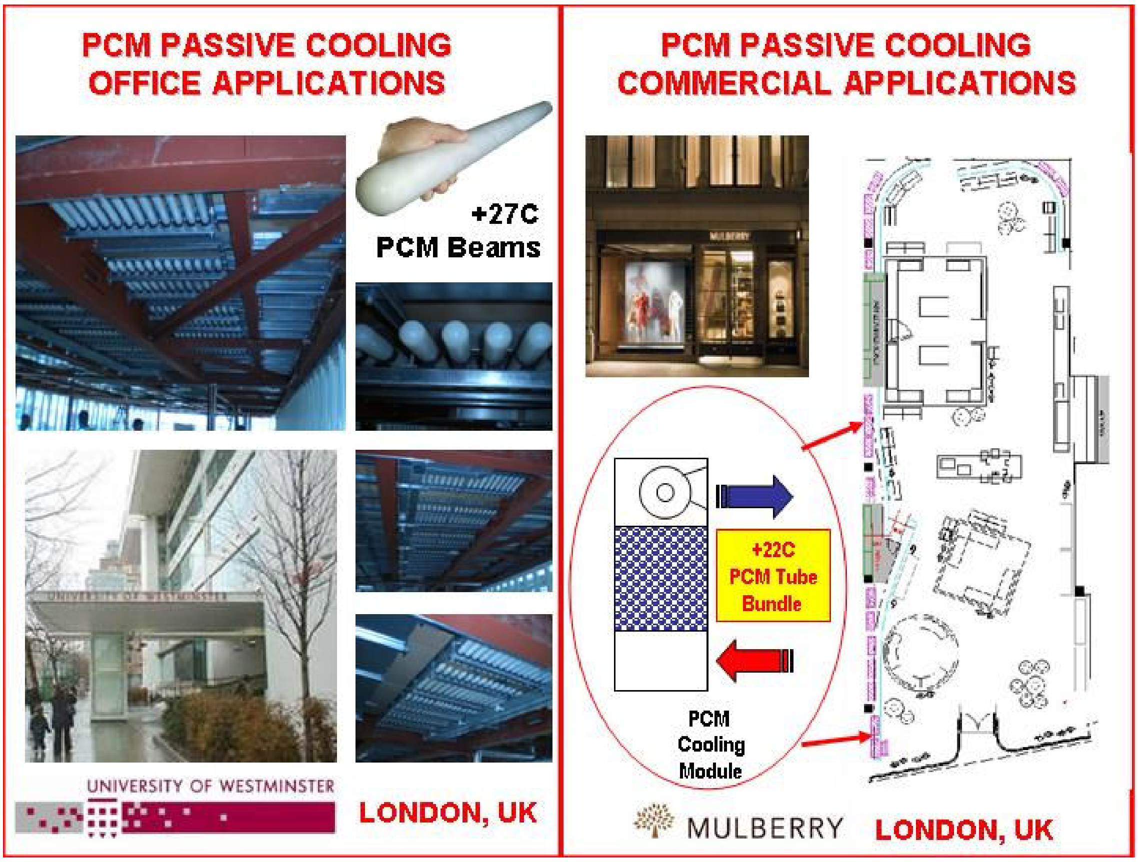
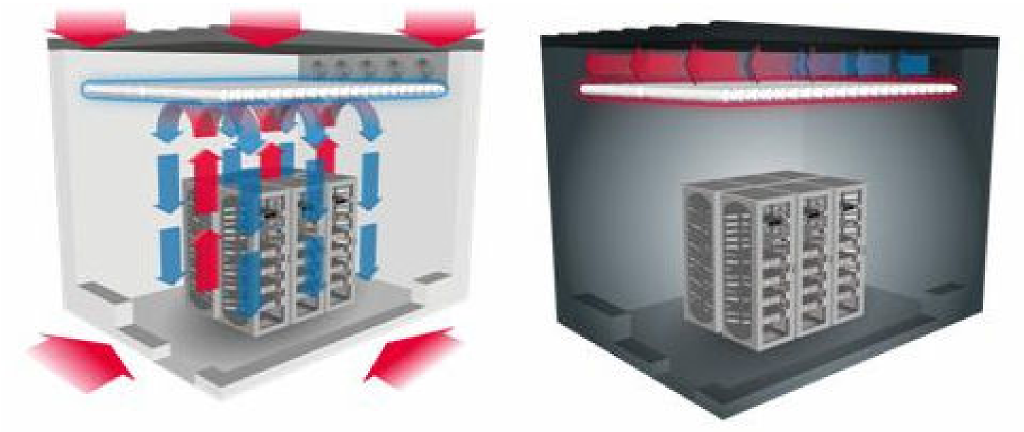


Figure 4.1.7- PCM based passive cooing for commercial applications

4.2- Industrial Applications

Although passive cooling applications are restricted in moderate climate conditions but passive PCM cooling benefits can also be applied anywhere in the World for non-office (i.e. unoccupied) areas to cool the electronic chambers as they could tolerate space temperatures as high as 45 ºC (115 ºF) and as the night ambient temperatures over night time remains less than the space temperature, it allows cool night energy to charge the PCM.

This concept is widely applied for electronic chamber cooling for remote location whereby the lack of electricity eliminated the mechanical air conditioning and a typical cooling system as illustrated in Figure 4.2.1.



DAY TIME DICHARGE
NIGHT TIME CHARGING

Figure 4.2.1- Electronic Chamber Passive Cooling Concept

These systems even operate in hot countries and desert environments like the Middle East due to higher space temperature requirements in comparison with Office Cooling. A PCM solution of 32ºC (90 ºF) is sufficient to maintain the room temperature below 45ºC (115ºF) by simply using the temperature swing between day and night time as illustrated in Figure 4.2.2 for shelter passive cooling applications.

Figure 4.2.2- Shelter passive cooling applications.

4.3- Transport & Refrigeration Applications

The same concept has also been successfully applied for cold storage transport applications. The majority of the perishable food must be chilled during transport but the cost of refrigerated truck restricts the use of transport cooling in particular in the third world where the biggest waste occurs. A PCM filled high ceiling beams can be simple charged using standard cold storage can keep the product temperature under control at a very attractive lower cost to install and run. The typical application modules are shown in Figure 4.3.1 for transport passive cooling units.

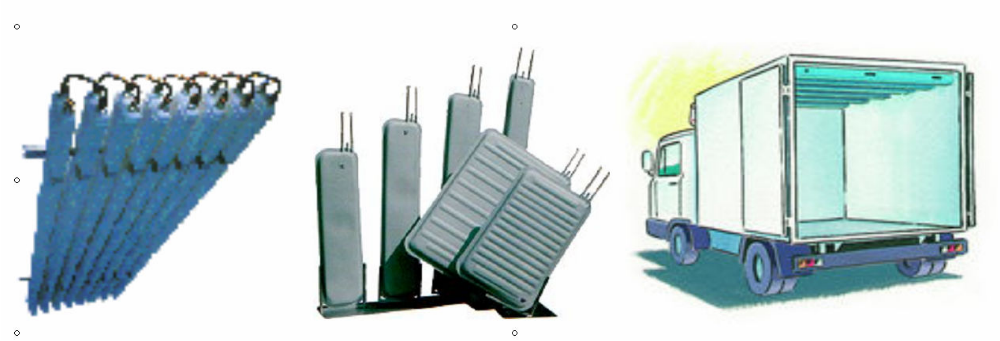


Figure 4.3.1- Transport Passive Cooling Concept

These passive cooling units can be supplemented using a very small refrigeration compressor or a chilled water circuit for lower temperatures but products like chocolate, bakery and flowers can be easily maintained under control by simply charging these beams / containers over-night and utilising the stored energy during day-time transport. Furthermore, this concept enables the owners utilise their standard lorries to be used as refrigerated truck during harvest / peak season at a fraction of the cost for a conventional refrigerated truck.

A PCM based load shifting concept can also be applied to cold stores. By placing the Eutectic products within the cold store, one can create a TES facility whereby the excess refrigeration capacity during off-peak periods and lower ambient conditions over-night can be utilised to shift the peak load. Eutectic TES can either be installed as part of the cold store fabric for example hanging tubes on ceiling/walls or alternatively containers like flat ice packs can be placed on pallets and stored with the as illustrated in Figure 4.3.2.

Figure 4.3.2- Cold storage passive cooling

Although one may over-cool the stored products to create a small load shifting capability but using the Latent Heat Capacity of the Eutectic TES one can increase the thermal energy storage capacity by as much as 10~15 times for a given volume.

As the cooling load significantly varies over daily or weekly periods, Eutectic TES enables the operator to spread the load over a 24 hour period which in return offers the facility of running the refrigeration machinery during lower night-time ambient conditions to charge the Eutectic TES. Later during day-time / peak cooling periods this over-night stored energy can be utilised to top up the refrigeration load without the need for full load mechanical cooling as illustrated in Figure 4.3.3.

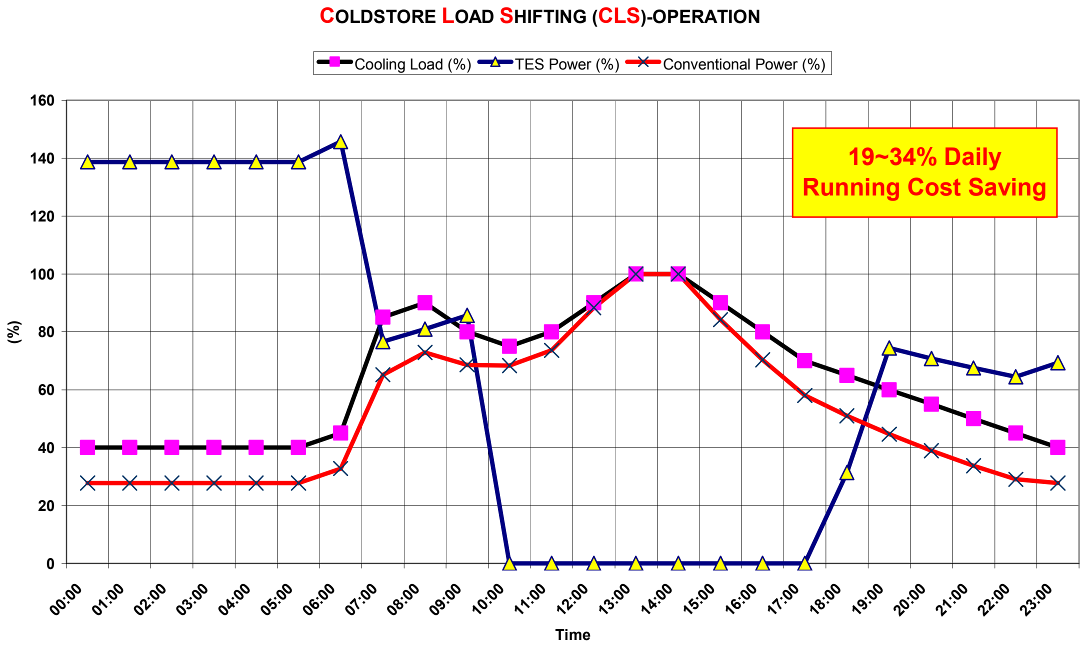


Figure 4.3.3- Cold store load shifting using passive PCM cooling

A Eutectic PCM based TES is a static system i.e. no moving parts offering a full stand-by capability in case of any mechanical failures and offers a maintenance free back-up facility.

This load shifting and storing the energy becomes vital for a solar refrigeration applications whereby the need for cooling when the sun goes down is essential for a successful solar driven cold store application.

Many remote islands and location around the World can utilise the solar energy to drive their refrigeration machines using Photo Voltaic (PV) cells and charge the PCM cells during day time and over night until the day light the stored energy can keep the cold store below its upper limit and protect the products inside the cold room. A typical application example applied in the Far East islands is illustrated in Figure 4.3.4.

Figure 4.3.4-Cold storage passive cooling application

4.4- Comparison with other cooling systems

The office passive cooling concept were compared with those obtained from another example of a passive-cooling devices such as concrete slab which has a high thermal mass and it is cooled by night ventilation, and / or alternatively chilled water is passed through pipes embedded within the slab. According to the manufacturers and published data the performance of the various types of concrete ceiling is as follows:

PRODUCT TYPE	Rate of cooling (W / m^2)
Overnight cooling only (convective)	15
Ground-water cooled slab	30
Passive Cooling PCM Cells	50
Chilled Ceiling	60+

Table 4.4.1: Rates of cooling for different techniques of cooling a concrete slab

Low ambient temperatures coupled with free cooling offer a significant reduction of energy consumption relating to the cooling operation, which is in the region of 16-46 % depending on the type of passive cooling unit and location.

A conventional design must cater for the peak ambient conditions which occur only a few days or weeks of the year [(6)]. Typical UK annual average daily wet and dry bulb temperatures as well as standard design levels are illustrated in Figure 4.4.1. [(7)].

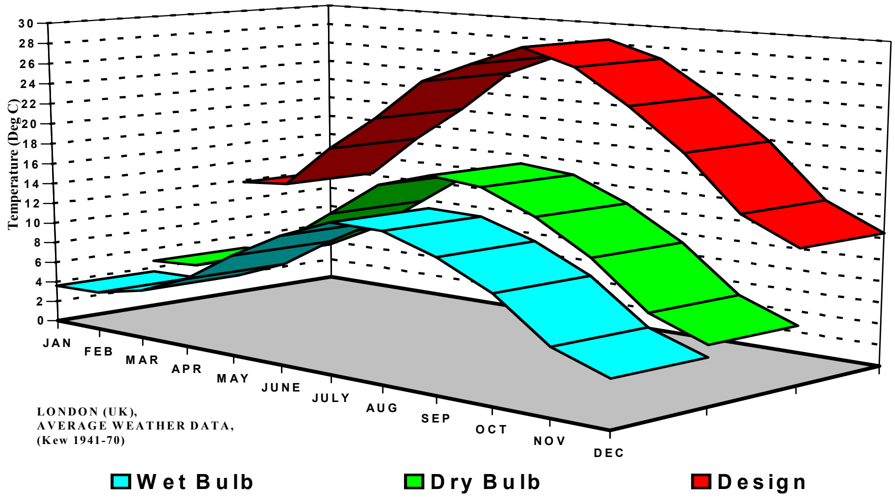


Figure 4.4.1 - Typical UK Annual Average Ambient Profile Vs Design Ambient

Based on the applied projects, ambient profiles in many parts of the world and associated feasibility studies indicates that PCM assisted Passive Cooling concept offers economical and very environmentally friendly cooling options [(8)].

Any country whereby the night ambient does not allow being sufficiently low enough to charge PCM cells over-night, a supplementary dry cooler and / or small chiller can be added to top up the difference between the ambient and PCM temperature for an economical solution.

5.0 - CONCLUSION:

Modern society's reliance on refrigeration and air conditioning indicates that refrigeration and the associated environmental issues will be with us for a considerable time and therefore one has to utilise existing and available alternative technologies with minimum usage of energy.

A Positive Temperature Eutectic " *PlusICE* " Thermal Energy Storage not only provides the end user with an Environmentally Friendly design but also the following additional benefits can be obtained:

- **Reduced and No Refrigeration Equipment**
- **Capital Cost Saving**
- **Reduced Maintenance.**
- **Energy Cost Saving**
- **Reduced CO2 Emission**
- **Environmentally Friendly Installation**
- **Improved System Operation / Reliability**
- **Flexibility for the Future Capacities Changes**

The temperature ranges offered by the proposed PCM solutions utilise free ambient cooling, conventional chilled water temperature ranges for both the charging and discharging sides of the system. Hence, they can be applied to any new or retrofit application with minimal technical and economical impacts.

Furthermore, the possibility of Free Cooling Cycle TES system offer new horizons for designers to control the energy balance to match the load and electricity demand / consumption of the system as a whole.

The task for designers is to explore all available technologies towards achieving improved efficiency regardless of which refrigerant is used, and apply where and when possible diversification technologies in order to minimise the overall CO_2 emission related to energy usage. A carefully balanced *PlusICE* Passive Cooling Thermal Energy Storage may be the answer for some of the cooling applications for an Environmentally Friendly and Economical alternative.

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