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TITLE

PHASE CHANGE MATERIAL (PCM) BASED ENERGY STORAGE MATERIALS AND GLOBAL APPLICATION EXAMPLES

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Summary;

Thermal Energy Storage (TES) is the temporary storage of high or low temperature energy for later use. It bridges the time gap between energy requirement and energy use. For HVAC and refrigeration application purposes, water and water ice constitute the principal storage media.

Water has the advantage of universal availability and low cost but it can only be produced using inefficient low temperature refrigeration units if one wishes to use the latent heat capacity. If it is applied purely for sensible energy storage capacity it requires large storage tanks.

Phase Change Materials (PCM) between +4°C and +90°C range over comes the water disadvantages by combining the latent and sensible energy storage capacities into a single storage unit and therefore offer designers new horizons and practical application options.

PCM latent heat cool energy storage can be provided by utilising conventional water chillers for new and retrofit applications without the need for any modifications as well as having the possibility of free cooling.

By storing day-time warm energy for evening periods and over-night cool energy for day-time cooling requirements, a PCM system can simply bridge the gap between energy availability and energy use and therefore has the potential to achieve considerable environmental as well as economical benefits for many heating and cooling applications.

The aim of this paper is to raise awareness of commercially available PCM solutions and products together with their practical worldwide applications. Typical installation examples around the World will be presented in a format that will aid practising engineers and consultants to develop an effective and low energy based design on PCM based TES cooling / heating and heat recovery systems.

Key Words; Phase Change Materials (PCM), Thermal Energy Storage (TES), Eutectics, Heating, Cooling

1.0 - BACKGROUND

Energy usage, economical and environmental issues are becoming a focal point 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 type of energy used is becoming the main criteria for price structuring rather than overall energy consumption [(1)].

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 (TES) 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.

However, Phase Change Materials (PCM) freeze and melt above or below 0°C (32°F) offering new opportunities for environmentally friendly and economical systems for both New and Retrofit process, cooling or heating load shifting applications.

This paper explores commercially available PCM solutions together with encapsulated products and their Global application examples.

2.0 - THERMAL ENERGY STORAGE (TES):

Thermal Energy Storage bridges the time gap between energy requirement and energy use. A thermal storage application may involve a 24-hour or alternatively weekly or seasonal storage cycles depending on the system design requirements. Whilst the output is always thermal, the input energy may be either thermal or electrical [(2)].

In full storage systems, the entire daily design loads are generated off peak and stored for use during the following peak periods. In partial storage systems, only a portion of the daily load is generated during off peak and used during peak periods to top up the system.

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- Water/Ice Latent Heat Energy Storage;

Water has the advantage of universal availability, low cost and easily transported through other system components. However, conventional water based TES systems for air conditioning applications[3] 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- Phase Change Materials Energy Storage;

In simple terms, Phase Change Materials (PCMs) [4] can be described as mixtures of chemicals having freezing and melting points above or below the water freezing temperature of 0°C (32°F). They are ideal products for thermal management solutions as they store and release thermal energy during the process of melting & freezing (changing from one phase to another).

When such a material freezes, it releases large amounts of energy in the form of latent heat of fusion, or energy of crystallisation. Conversely, when the material is melted, an equal amount of energy is absorbed from the immediate environment as it changes from solid to liquid.

To be a useful PCM, a material has to meet several criteria:

- ***Release and absorb large amounts of energy when freezing and melting*****;** This requires the PCM to have a large latent heat of fusion and to be as dense as possible.
- ***Have a fixed and clearly determined phase change temperature (freeze/melt point);*** The PCM needs to freeze and melt cleanly over as small a temperature range as possible. Water is ideal in this respect, since it freezes and melts at exactly 0°C (32°F). However, many PCMs freeze or melt over a range of several degrees, and will often have a melting point that is slightly higher or lower than the freezing point. This phenomenon is known as hysteresis.
- ***Avoid excessive supercooling****;* Supercooling is observed with many eutectic solutions and salt hydrates. The PCM in its liquid state can be cooled below its freezing point whilst remaining a liquid. Some salt hydrates can be cooled to +50°C (122°F) below their freezing point without crystallisation occurring. This can be beneficial, for example in hot packs where a +48°C (118.4°F) PCM is kept as a supercooled liquid at room temperature until the hot pack is required and supercooling is broken by mechanical or chemical nucleation. However for most applications, supercooling must be kept to a minimum by the addition of suitable nucleating agents to the PCM.
- ***Remain stable and unchanged over many freeze/melt cycles;*** PCMs are usually used many times over, and often have an operational lifespan of many years in which they will be subjected to thousands of freeze/melt cycles. It is very important that the PCM is not prone to chemical or physical degradation over time which will affect the energy storage capability of the PCM.

Some eutectic solutions may be susceptible to microbiological attack, so must be protected with biocides. Long term stability can be a problem in some salt hydrate PCMs, unless they are modified to prevent separation of the component materials over successive freeze/melt cycles.

- ***Non-hazardous*;** PCMs are often used in applications whereby they could come in contact with people, for example in food cooling or heating applications, or in building temperature maintenance. For this reason they should be safe. Ideally a PCM should be non-toxic, non-corrosive, non-hazardous and non-flammable. There are many substances that behave excellently as PCMs but cannot be used due to issues over safety.
- ***Economical*;** It doesn't matter how well a substance can perform as a PCM is if is prohibitively expensive. PCMs can range in price from very cheap (e.g. water) to very expensive (e.g. pure linear hydrocarbons). If cost outweighs the benefits obtained using the PCM, its use will be very limited.

The simplest, cheapest, and most effective phase change material is water/ice. Unfortunately, the freezing temperature of water is fixed at **0°C (32°F)** making it unsuitable for the majority of energy storage applications. Therefore a number of different materials have been identified and developed to offer products that freeze and melt like water/ice, but at temperatures from the cryogenic range to several hundred degrees centigrade.

PCMs can broadly be arranged into five categories: eutectics, salt hydrates, organic, solid-solid and molten salt materials.

- **Eutectics** tend to be solutions of salts desolved in water that have a phase change temperature **below 0°C (32°F).**

- **Salt hydrates** are specific salts that are able to incorporate water of crystallisation during their freezing process and tend to change phase **above 0°C (32°F).**

- **Organic materials** used as PCMs tend to be polymers with long chain molecules composed primarily of carbon and hydrogen. They tend to exhibit high orders of crystallinity when freezing and mostly change phase **above or below 0°C (32°F).** Examples of materials used as positive temperature organic PCMs include alcohols, waxes, oils, fatty acids and polyglycols.

- **Solid-Solid PCMs** that undergo a solid/solid phase transition with the associated absorption and release of large amounts of heat. These materials change their crystalline structure from one lattice configuration to another at a fixed and well-defined temperature, and the transformation can involve latent heats comparable to the most effective solid/liquid PCMs.

Such materials are useful because, unlike solid/liquid PCMs, they do not require nucleation to prevent supercooling. Additionally, because it is a solid/solid phase change, there is no visible change in the appearance of the PCM (other than a slight expansion/contraction), and there are no problems associated with handling liquids, i.e. containment, potential leakage, etc.

- **Molten Salts** are naturally solid salt materials which turn liquid when they are heated above their transition temperatures and act as a PCM energy storage material.

Clathrates may also be used. They look like a solid crystalline material, store large amounts of heat when they melt, and some have melting temperatures that are attractive to energy storage applications. Unfortunately, clathrates can currently only be produced by mixing the the host and trapped species under very large pressure, and once the clathrate has melted the two species cannot easily be reincorporated, thus can only be used once as a PCM.

Some liquid/gas phase change materials can be used the energy storage but they tend to involve large changes in volume or pressure when going from the liquid to the gaseous phase, this prevents effective and economical encapsulation.

The summary of the commercially available and widely applied. PCM solutions [5] are highlighted in Table 2.2.1.

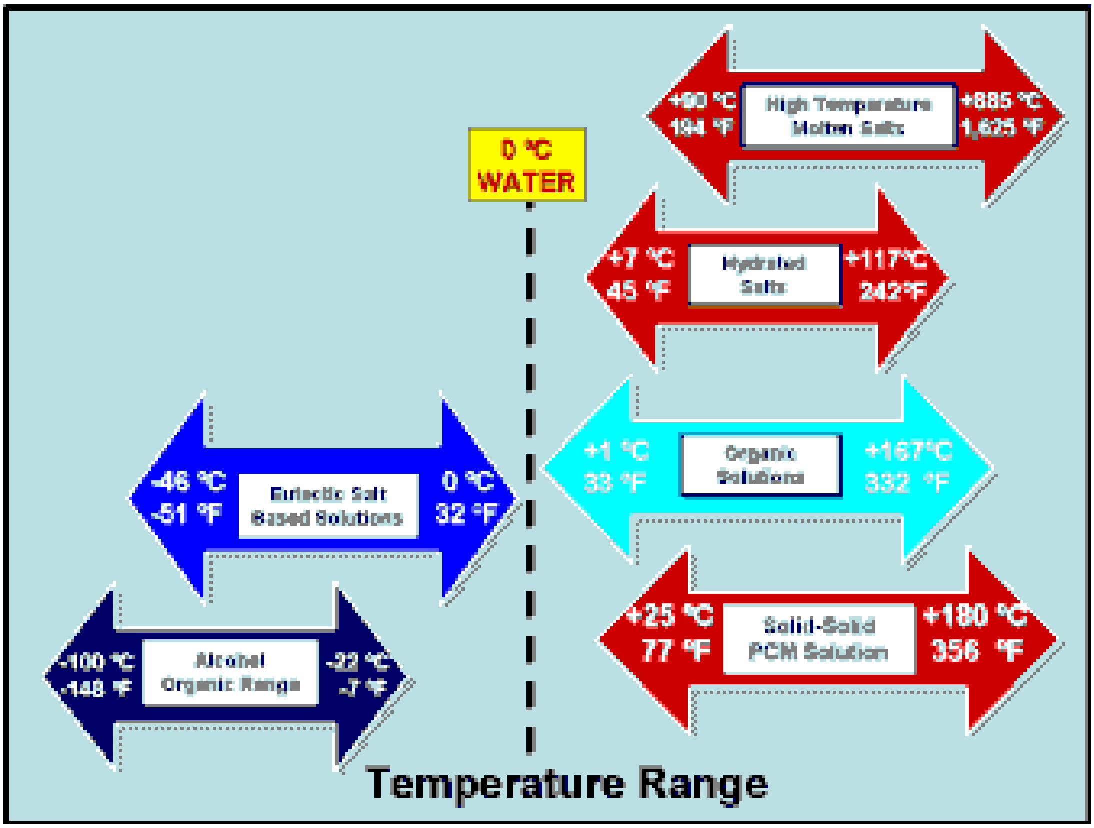

Table 2.2.1- Commercially available PCM solutions.

3.0- ENCAPSULATED PCM PRODUCTS:

Most aqueous salt based PCM solutions have a tendency to either absorb moisture from the atmosphere (hygroscobic), or lose water through evaporation, and therefore they must be encapsulted in air tight/sealed containers.

Although organic solutions can be exposed to air as they are not water based, contamination and fire risk due to low flash point make it necesary for them to be encapsulated in air tight containers.

Salt based PCM solutions are corrosive and the most practical and economical method is to use plastic containers[(6)]. However, plastic becomes soft at high temperatures which restricts the application range to below +80~+90ºC levels. Some commercially available plastic encapsulation examples are illustrated in Figure 3.1.

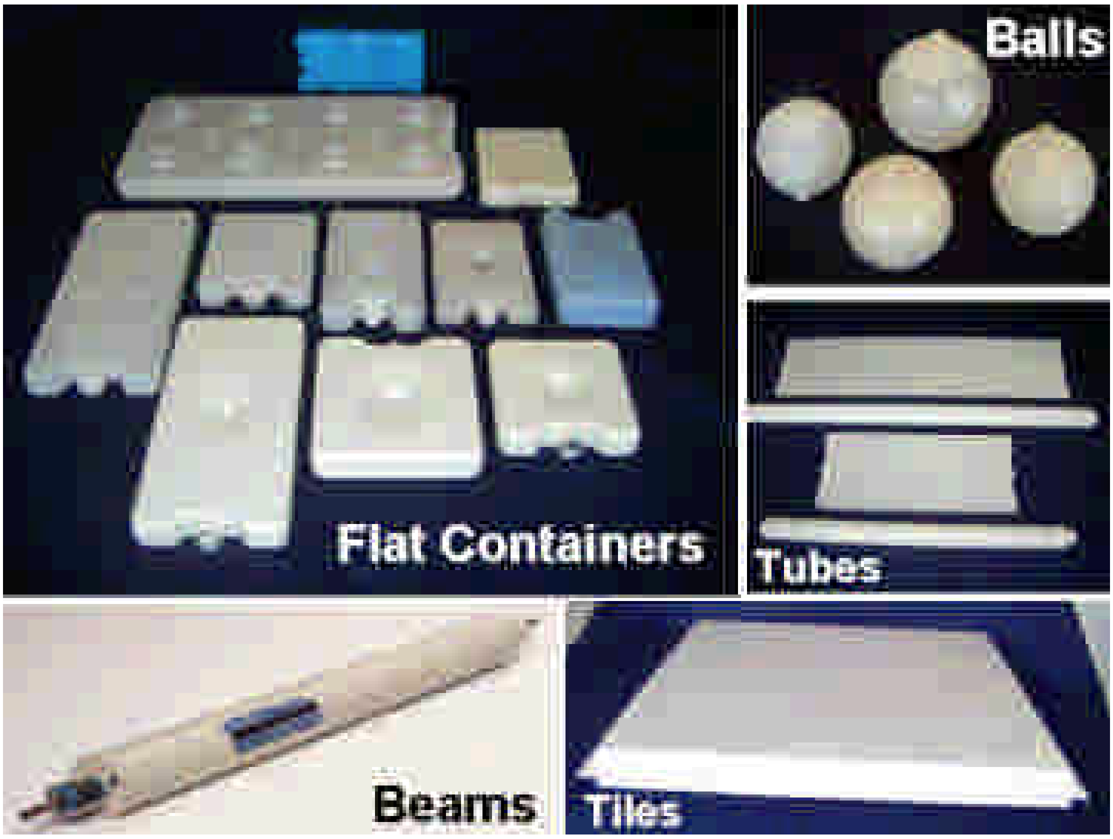

Figure 3.1- Solid plastic encapsulated PCM products.

As well as rigid plastic containers, a wide range of flexible pouches filled with various PCM solutions are produced enabling a wide range of low cost applications. Pouches are made usuing thin film and they offer good heat transfer efficiency however, because they are prone to physical damage and puncture some of the organic solutions are offered in powder, granule or even solid sheet forms which offer flexibility and safety. Examples of the most commonly used methods of encapsulation are illustrated in Figure 3.2.

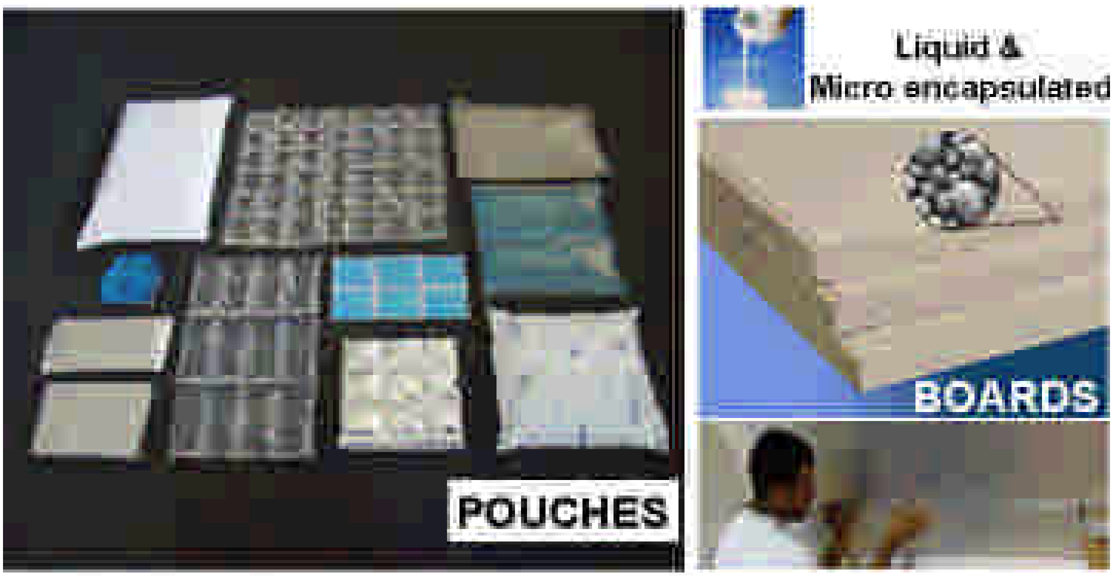

Figure 3.2- Flexible encapsulated PCM products.

Although plastic, and to a certain extent pouches, are economical, their heat transfer rate and/or limited temperature range restricts their wide scale use. In order to extend the temperature range or improve the heat transfer rate, metal containers have been extensively used for special applications. Some of the comercially applied metal encapsulation products are illustrated in Figure 3.3.

Figure 3.3- Metal encapsulated PCM products.

Organic solutions are water free and can be modified in the form of dust, granules or even solid rubber forms and they can be mixed with other products such as concrete, mortar, bricks, etc..They can be also thermoformed by simply mixing with plastic materials as part of the injection moulding process.

Organic PCM variation examples are illustrated in Figure 3.4.

Figure 3.4- Organic PCM variations examples.

3.0- PCM GLOBAL APPLICATION EXAMPLES:

The energy storage capacity of PCMs can be utilised in a number of ways (7), for example thermal energy storage whereby heat or cool energies can be stored from one process or period in time, and used at a later date or different location. PCMs are also very useful in providing thermal barriers or insulation.

Each PCM solution can be used in many different applications (8) and when considering building services it might be best to cover the PCM usage sector by sector.

4.1- Chilled Water Systems;

Using +8~+10ºC PCM energy storage one can utilise a conventional water chiller without the need for a low temperature Glycol chillers. The benefits of using PCM against a conventional water/ice low temperature chiller charging operation are illustrated for an air cooled chiller operation over a range of operating temperatures in Figure 4.1.1(9).

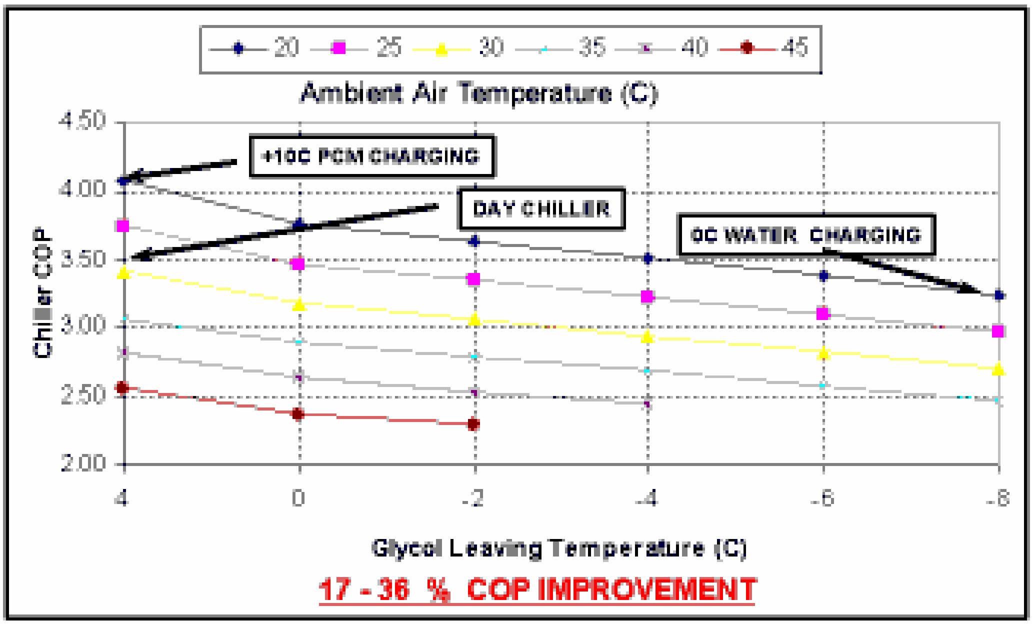

Figure 4.1.1 – PCM Based Vs Conventional Ice TES charging comparison.

Low ambient temperatures coupled with higher evaporation temperatures offer a significant overall COP improvement, in the region of 17-36 % depending on the type of unit and location. Typical PCM based energy storage options are illustrated in Figure 4.1.2.

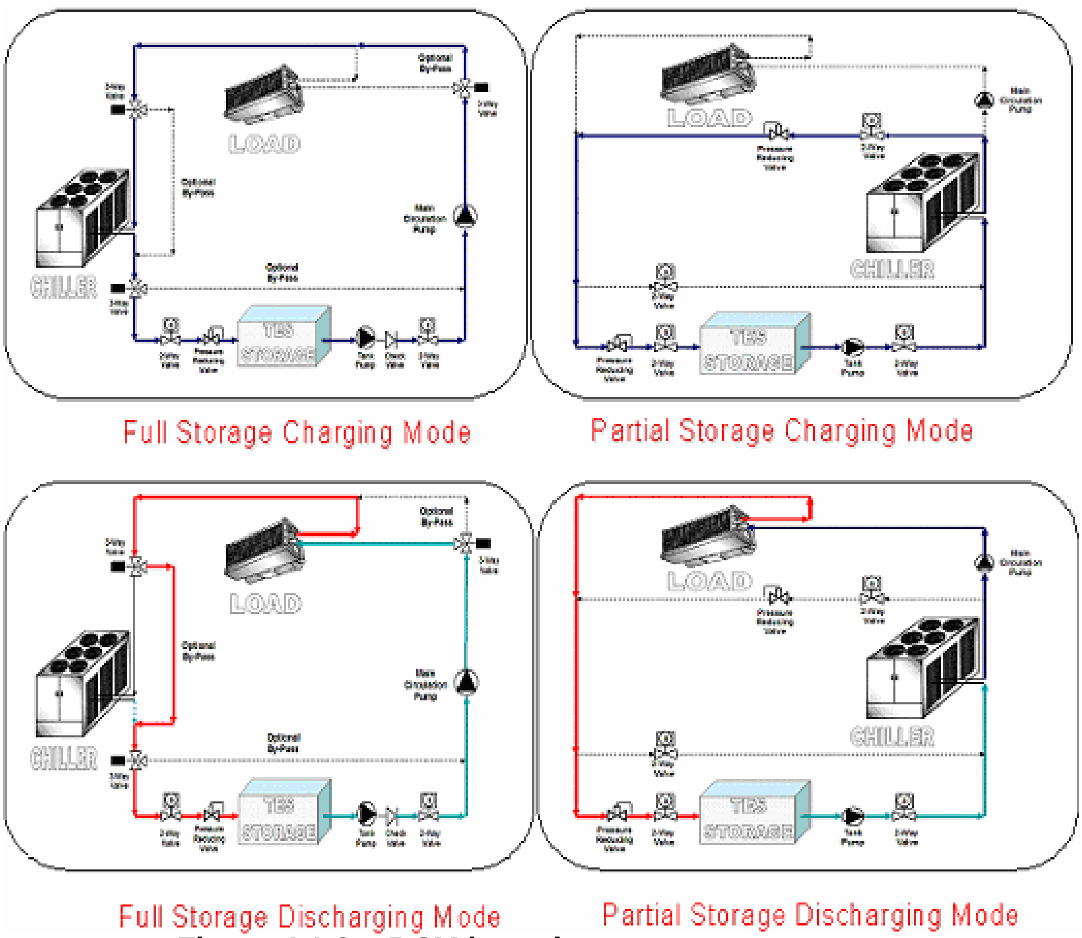

Figure 4.1.2 – PCM based energy storage concept.

Global chilled water cooling application examples are illustrated in Figures 4.1.3 to 4.1.5.

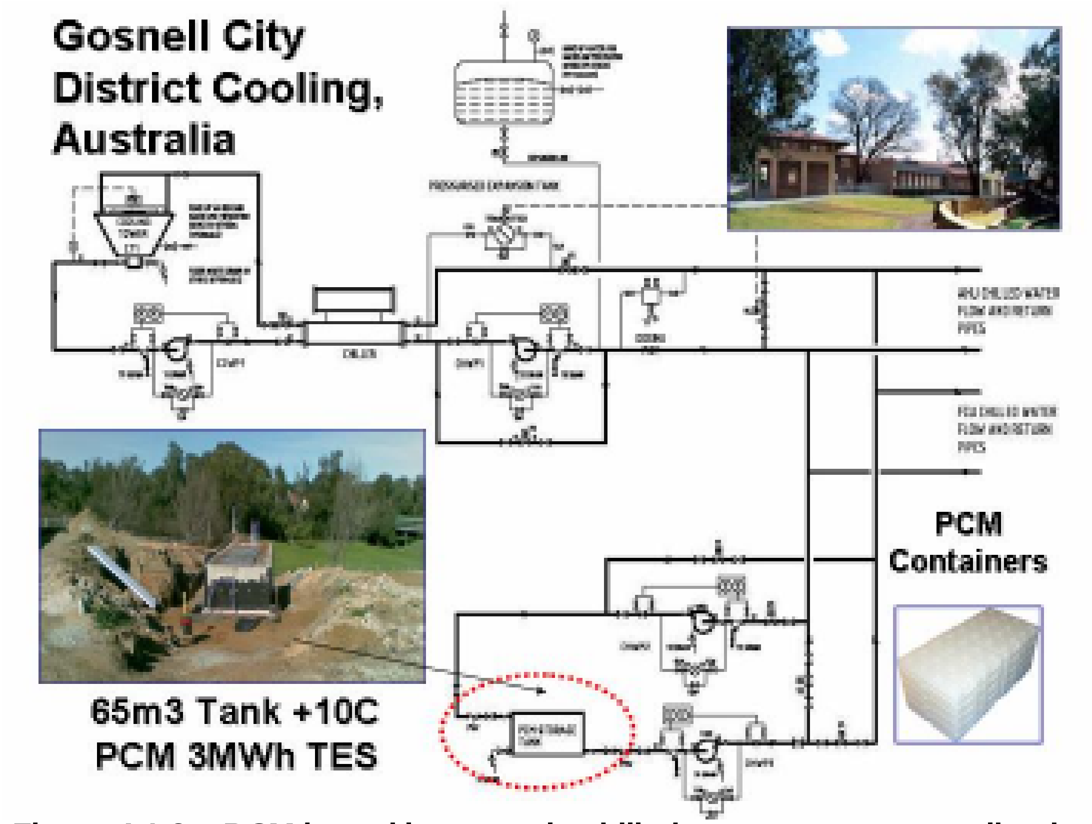

Figure 4.1.3 – PCM based large scale chilled energy storage applications.

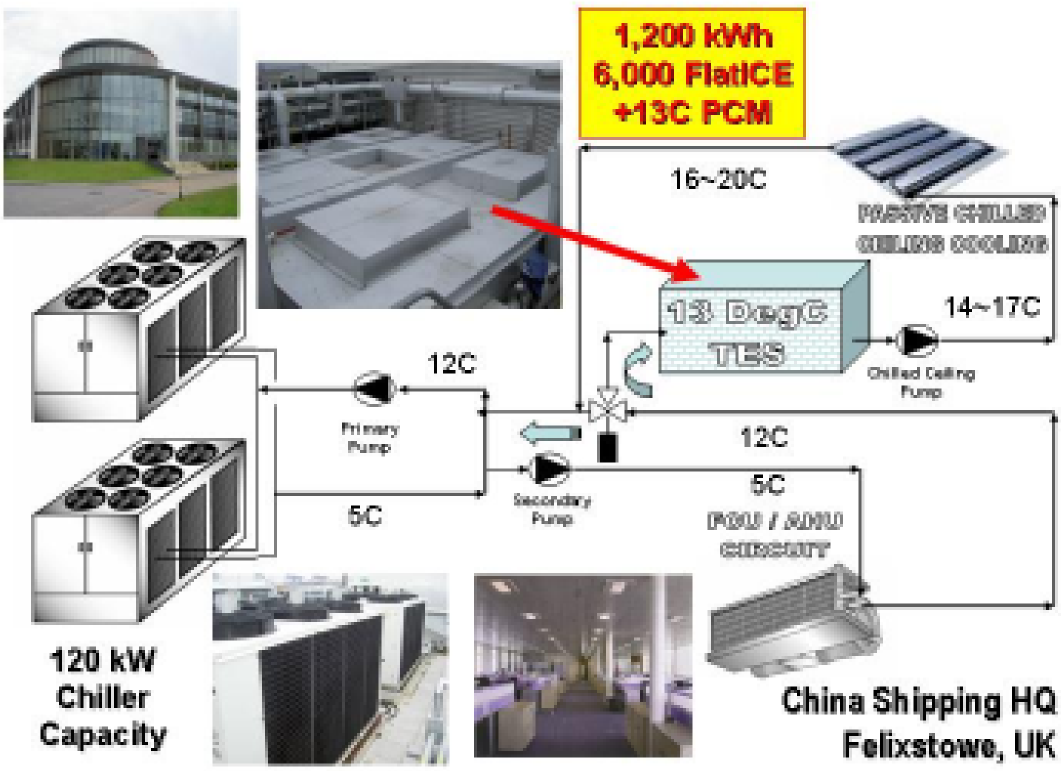

Figure 4.1.4 – PCM based chilled beams energy storage applications.

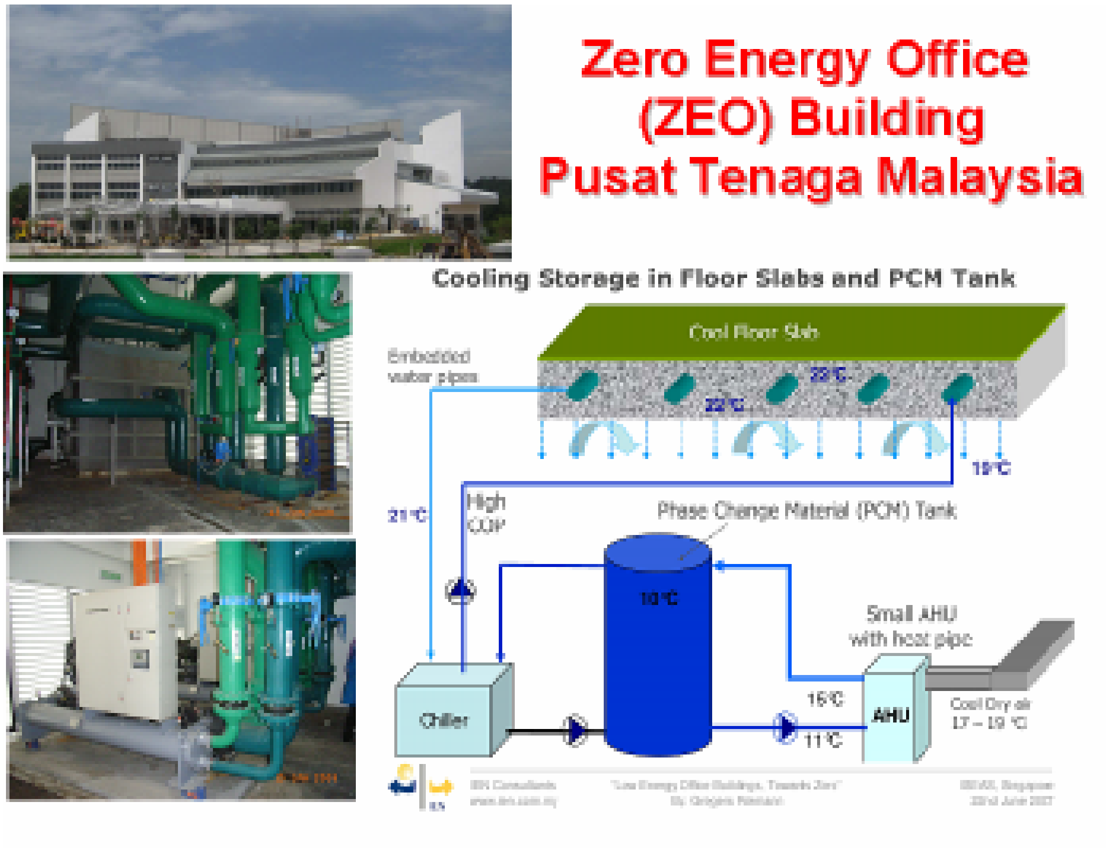

Figure 4.1.5 – PCM based chilled water energy storage application.

4.2- Heat Pump Systems;

Heat pumps remove heat from one side of the refrigeration circuit and transfer to another side of the system. The heat rejection media could be air, water or ground source [(10)].

A heat pump removes energy from one side of the refrigeration circuit either using air/water or ground sources and transfers that energy into the other side of the refrigeration cycle. Although this is a very efficient way to generate heat, if the removed energy is later required it can be considered as a waste. By simply storing this waste energy in the form of +10ºC for cold or +46ºC hot PCM energy storage, one can utilise this stored energy during peak periods and as a result the heat pump size as well as the overall system energy usage can be reduced by as much as 50% by spreading the loads over a 24 hours cycle.

A heat pump combined with PCM energy storage not only reduces running costs due to lower over-night electricity rates but also provides an increased combined COP which effectively reduces the overall power requirement as well. The combination of these two benefits can reduce the overall running cost of the system significantly.

PCMs have been applied in a number of large scale as well as small scale heat pump applications [(11)] and a typical large scale industrial PCM application example applied in Italy for an electronic factory is illustrated in Figure 4.2.

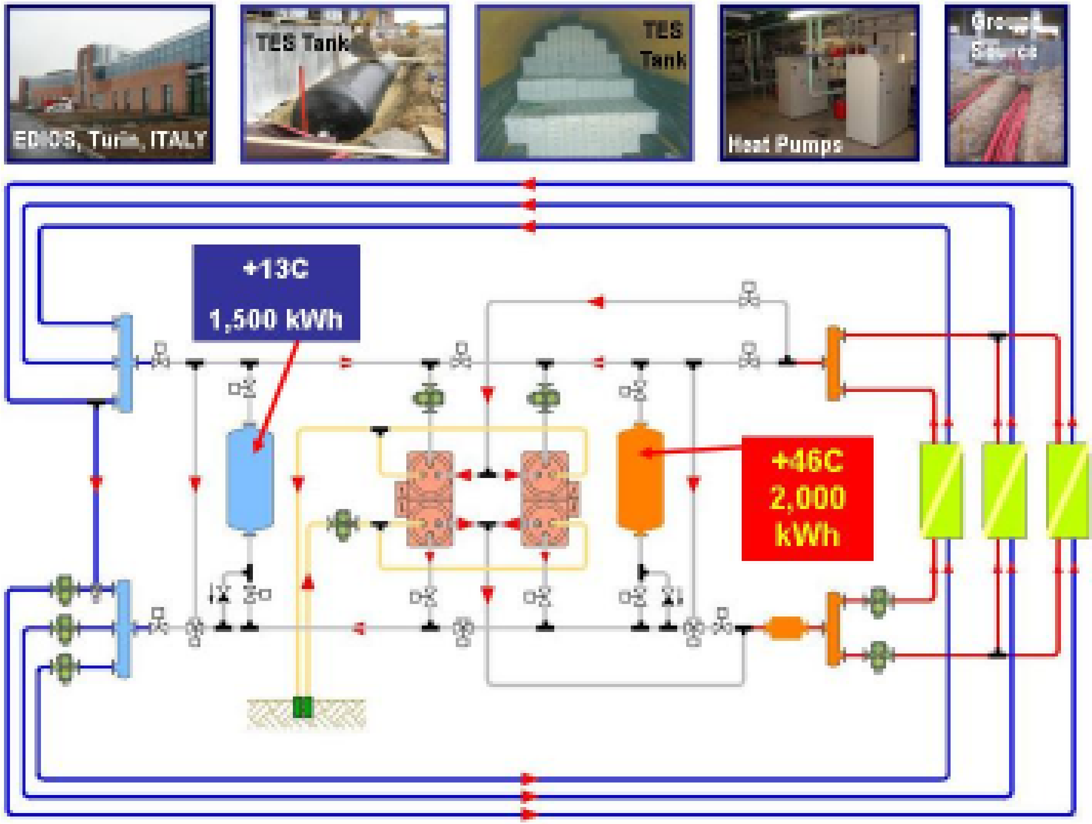

Figure 4.2.1- Large scale heat pump PCM energy storage application.

PCM based heat pumps rely on extracting heat from either an air or ground source and this extracted energy is later put into either water or air circuits for the most common hot water, heating and cooling applications.

A PCM storage system can eliminate some operational issues such as air source defrost penalties as heat pumps struggle if the ambient goes below 0ºC, they require constant defrost due to icing on the coil and making them very inefficient. Similarly ground source heat pumps require large numbers of boreholes which are expensive and sometimes restricted due to lack of space.

In order to overcome these issues a number of PCM energy storage systems have been successfully applied in the UK.

Figure 4.2.2 illustrates a surface PCM energy storage used to eliminate the defrost issues related to air source heat pump applications and by simply extracting heat from the PCM storage as opposed to air, the heat pump circuit can be operated without a defrost at low ambient conditions.

Figure 4.2.3. illustrates a typical ground source heat pump application without the need for boreholes by simply using a dry cooler and a matching PCM energy storage system combination to reject the heat during peak loads in order to cover the whole year operation.

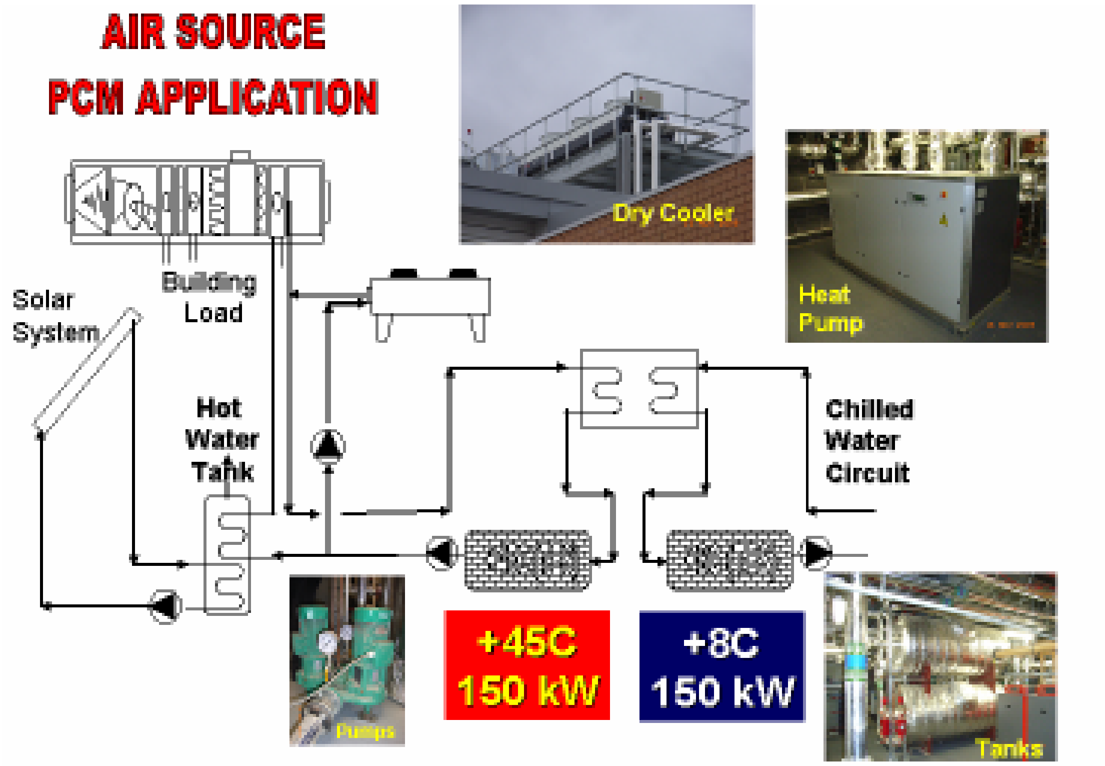

Figure 4.2.2- Air source heat pump PCM energy storage application.

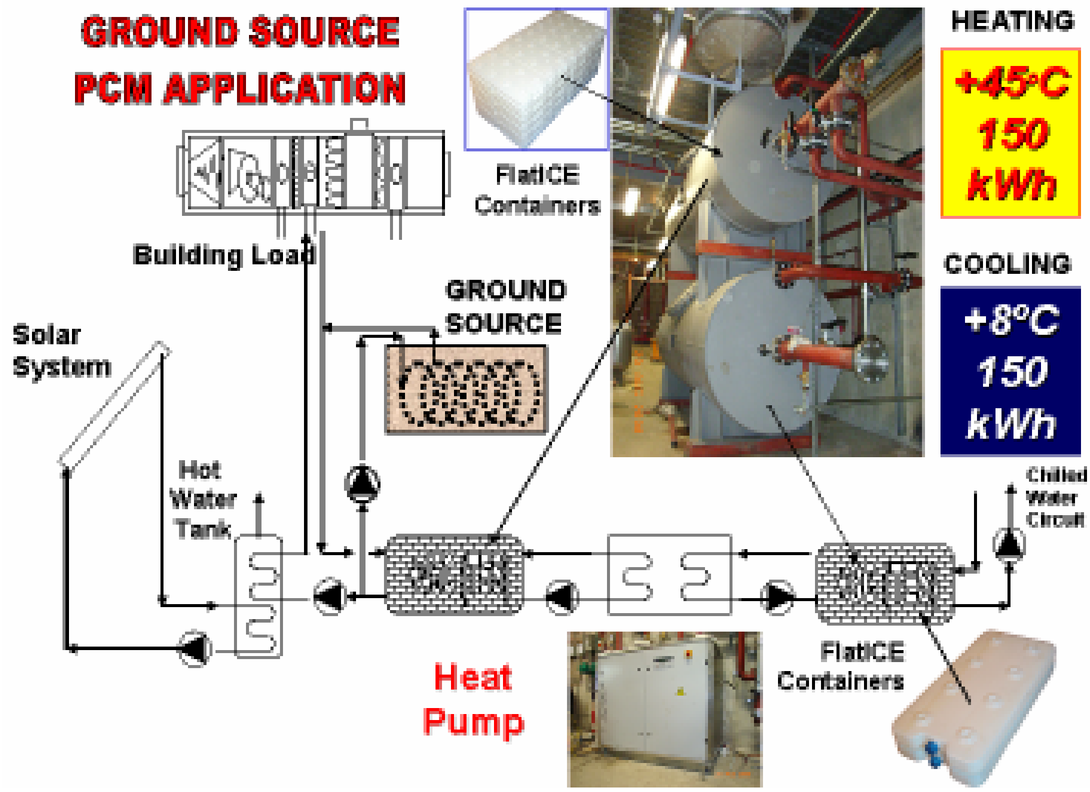

Figure 4.2.3- Ground source heat pump PCM energy storage application.

PCM energy storage can also be applied to a number of water-water source heat pump systems where it is critical to keep the main close-loop heat rejection circuit around +20~+25ºC levels throughout the year. However, if the majority of the self-contained heat pumps are in cooling mode, the main buffer circuit requires a chiller to cool. On the opposite end, if the majority of the units are in heating mode, the main circuit requires a boiler to heat the buffer circuit to remain within the design limits.

Many UK water-water heat pump systems initially start in heating mode but mid-day revert back to cooling mode. Rather than using a boiler and chiller combination to balance the buffer circuit, the designers can utilise a +22ºC PCM buffer vessel to store the surplus energy and balance the buffer circuit over a 24 hour period as illustrated in Figure 4.2.4. PCM energy storage cost can be covered by eliminating the need for a boiler or chiller. Moreover, the running and maintenance costs of the system can be significantly reduced as a result.

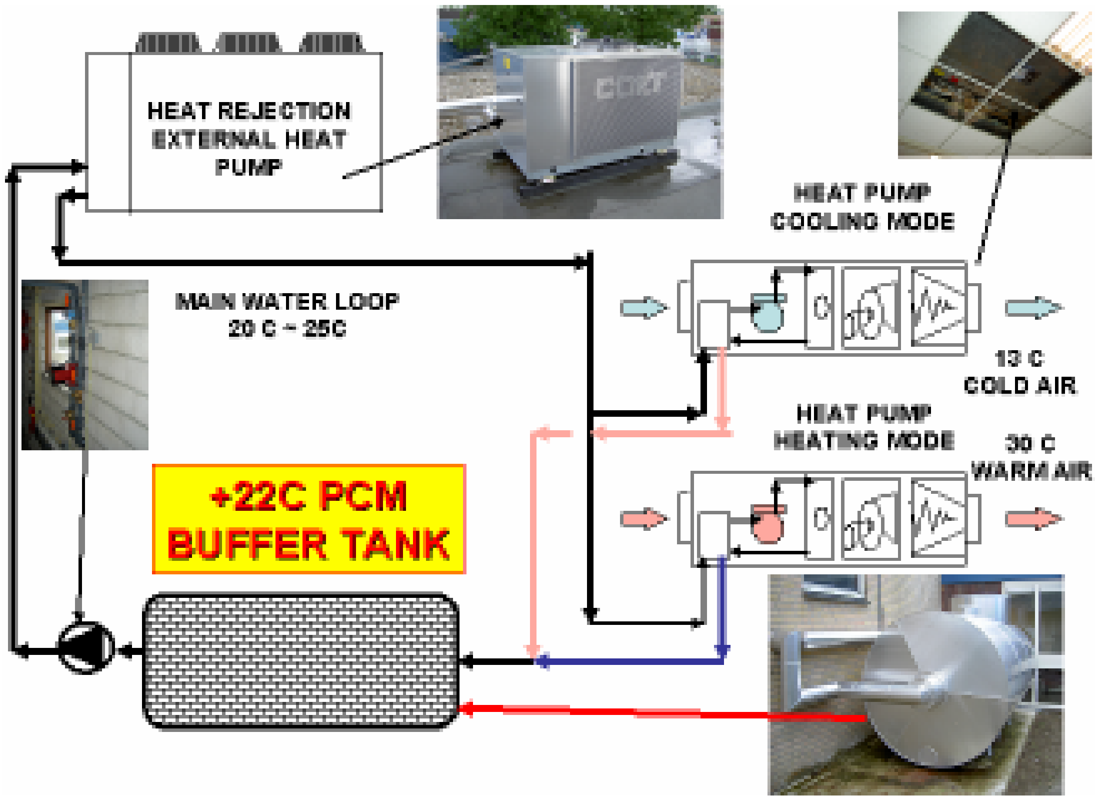

Figure 4.2.4- Water-water source heat pump PCM energy storage.

4.3- Passive Cooling;

Passive cooling relies on naturally occurring night and day time temperature swings. The cool energy available over-night is stored within the PCM and later this stored energy is used to absorb the internal and solar gains during day-time for an energy free passive cooling system. A typical energy free passive cooling concept is illustrated in Figure 4.3.1.

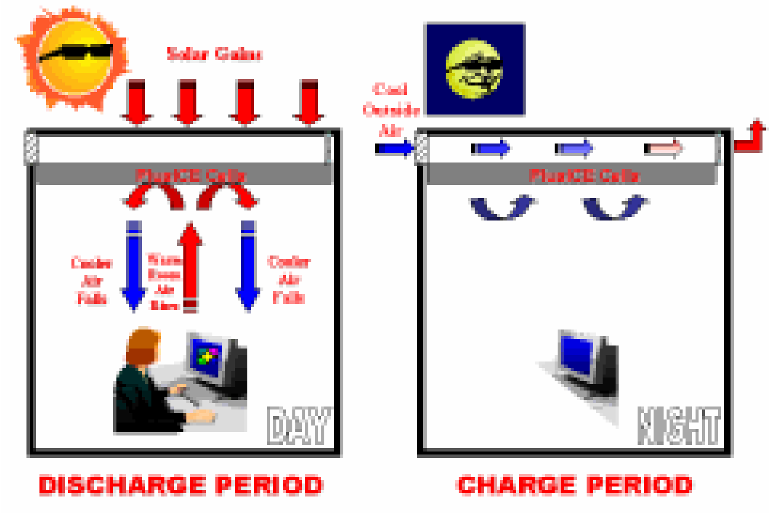

Figure 4.3.1- Energy free passive cooling building application.

Figure 4.3.1. illustrates a typical building passive cooling concept for the northern European climate as the night ambient goes well below the internal design temperatures for a free cooling option all year round. In warmer climates like southern Europe or Middle East this energy free cooling can only be achieved during colder winter / autumn or early spring periods.

However, by simply running the air conditioning system to charge the passive cooling over-night, designers may be able to shift some of the daily peak load to over-night low ambient, hence, higher efficiency operation and possibly using the low electricity cost periods. Some of the passive cooling application examples are highlighted in between Figures 4.3.2. and Figure 4.3.4.

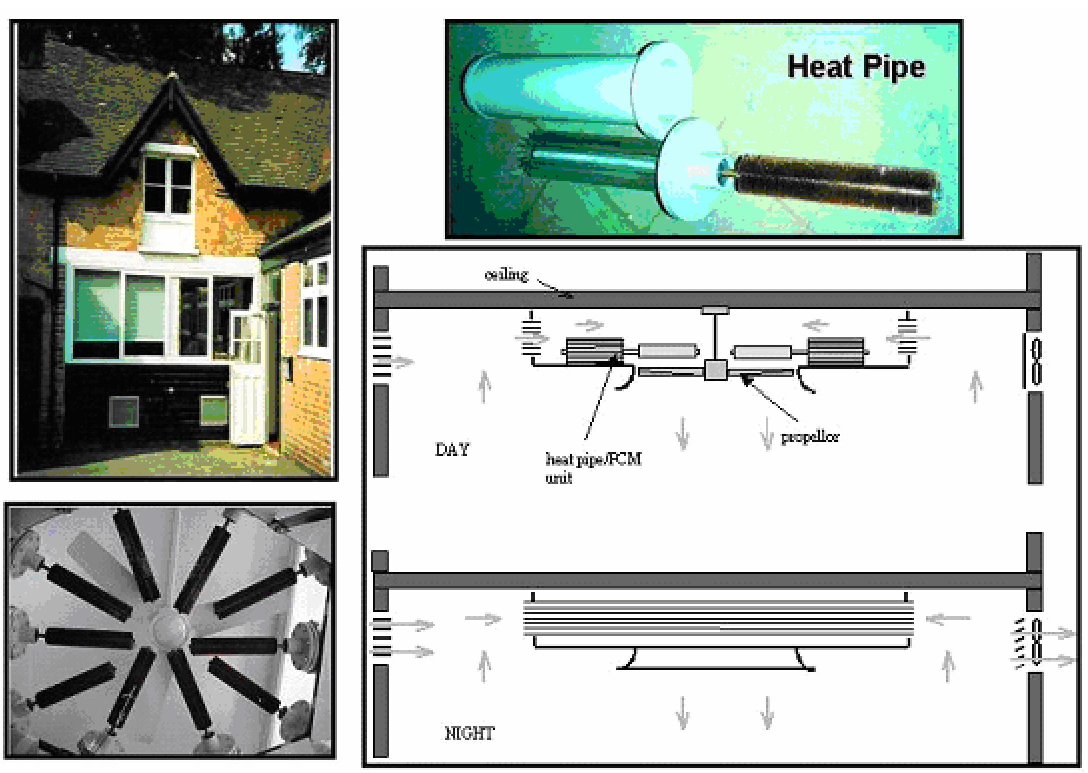

Figure 4.3.2. Office passive cooling application in the UK.

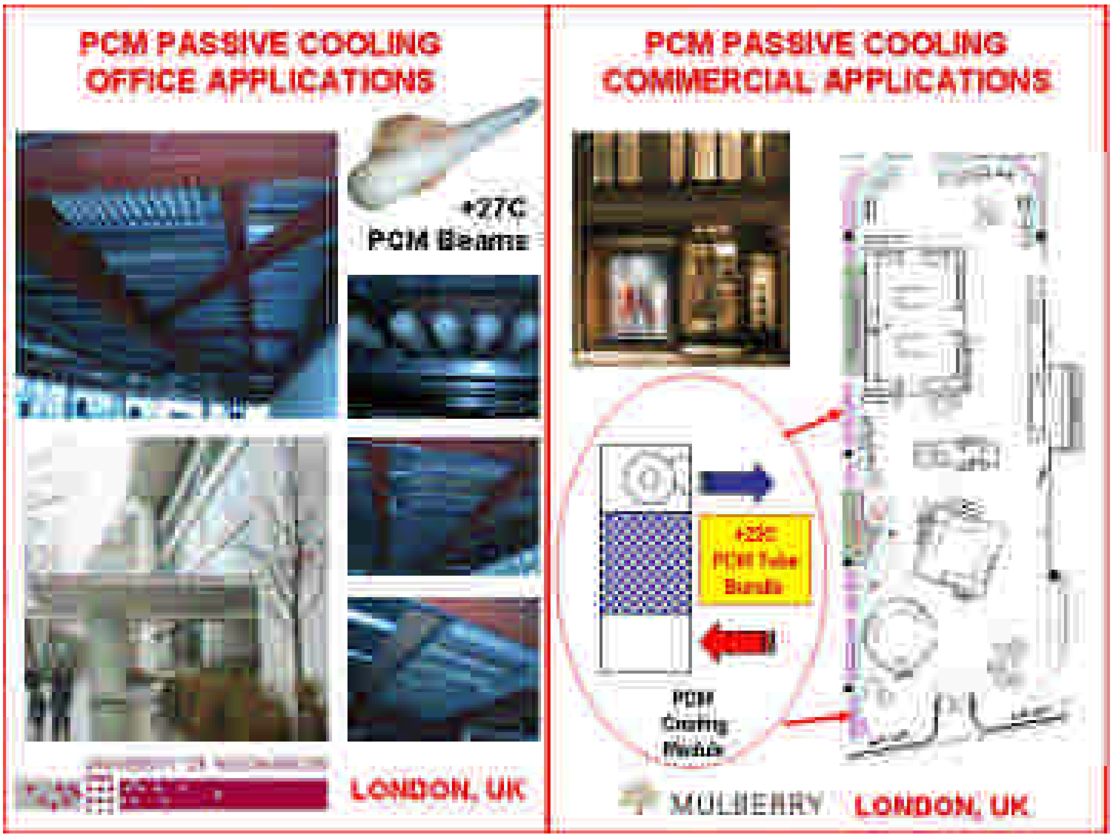

Figure 4.3.3. Passive cooling commercial application examples.

Figure 4.3.4. Passive cooling UK school application examples.

The same passive cooling concept can also be applied for electronic shelters anywhere in the World as the internal temperatures can be elevated up to +45ºC as opposed to comfort cooling limit of +24ºC. Having this high internal temperature limit, even in the middle of a desert the night's cool energy can be stored and using this stored energy during day-time the shelter's internal temperatures can be maintained well below the upper limit without any mechanical refrigeration.

Some of these passive cooling shelter applications are illustrated in Figure 4.3.5.

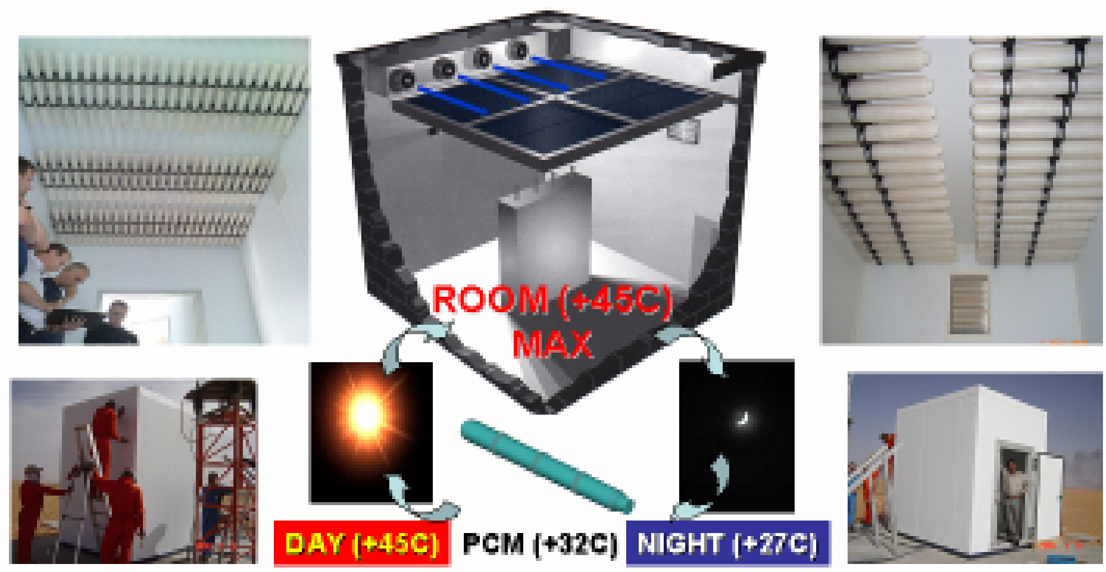

Figure 4.3.5- Passive electronic shelter cooling applications.

4.4- Solar Energy Storage;

Solar energy is only available during light hours and this free energy can be used either for heating or cooling [12] but generally it is available during only for a limited day period. By storing this free energy one can either produce heat or alternatively provide a cooling source.

Example of an under floor heating using solar collectors and warm PCM containers is illustrated in Figure 4.4.1.

Although conventional solar collectors may not generate enough energy to charge an water tank during winter months they could still generate low grade heat around 30~35ºC which is more than enough to charge PCM modules during day-time. Once the sun goes down the stored energy keeps the occupied space warm and the outside cold energy freezes the PCM rather than penetrating into the occupied space. This way the space conditions can be stabilised over a 24 hour day and night cycle.

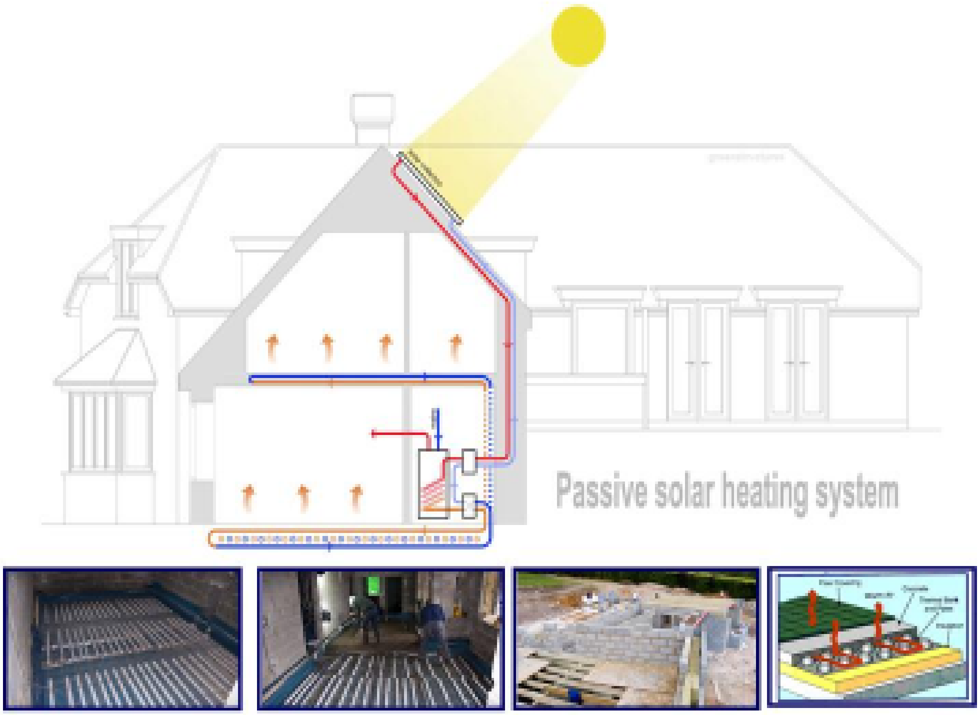

Figure 4.4.1- Solar + PCM integrated under floor & DHW heating application.

Using conventional solar collectors one can store hot water in simple water tanks but once the sun goes down and water is gradually drawn the tank can not maintain a steady output temperature due to strafication. However, if the latent heat capacity of PCM is added to the water tank not only can the capacity of the tank be increased by as much as 3~4 times but also having fixed phase change the water outlet temperature can be fixed until the PCM energy is fully depleted.

Using thermofomed plastic rubber PCM balls as illustrated in Figure 4.4.2 any existing hot water tank capacity can be increased 2~3 fold however, the high cost of these rubber balls restricts their wide usage and this technology is applied mainly to sites which have limited space available and the tank size can not be increased.

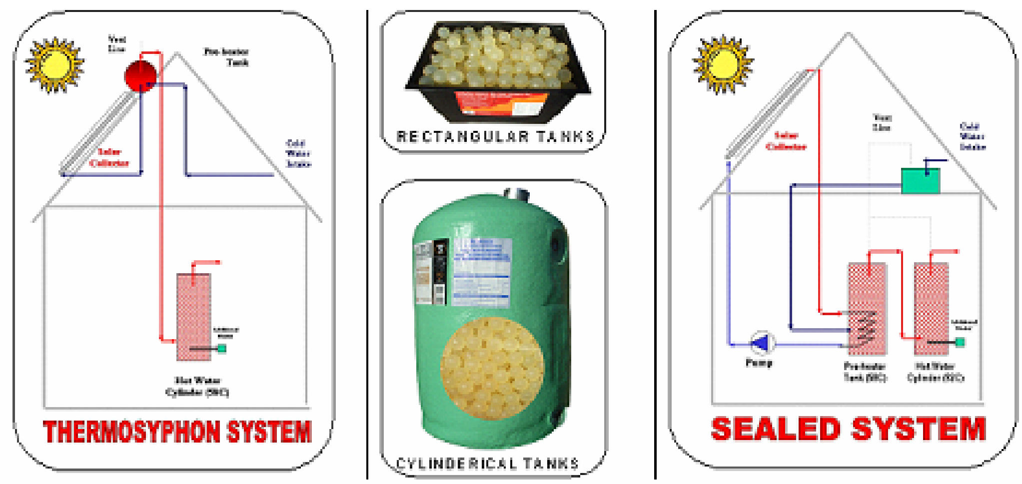

Figure 4.4.2- PCM rubber balls hot water energy storage applications.

Rubber PCM balls may be applicable for small scale tanks but for larger applications steel balls / tubes might be a better option. During the 2006 Commonwealth Games in Melbourne organisers aimed to build standard houses with a view to sell these houses to the public after the games.

During the games these houses had a 3~4 times higher occupancy rate than an average family and the lack of space for the hot water tank and effectively lack of hot water for the athletes was eliminated by simply adding +58ºC PCM balls using a standard size hot water tank. The PCM addition provided 3~4 times more hot water storage to handle the higher occupancy rate as illustrated in Figure 4.4.3.

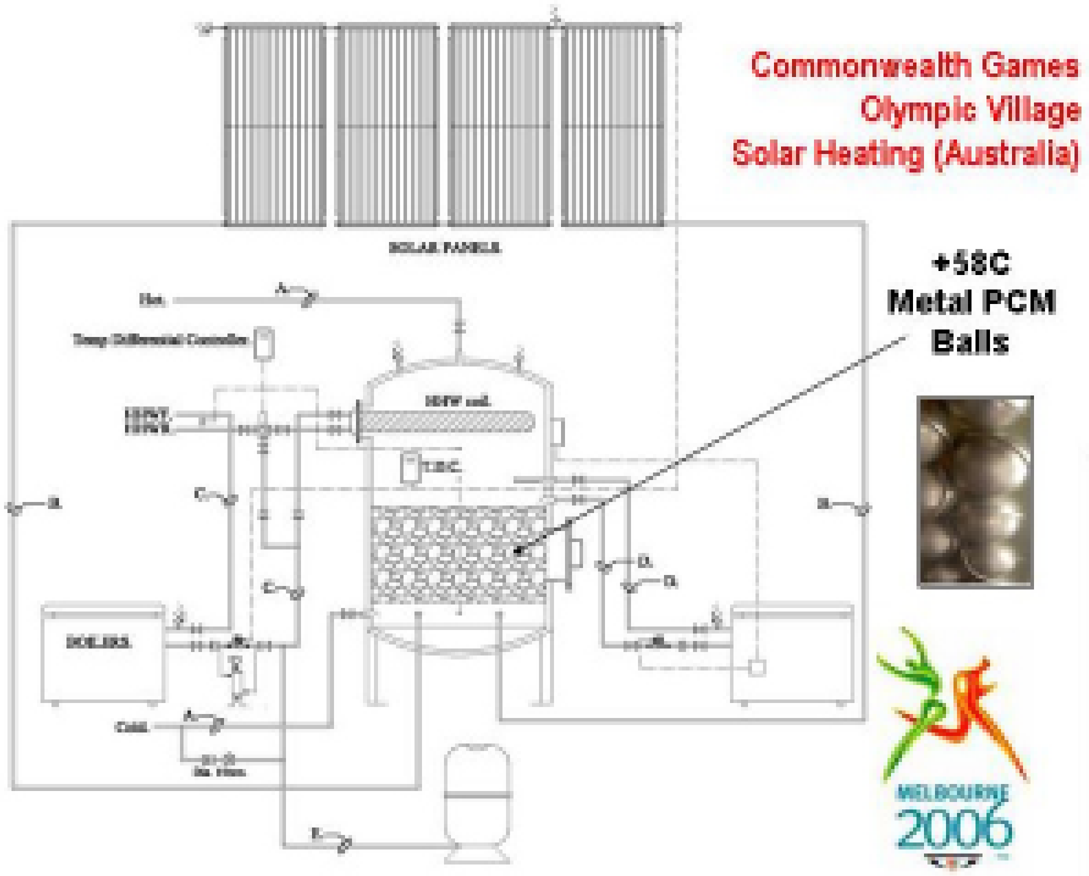

Figure 4.4.3- PCM based solar hot water TES application.

There is a natural match between air conditioning loads and solar gains and by simply using free solar energy one can generate cooling using various technologies such as absorption, adsorption and steam driven cooling machines. However, the cooling is required well beyond the peak mid-day sunny periods and to bridge the gap one has to store either the hot or cold side of the cooling circuit.

Generally storing the hot side of the heat driven cooling machines is not economically viable. It is far more practical and economical to store cold energy side of the circuit and a large scale Doha FIFA 2022 stadium solar cooling with PCM energy storage application is illustrated in Figure 4.4.4.

For this application the Qatar FIFA World Cup bid was based on using energy free solar air conditioning for the stadiums and the demonstration stadium was built to prove the concept would work.

The highest solar energy occurs during mid-day but all games will take place after sunset, so by simply running the solar driven air conditioning machines during the peak mid-day period and storing the cooling in +10ºC PCM solution, full air conditioning capacity can be provided by simply running the TES tank as a cooling source during the game.

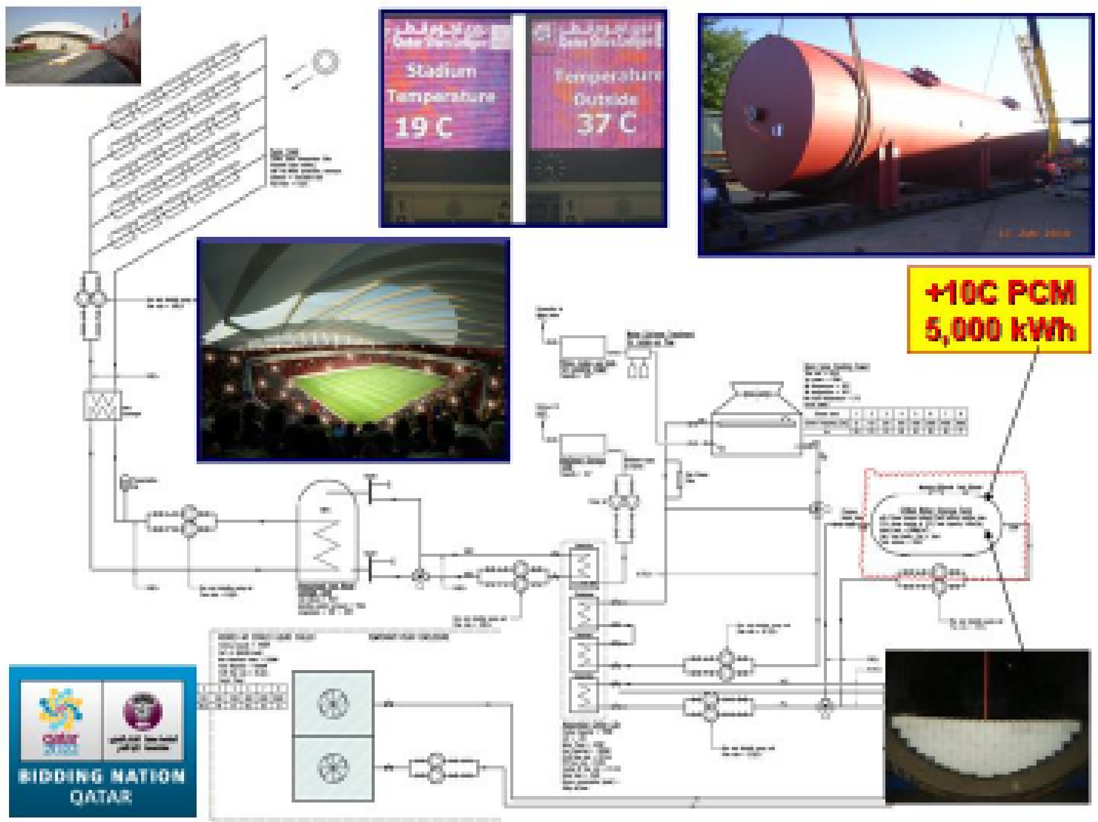

Figure 4.4.4- PCM Based solar air conditioning application in Qatar.

4.5- Free Cooling;

In certain climates the night-time ambient temperatures offer cool energy storage which can be used for day-time cooling. Using a PCM energy storage offers energy free cooling options.

A typical example for this concept is the Headquarters of Melbourne City Council, also known as the CH2 building which is the only 6* energy efficiency building in the world. Cooling towers are designed to run during hours of darkness, freezing the PCM energy storage which is then released as cool during the day.

Design is based on having a cooling tower on the roof to utilise lower wet bulb temperatures to charge +15ºC PCM tanks located in the basement without any mechanical refrigeration i.e. chillers. The night-time cool energy is stored in PCM tanks over-night and during day-time this stored energy is distributed throughout the building via chilled ceilings to soak up the internal and solar gains.

Simplified design details for the CH2 building are illustrated in Figure 4.5.1.

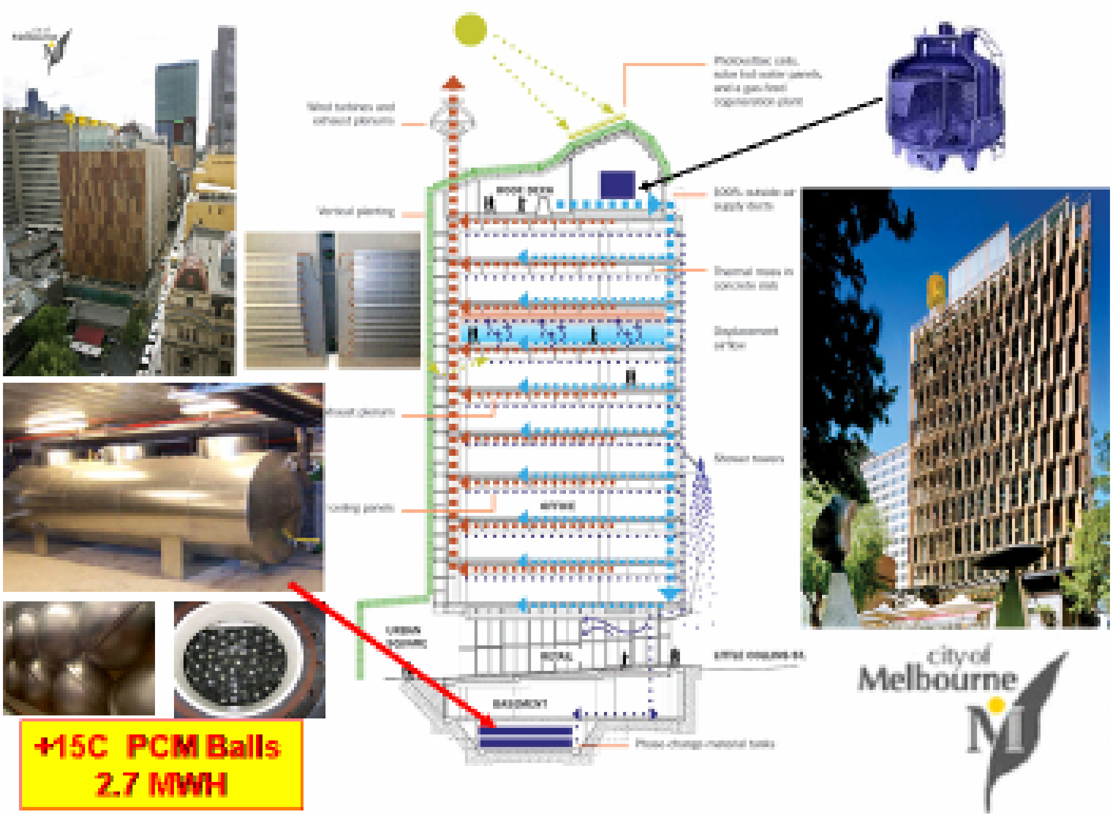

Figure 4.5.1- Melbourne CH2 building free cooling application.

4.6- Heating Systems;

In principal PCM would be helpful for any heating energy storage applications and save some storage space but higher circulation temperatures associated with the heating makes PCM encapsulation very costly. On top of this handicap the larger circulation temperature differences closer to 20K and associated high sensible heat capacity of water storage reduces the benefits of PCM energy storage further.

However, if a design allows circulation temperatures to be above +100ºC, utilising PCM's latent heat plus that of the heat transfer fluid the PCM's sensible heat capacity reduce the energy storage tank size significantly. A typical comparison calculation is illustrated in Figure 4.6.1.

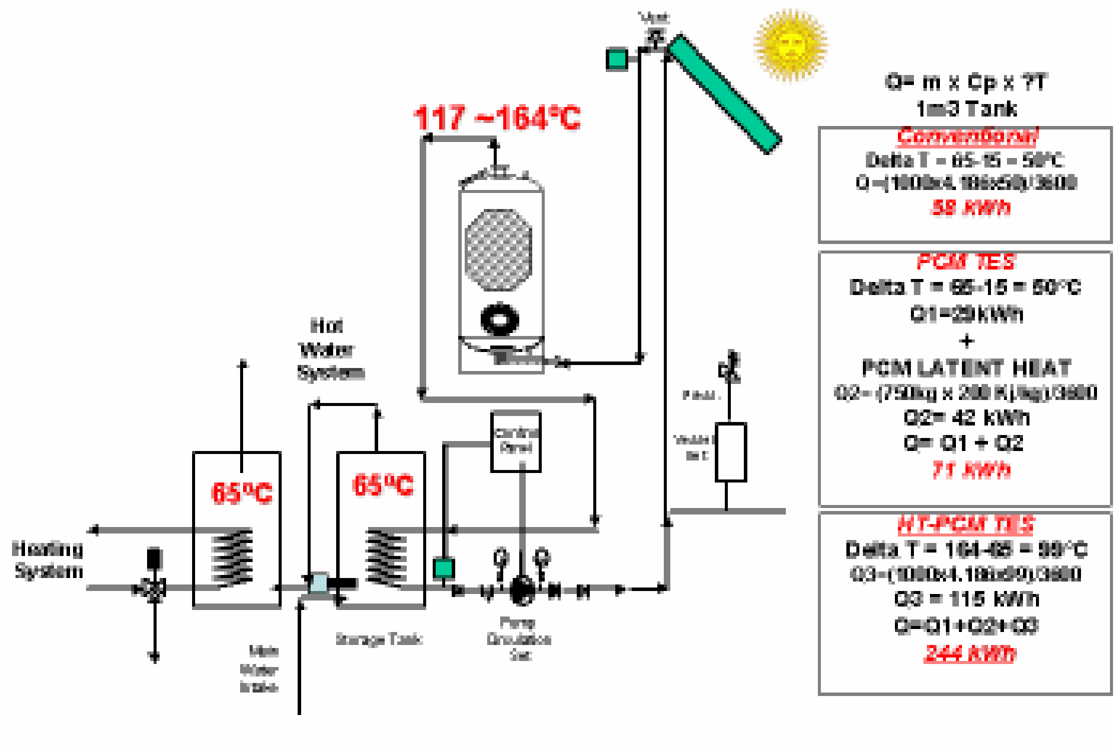

Figure 4.6.1- High temperature solar hot water PCM energy storage.

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.

PCM 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 PCM energy storage may be the answer for many of the cooling applications for an Environmentally Friendly and Economical alternative.

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