COBRA 2001

conference papers

SOLAR THERMAL STORAGE USING PHASE CHANGE MATERIALS FOR SPACE HEATING OF RESIDENTIAL BUILDINGS

Kenneth Ip PhD MSc MCIBSE CEng and Jonathan Gates BSc

University of Brighton, School of the Environment

ABSTRACT

A solar thermal energy storage system utilising phase change material (PCM) has been proposed that can overcome the time mismatch between solar availability and demand. The system consists of an array of flat plate solar collectors, which delivers heated water to a storage tank and a number of PCM filled panels. The panels are manufactured from aluminium sheet, which have a length of 15 mm-coiled copper tube running through them. The panels are connected together using push fit connectors for easy assembly. During operation hot water is circulated through the panels, which melts the PCM in the panels thus storing this thermal energy as both latent and sensible heat. When the heat is drawn from the panels the PCM begins to solidify thus releasing its stored sensible and latent energy, which provides space heating. A model of the system will be constructed in the laboratory and thermal performance assessed. The measured heat output of the system will be used in a thermal simulation program to predict potential energy savings if the system is used in a house. Previous theoretical research on a similar system has indicated that energy use can be reduced by between 18 – 32 %.

Keywords: Phase change materials, latent heat storage, solar thermal storage, thermal simulation

1.0 INTRODUCTION

In 1999 the domestic housing sector was responsible for over 29% of the UK's final energy consumption resulting in over 23 million tonnes of carbon dioxide (DTI 2000). The UK government in its policy for new and renewable energy acknowledges that renewables such as solar energy can play an important role in reducing CO_2 emissions as well as adding diversity and security of supply to the energy mix.

It is a common misconception that the UK does not receive enough solar irradiation to make solar panels a viable option. A solar collector located in the South of England at a 30° angle of inclination would receive approximately 50% of the solar irradiation received in Southern Europe (Halcrow Gilbert Associates and Stammers 1992). Solar energy offers a free, renewable and non-polluting source of energy, however the main problem with utilising this energy is that its availability is intermittent, variable and unpredictable. These problems can be addressed by the use of a thermal storage system, for instance an active solar combi-system that uses a phase change material (PCM) for thermal storage, which is being proposed in this paper. It has long been acknowledged that the inclusion of thermal storage can bring about a large increase in solar system efficiency to the point where it is only excluded in the most simplistic applications.

2.0 THERMAL STORAGE

Thermal storage can take the form of sensible heat storage (SHS), where thermal energy is stored as a result of a change in temperature of a material, or latent heat storage (LHS), where thermal energy is stored as a result of a change in physical state with no change in temperature. Materials that are used to store latent heat are termed PCMs. Builders have used sensible heat storage for centuries, because the cost of the storage material is low and readily available and the storage material can be incorporated into the building. There are some major problems with the use of SHS namely; they can result in excessive mass and undesirable temperature swings. There is also the argument that SHS involves a temperature change in the storage medium and yet thermal comfort in buildings is not aided by temperature fluctuations.

Larger quantities of energy are needed to change a material's physical state than is required to change a material's temperature. For example in order to store a given amount of energy the mass of concrete needed would be 8.4 times larger and its volume would be 5.9 larger, than if calcium chloride hexahydrate a PCM were to be used (Swet 1980).

3.0 PHASE CHANGE MATERIALS

Extensive research (Biswas 1977, Bourdeu 1980, Buddhi *et al* 1988, Farid 1968) has been carried out in the use of solid-liquid PCMs for the storage of solar thermal energy and it is this type of PCM that the current research will focus on.

A solid-liquid PCM (SLPCM) stores thermal energy when it melts and releases this when it solidifies. When thermal energy at a higher temperature is passed through a SLPCM below its melting point this energy is stored as sensible heat, but when the PCMs melting point is reached the material begins to melt and energy is stored as latent heat, this is termed the charge period. The PCM's temperature will begin to fall as it loses its thermal energy and when this reaches the melting point of the PCM, it will begin to solidify thus releasing its stored latent energy, this is termed the discharge period.

3.1 Selection of PCMs

There are two main types of solid-liquid PCMs, inorganic PCMs and organic PCMs. Inorganic PCMs include salt hydrates, salts, metals and alloys. Inorganic PCMs have a high heat of fusion per unit volume and possess good thermal conductivity (Jotshi and Goswami 1992). A major drawback with the use of inorganic PCMs in a storage system is that they suffer from supercooling (Lane 1991), which can prevent withdrawal of heat from the PCM and they degrade over time resulting in a decrease in overall heat capacity (Dincer and Dost 1996). Due to the aforementioned reasons an inorganic PCM was not selected for the study.

Organic PCMs include paraffins, polyalcohols and fatty acids. The advantages of organic PCMs are; they have a wide range of melting temperatures, high latent heat per unit weight, are non corrosive, non toxic and chemically stable and they are thermally stable in that they do not suffer from supercooling or phase segregation (Jotshi *et al* 1992). Organics are subject to changes in volume during phase transition, but this can be addressed by careful container design (Jotshi *et al* 1992). Organic PCMs are flammable but they can be combined with a small quantity of fire retardant (Salyer and Sircar 1990) and it has been argued that due to their low vapour pressure they present little fire hazard (Lane 1983a). Organics suffer from low thermal conductivity, but this problem can be addressed by using aluminium honeycomb or the addition of fins to the heat exchanger (Jotshi *et al* 1992). It can be seen that any disadvantages that organic PCMs possess can be overcome and are compensated by the fact that their thermal performance over the long term is consistent, which is why they have been selected for the current study.

4.0 Solar Energy Storage

Early attempts at solar thermal PCM storage had gained a bad reputation due to segregation and corrosion problems that made the systems unreliable (Lane 1983b). PCM research really began to pick up momentum once again during the Arab-Israel war that resulted in an oil embargo in the early 1970s, as countries began to research alternative energy supplies. Researchers realised that in order to utilise solar energy effectively an efficient thermal storage system was needed and PCM could provide high storage densities with minimal volume. When a PCM is used for thermal storage in conjunction with solar panels it can bring about a reduction in collector area in the order of 20 – 30 %, which reduces capital costs (Lane 1985a).

Researchers such as Dr George Lane undertook extensive research into isolating potential PCM candidates and investigated ways into which problems such as supercooling and phase decomposition could be addressed.

Most previously proposed PCM solar energy storage systems rely on the use of centralised storage of the PCM, such systems require purpose-built storage equipment (Ghonheim and Klein 1989) hence the implications of cost and space often prevent their use in domestic buildings.

The problem of storage space can be addressed if the PCM is impregnated into common building materials such as bricks or plasterboard (Athienitis *et al* 1997). However the PCM impregnated material may be difficult to retrieve if the building is refurbished or demolished. The proposed system described in section 5 aims to overcome these problems.

4.1 PCMs for Space Heating

A key advantage with the use of a PCM is that heat storage and recovery occurs isothermally which makes them ideal for space heating applications, where improved occupancy comfort can be obtained as a result of a reduction in temperature swings. Phase change materials have been used successfully for thermal storage in conjunction with both passive solar storage and active solar storage. For example the inclusion of a small volume of PCM in a Trombe passive solar storage collector wall can provide additional heat to warm a building throughout the night (Bourdeau 1980).

Using solar panels to provide thermal energy to an underfloor heating system forms a good partnership as higher collector efficiencies can be obtained due to the low flow temperatures required for underfloor heating. It has been shown that large energy savings are possible when an underfloor heating system is used in conjunction with direct gain passive solar storage, energy savings between 32% - 53% can be achieved (Athienitis and Chen 2000).

A space heating system that incorporates a PCM located in the ceiling void has been developed. Sun deflectors are used to direct solar energy entering via the windows onto the PCMs. The main advantage of the system is that it allows a large area to be dedicated to heat storage without the need for large volumes of storage medium that would be required with sensible heat storage. It has been shown that the use of such a system has the potential to recover 17 % - 36 % of heat lost over the initial percentage recovered from the internal gains (Gurtherz and Schiler 1991).

In some areas of Japan where overnight temperatures can fall undesirably low and morning temperatures can be uncomfortably high, a PCM incorporated into a floor has been used successfully in a house in order to mitigate temperature fluctuations (Hokoi and Kuroki 1997).

An electrical underfloor heating system that uses a paraffin wax with a melting point of 40º C has been proposed (Farid and Chen 1999). A 30 mm layer of PCM was placed between the heating surface and the floor tiles. Using computer simulation it was found that the heat output of the floor could be raised significantly form 30 W/m^2 to 75 W/m^2 if PCM storage is used.

A demonstration project by the Australian CADDET National team has shown that an underfloor heating system containing PCM can be charged by the use of solar panels. Performance data is not yet available but the floor is capable of storing 0.75 kWh/m^2 of latent heat.

The current research builds upon previous work carried out by Dr Ip at the University of Brighton in which he investigated and analysed a solar space heating system that incorporated a PCM for use in domestic buildings in the UK. The system comprised of an array of solar collectors and lengths of double walled copper tubing in which the PCM (calcium chloride) was encapsulated between the pipe walls. Water heated by the solar panel is circulated through the inner pipe and the heat is conducted to the PCM contained in the outer tube, thus melting the PCM. The pipes are located under the floor void and a series of fan coil units passes air over the pipes, which heats the air and this is then delivered to the space to be heated. By using a dynamic modular simulation programme (Ip 1991) seven different system configurations were analysed. Computer modelling showed that this system has the potential to reduce energy savings between 18–32% (Ip 1998).

The aforementioned research programmes highlight the potential of using PCMs for space heating. However, a criticism of some of the systems previously proposed is that they can only be used with suspended timber floors or they are cemented into the floor slab and so are difficult to remove if the building is decommissioned. The current research aims to evaluate the thermal performance of a PCM panel system, which can address such problems.

5.0 PROPOSED SYSTEM

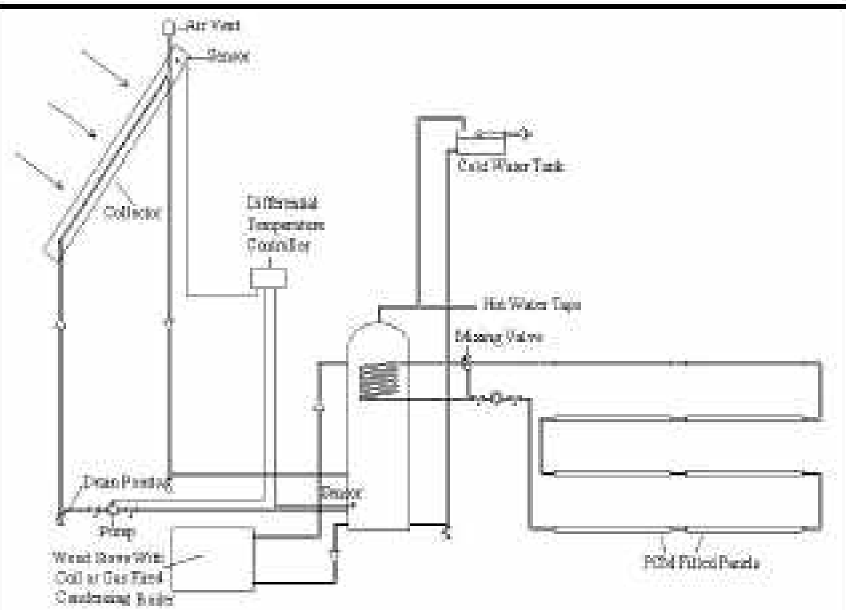

Fig. 1 System Schematic

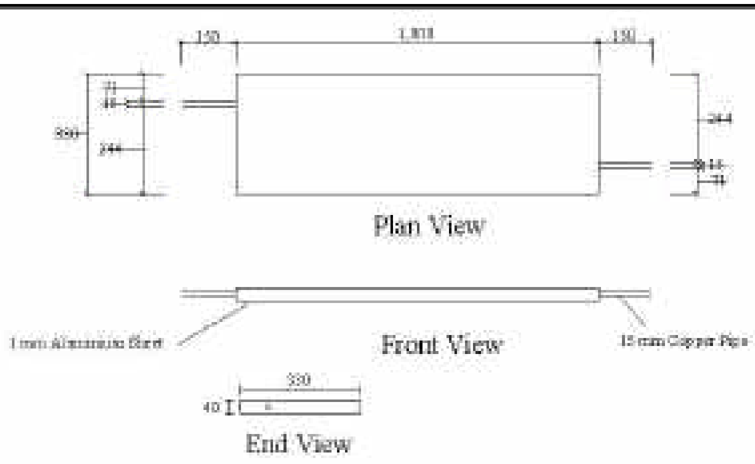

Fig. 2 PCM Filled Panels

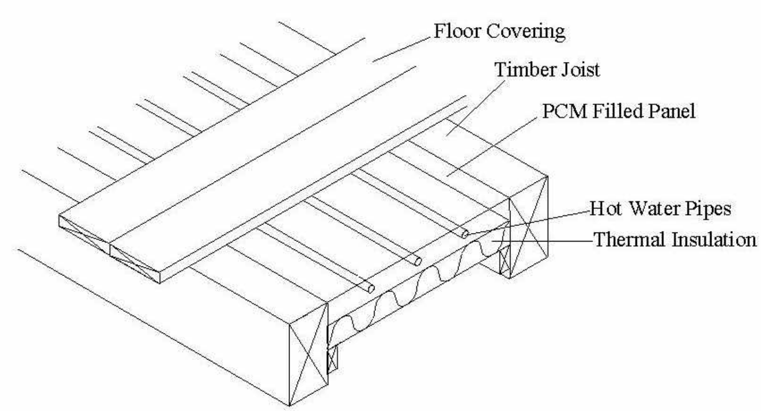

Fig. 3 PCM Panels Installed In A Suspended Timber Floor

The system proposed is a combi-system, as illustrated in Fig. 1. It is able to make a contribution to the space heating load and hot water demands. The system consists of an array of solar panels and a number of interconnected metal panels filled with a paraffin wax as a PCM. The panels are manufactured from aluminium plate and have a coil of copper tubing running through them.

A length of copper tube protrudes from each end of the PCM panel as illustrated in Fig. 2. These are used to connect the panels together using push fit connectors. The panels can be located either in the floor void of a suspended timber floor or on top of a concrete floor as illustrated in Fig. 3. Back up heating can be provided by a gas fired condensing Boiler or a wood stove.

5.1 System operation

Water heated by the solar collector is circulated through the copper tubes that run through the panel. The heat conducted through the walls of the copper tube will melt the PCM and so store solar thermal energy. A photovoltaic panel (PV) is used to drive the pump that circulates the water through the solar panel. The use of a PV panel allows the flow rate to be adjusted according to solar availability. For instance during periods of low solar irradiation the flow rate will be low thus giving the water more time in the panel to heat up. When heat is drawn from the PCM panels for space heating the PCM will begin to solidify when it reaches its melting point and in doing so release its latent energy. Water heated by the solar collector can also be used to provide hot water for bathing or washing.

5.2 System Features

The proposed system aims not only to reduce the use of fossil fuel, but also to address the environmental and practical construction issues. The following are some of the key features that offer advantages over the other systems.

- The geometry of the panels is such that it should address the problem of PCMs becoming self-insulating materials
- It is suitable for both new build and retrofit applications
- It can be taken out of a building and re-used if the building is decommissioned
- It is capable of reducing energy use and hence CO_2 emissions on an all year round basis
- It offers the possibility of using multiple PCMs in the same system. Some research suggests that the use of multiple PCMs can increase system efficiency by 13-26% (Gong and Mujumdar 1997). This is because in a single PCM system the temperature of the heat transfer fluid falls as it circulates through the system. This can mean that at the end of the circuit the temperature is not high enough to melt the PCM and store the thermal energy.
- High solar collector efficiencies can be produced due to low flow temperatures needed
- Similar advantages to underfloor heating; increased occupant comfort improved aesthetics over conventional space heating systems and flexibility of internal layout
- Reduced pay back time when compared with solar hot water systems
- An active solar system is more efficient than a passive system and more flexible in space utilisation

6.0 METHODOLOGY

The purpose of the experimental measurement is to evaluate the thermal performance of the PCM panel system. It is necessary to measure the panel performance empirically due to the fact that PCMs are notoriously difficult to mathematically model as they involve the so called moving boundary problems, which are dependant on time and are non linear in nature (Hasnain 1998).

6.1 Experimental Set Up

Four full size panels will be manufactured and these will be connected in series and installed in a highly insulated test box as shown in Fig. 4.

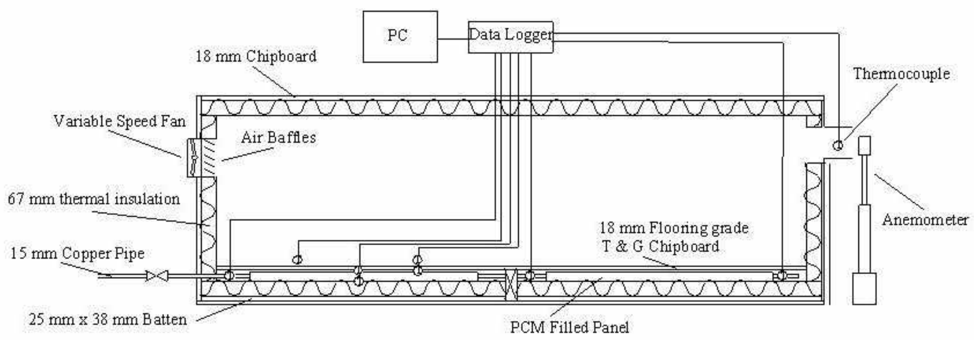

Fig. 4 Test Box

The test box has been designed to try to simulate the same conditions that would exist if the system were to operate in a real building. To this end the floor system can be changed in the test box from a suspended timber floor system to a concrete slab floor and floor coverings can be changed.

A solar panel will be installed on the roof of the laboratory and will provide the hot water that will be cycled through the PCM test panels. The angle of inclination of the panel will be 50º to the horizontal and 5º west of south in order to collect more solar irradiation in the winter when it is needed for space heating. The temperature of the water entering and exiting the solar panel will be measured using type K thermocouples and their outputs fed into a data logger. The amount of solar radiation falling on the panel will be measured using a solar flux sensor and the flow rate of water entering the panel will be measured using a flow meter connected to a data logger. The temperature of the water in the storage cylinder will also be measured using a thermocouple.

Water heated by the solar collector will be pumped via a variable speed pump through the PCM filled panels. Flow rate and flow temperatures are the two main variables that affect the charge time of the PCM panels. Flow rates will be measured using a flow rate meter and a thermocouple will be used to measure flow temperature. A variable speed fan will force air through the box and a baffle will be used to direct the flow of air inside the box. An anemometer will be located at a duct leading from an air vent at one end of the box in order to measure air speed.

Thermocouples will be sited in the copper tubes that run in between the panels and this will allow charge times and thermal performance to be established. A thermocouple will also be used to measure ambient air temperature. Thermocouples will also be located on the front and back of the PCM panels and the floor surface, directly above the PCM filled panels.

A pilot experiment will be carried out in order to check the operation of the system and that the measurements are sensible and provide the information required for the analysis. If the readings are satisfactory they will be used as a datum to check the readings taken during the full-scale experiment.

6.2 Analysis

The effect the flow rate and flow temperature has on charge and discharge times will be determined by analysing the thermocouple readings. Charge times will be ascertained by monitoring inlet and outlet temperatures of each panel, when inlet temperature is close to the outlet temperature the panel is deemed to be fully charged. Discharge times will be ascertained by analysing the temperature of the floor. During discharge heat output should be isothermal for a period of time, when this begins to fall steadily this is a sign that the PCM has solidified and all that is being released is stored sensible energy.

The heat output curve of the solar panel will be determined which will help to ascertain the maximum temperature that can be reached in different months of the year at different times of the day. The solar fraction and the energy delivered to the heating system by the active solar system will be calculated along with the collector loop efficiency.

When all of the collected data is analysed holistically it will be possible to determine methods for system optimisation and to devise the most efficient heating strategy to make efficient use of available solar irradiation and combine this with hours of occupation.

The measured heat output of the panels will be used in the APACHE thermal simulation programme so that the potential energy reductions the use of such a system can produce can be determined. A three bedroom house located in the South East of England will be used for modelling purposes. Parameters such as; location, orientation, size of openings and levels of thermal insulation can easily be altered inside the program in order that the affect these have on system performance can be determined.

One of the most important elements in data analysis is determining the accuracy of the collected data. The following issues will be addressed:

1. The extent to which the instrumentation affects the phenomenon being investigated.

2. How accurately the experimental set up reflects the real life scenario.

7.0 PROGRESS

A review on the state of the art use of PCMs for energy storage has been carried out. System requirements and criteria for system configuration have been drawn up. Phase change materials that possess the required properties for the application have been identified. A PCM energy storage system has been proposed using the system criteria previously established. The experimental set up has been designed and a potential location for the solar panel has been located on the roof of the University’s laboratory. Suitable solar collector systems have been identified and discussions are underway to secure sponsorship for the project. A three bedroom house located in South East England has been modelled in the APACHE thermal simulation programme and its heating load has been determined. The cost of the experimental set up has been calculated.

8.0 CONCLUSION

A solar energy storage system has been proposed that can address the problem of the mismatch between solar availability and demand. The proposed system combines the advantages of underfloor heating with the use of a PCM as a solar energy store without large volumes of storage medium being required. The research will provide important design information that will enable thermal storage systems to be incorporated in dwellings, which can reduce hot water and space heating energy use.
Although no experimental data on system performance is yet available previous research has indicated that the system should be capable of reducing CO_2 emissions on an all year round basis, which can help in the move towards more sustainable dwellings.

REFERENCES

Athienitis, A. K., Liu, C., Hawes, D., Banu, D. and Feldman, D., (1997). Investigation of the thermal performance of a passive solar test-room with wall latent heat storage. *Building and Environment*, **32,** pp405-410.
Athienitis, A. and Chen, Y., (2000). The effect of solar radiation on dynamic thermal performance of floor heating systems. *Solar Energy,* **69** pp229-237.
Biswas, D., (1977). Thermal energy storage using Sodium Sulfate Decahydrate and Water. *Solar Energy,* **9,** pp99-100.
Buddhi, D., Bansal, N.K., Sawney, R.L. and Sodha, M.S., (1988). Solar thermal storage systems using phase change materials. *International Journal of Energy Research*, **12** pp547-555.
Bourdeau, L. E., (1980). Study of two passive solar systems containing phase change material for thermal storage. *In: the 5th National Passive Solar Conference*, pp297-301.
Department of Trade and Industry (2000). *UK Energy In Brief,* Government Statistical Service.
Dincer, I. and Dost, S., (1996). A perspective on thermal energy storage systems for solar energy applications. *International Journal of Energy Research,* **20,** pp547-557.
Farid, M. M., (1968). Solar energy storage with phase change. *Solar Energy Research,* **4,** pp11-29.
Farid, M. M. and Chen, X.D., (1999). Domestic electrical space heating with heat storage. *Proc. Institute Mechanical Engineers*, **213,** pp83-92.
Ghoneim, A. A. and Klein, S.A. (1989). The effect of phase change material properties on the performance of solar air based heating systems. *Solar Energy,* **42,** pp441-447.
Gong, Z,X. and Mujumdar, A.S, (1997). Thermodynamic optimisation of the thermal process in energy storage using multiple phase change materials. *Applied Thermal Engineering*, **17** pp 1067-1083.
Gutherz, J. M. and Schiler, M. E., (1991). A passive solar heating system for the perimeter zone of office buildings. *Energy Sources,* **13,** pp39-54.

Halcrow Gilbert Associates. and Stammers, J., (1992). *Review of Active Solar Technologies*, DTI.

Hasnain, S. M., (1998). Review on sustainable thermal energy storage technologies, part 1: heat storage materials and techniques. *Energy Conversion Management,* **39,** pp1127-1138.

Hokoi, S. and Kuroki, T., (1997). Application of phase change material to passive solar heating. *In: Second International Conference Buildings and the Environment*, pp 585-592.

Ip, K. C. W., (1991). *Dynamic modular simulation of variable water and air volume flow systems in buildings.* University of Bristol, Bristol.

Ip, K. C. W., (1998). Solar thermal storage with phase change materials in domestic buildings *In: CIB World Congress* Gavle, Sweden, pp1265-1272.

Jotshi, C. K., Goswami, D. Y. and Tomlinson, J. J., (1992). Solar Thermal Energy storage in phase change material. *In: Proceedings of the Annual Conference of the American Solar Energy Society*, pp175-179.

Lane, G. A., (1983a). *Solar heat storage: latent heat materials Volume II: technology,* CRC Press Inc, Florida.

Lane, G. A., (1983b). *Solar heat storage: latent heat materials volume I: background and scientific principles,* CRC Press, Inc, Florida.

Lane, G. A., (1991). Phase change materials for energy storage nucleation to prevent supercooling. *Solar energy materials and solar cells*, **27,** pp135-160.

Salyer, I. O. and Sircar, A. K., (1990). Phase change materials for heating and cooling of residential buildings and other applications. *In: Proceedings of the 25th intersociety society energy conversion engineering*, pp236-243.

Swet, C.J. (1980). Phase change storage in passive solar architecture. *In: The National Passive Solar Conference,* pp282-286.