Solar thermal storage with phase change materials in domestic buildings

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Abstract
This paper summarises the investigation and analysis of a solar space heating system incorporating phase change materials for use in domestic buildings in the UK. Encapsulated phase change material modules designed to absorbed heat from water pipes are used for the thermal storage of solar energy. By choosing a suitable phase change material to take advantage of the latent heat absorbed during phase change of the material from solid form to liquid form, a large quantity of daytime solar energy can be stored and used for space heating at a later time. Conventional roof mounted flat plate solar panels have been selected for solar collection and the thermal energy is transferred to the phase change material through a series of pipes under the floor.

A dynamic modular simulation program is used to study the performance of the proposed space heating system. Components which simulate the two-dimensional heat transfer and the phase change process are established. Seven system configurations are analysed and their performances and energy savings are evaluated.

Results indicate the performance of the proposed system is affected by the attainment of phase change temperature in the phase change material. The generation of this phase change temperature is related to the area and efficiency of the solar panel, the temperature gradient along the length of pipe and the heat transfer characteristics of the equipment. The proposed system, which uses commonly available commercial materials and equipment, demonstrated to be viable. The results show the thermal effectiveness of phase change material and significant amount of energy saving can be achieved.
Keywords: Thermal storage, phase change materials, solar space heating, computer simulation

1 Introduction

Latent heat is the large quantity of energy which needs to be absorbed or released when a material changes phase from solid state to liquid state or vice versa. The magnitude of the energy involved can be demonstrated by comparing the sensible heat capacity of concrete with the latent heat capacity of a phase change material, calcium chloride for instance. Concrete has a sensible heat capacity of approximately 1.0 kJ/kgK [1] whereas calcium chlorine can store/release 190 kJ/kg [2] of energy during its phase change transition. It is obvious that any energy storage systems incorporating phase change materials will comprise significantly smaller volumes when compared to alternative materials storing only sensible heat.

One of the potential applications of phase change materials is the storage of solar energy. This is particularly suitable for dwellings where the roof can be used to collect the solar energy during the day, which is then used at a later time. As solar energy is a renewable energy source, reliance on fossil fuels and the greenhouse gas emissions can thus be reduced.

It is difficult to assess the performance of solar energy storage by phase change materials due to the dynamic nature of the system and the large number of variables involved. The main objectives of this study is therefore twofold. Firstly, to demonstrate the use of a computer simulation tool for the study of solar thermal storage systems incorporating phase change materials. Secondly, to use the simulation tool for investigating the performance of a proposed system. The following sections introduce the basic concepts of modular simulation, the functions of the modular components and the construction of the computer simulation models. The computer models of different configurations of the proposed system are simulated, the results are analysed and conclusions are summarised.

2 Simulation program

The simulation program used in this study is a dynamic modular simulation program [3]. The modular concept is to represent each component of a system as one module such that they can be linked together to form a complete network and subsequently the behaviour of the system can be studied. Each component is "self-contained" in the sense that information can only be conveyed through connecting nodes, the components react according to the information received and subsequently write new information to the nodes.

3 The components

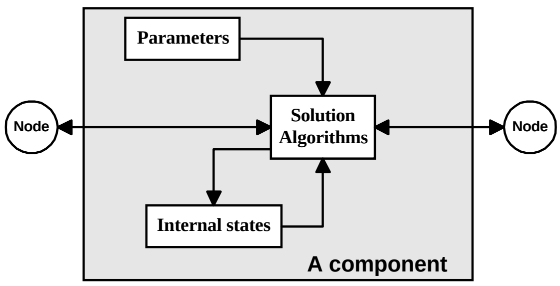


Figure 1 A component

Solution algorithms are contained within the component for describing its process. The component reads information from its nodes, parameters and internal states. The outputs are sent to the nodes and internal states.

Figure 1 shows the conceptual configuration of a component.

3.1 Pipe with phase change material

This is formed by two concentric pipes (see figure 5b) with the phase change material sandwiched between the two pipes. This component computes: 1) the radial heat transfer between the fluid, the phase change material and the ambient; 2) the heat transfer due to latent heat at phase change temperature; 3) the axial heat transfer along the length of the pipe and; 4) the water flow generation due to pressure difference exerted at its two ends. The descriptions and algorithms for these four functions are as follows:

1) Radial heat transfer

The pipe with phase change material calculates the radial heat transfer from the water inside the pipe to the surrounding air by the lump parameter procedure [3]. Figure 2 is the circuit representing the one dimensional radial heat flow of a section of the pipe. The governing radial heat transfer equations for a section j of the phase change material pipe are [4]:

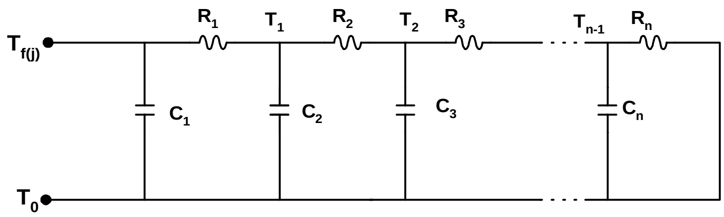


Figure 2 Radial heat flow network

$$m_f C_f (T_{f(j)} - T_{f(j-1)}) = C_1 \frac{dT_{f(j)}}{dt} + \frac{T_{f(j)} - T_1}{dt}$$

$$\frac{T_{f(j)} - T_1}{R_1} - \frac{T_1 - T_2}{R_2} = C_2 \frac{dT_1}{dt}$$

$$\frac{T_{(i-2)} - T_{(i-1)}}{R_{(i-1)}} - \frac{T_{(i-1)} - T_i}{R_i} = C_i \frac{dT_{(i-1)}}{dt}$$

$$\frac{T_{(n-2)} - T_{(n-1)}}{R_{(n-1)}} - \frac{T_{(n-1)} - T_o}{R_n} = C_n \frac{dT_{(n-1)}}{dt}$$

m_f = mass flow rate of fluid [kg s^{-1}]
$R_1 = R_{si} + 0.5\ R_{met}$ [K W^{-1}]
$R_2 = 0.5(R_{met} + R_{pcm})$ [K W^{-1}]
$R_{3\ to\ n-1}$ = thermal resistance of phase change material [K W^{-1}]
$R_n = R_{so} + 0.5R_{met}$ [K W^{-1}]
$C_1 = M_f C_f$ [J K^{-1}]
$C_2 = M_{met} C_{met}$ [J K^{-1}]
$C_{3\ to\ n}$ = thermal capacity of phase change material [J K^{-1}]
T = temperature [K]
M = mass [kg]
C = specific heat capacity [J kg^{-1} K^{-1}]
f, met, pcm = subscript for fluid, metal, phase change material
o, si, so = subscript for outside, inside surface, outside surface. All surface heat transfer coefficients are taken from the CIBSE guide [5].

2) Phase change heat transfer

When phase change occurs the latent heat effect is significantly greater than the sensible heat, hence the radial temperature distribution within each thin layer of the phase change material is assumed to be uniform [6]. This temperature uniformity is further maintained by subdividing the phase change material into thinner layers as shown in figure 2.

At phase change temperature T_{phc}, the heat energy is used for the phase change process. When the time step is small:

If $Q_{lhtmax} > Q_{lht} > 0$

$T_{pcm} = T_{phc}$

$Q_{lht} = \int W_{pcm}\, dt$

Q_{lht} = latent heat content of the phase change material [J kg^{-1}]
Q_{lhtmax} = maximum latent heat capacity of the phase change material [J kg^{-1}]
T_{pcm} = temperature of the phase change material [K]
W_{pcm} = rate of heat flow to the phase change material [Wkg^{-1}]

3) Axial heat transfer

To take into account the axial temperature gradient that exists in a long pipe and the narrow temperature range of the phase change process, each pipe component is subdivided into a number of sections along its length. The number of sections in each pipe is 16 but it can be increased by emulating a single pipe with several smaller pipes connected in series.

4) Water flow generation

The D'Arcy equation, which includes the static pressure generated by vertical pipes, is used:

$Rm^2 = |(P_1 - P_2) + P_h|$

P_1, P_2 = pressure at either ends of the pipe [Pa]
R = flow resistance of the pipe [Pa s^2 kg^{-2}]
P_h = static pressure [Pa]
m = mass flow rate of fluid [kgs^{-1}]

3.2 Solar panel

The basic equation for the solar heat Q collected from unit area of the solar panel is [7]:

$Q = F^*[I(t^*a) - U(T_i - T_a)]$

F = collector heat removal factor
t*a = product of transmittance and absorptance
U = the upward heat loss coefficient [$Wm^{-2}K^{-1}$]
T_i, T_a = water inlet temperature and atmospheric air temperature [K]
I = total solar irradiance [Wm^{-2}]

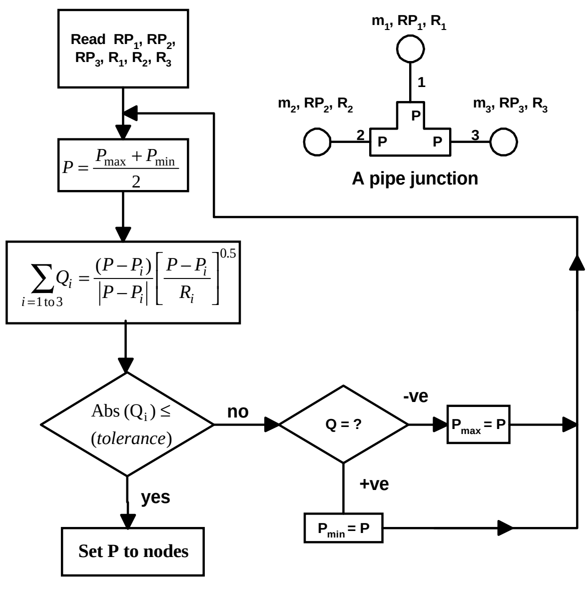


Figure 3 Flow chart for solving pressure at pipe junctions

3.3 Pipe junction

The pipe junction reads the mass flow rates m_i, remote pressures RP_i and pipe resistances R_i sent to it by the pipes on its branches and adjusts its own pressure in such a way that the sum of the mass flow will be zero. This new pressure P is found by a bi-sectional iterative method [3]. The flow chart in figure 3 shows the principle to achieve the solution.

3.4 Pump and fan

The pump or fan provides motive force for fluid, generates a pressure which drives flow through the attached components. The pressure developed by a pump or fan is a function of the flow it is called upon to deliver and is related to its characteristics. The equations governing the pump/fan component are:

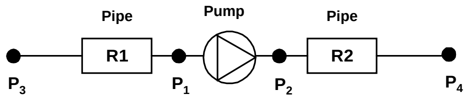


Figure 4 Pump with connecting pipes

$P_1 - P_2 = (am^2 + bm + c)$

$P_3 - P_1 = R_1 m^2$

$P_2 - P_4 = R_2 m^2$

P_1 to P_4 = total pressure [Pa]

m = mass flow rate of water [kg s^{-1}]

a, b, c = constants

Melting point	29°C
Heat of fusion	190.8 kJ/kg
Specific heat capacity	2.1 kJ/kgK (liquid at 48°C) 1.42 kJ/kgK (solid at 16°C)
Thermal conductivity	0.54 W/mK (liquid at 39°C) 1.008 W/mK (solid at 23 °C)
Density	1562 kg/m^3 (liquid at 32°C) 1820 kg/m^3 (solid at 23°C)

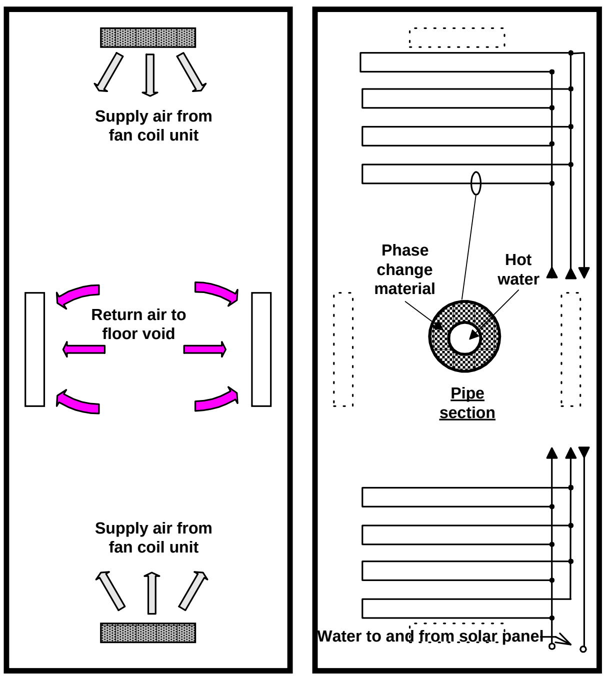
Table 1 Properties of phase change

3.5 Weather

The solar radiation data are based on the CIBSE guide section A2 [8] basic direct solar irradiances for southern England between October and March. The dry bulb temperatures are simulated using the factors given in the same section.

4 The model

The proposed building used in the simulation model is a typical two bedroom bungalow of 7m x 10m x 2.4m high. The sitting/dining room, which is to be heated by phase change material, has a measure of 3m x 7m. Solar panels of a total area of 20m^2 are installed on the south facing pitched roof. The phase change material is placed inside the house under the floor of the sitting/dining room. The phase



(a) (b)

Figure 5 Plans of room layout and phase change material under the floor void change material is contained within the pipe walls of two concentric copper pipes (see figure 5b). A pump in the loft circulates water between the solar panel and the pipes containing the phase change material. Two floor-standing fan coil units located at opposite sides of the room provide space heating for this room. Dampers are used to control air supply to the fan coil units. Air is drawn from the floor void below the units as long as the air temperature in the floor void is above the room air temperature. Otherwise air is drawn from the room through the front faces of the units. Any deficiency in heating requirement is complemented by the heating coils inside the fan coil units. Figure 5a illustrates the layout of the fan coil units and return air grilles. Figure 5b shows the layout of water pipes containing phase change material in the floor void and an exploded view of a pipe section.

5 Simulation

Flow networks similar to figure 6 are constructed using the components created in section 3. As preliminary studies indicated the importance of water temperature within the circuit, the investigation therefore focuses on the solar panel configuration and the length of the pipe containing the phase change material. Seven cases listed in table 2 are simulated to compare their performances. As effect of the latent heat is much greater than the sensible heat, only latter is considered in the simulation.

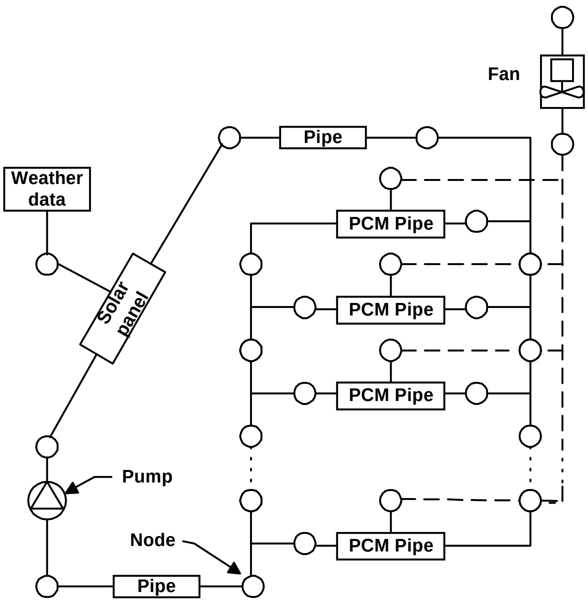


Figure 6 Computer simulation model

The space heating load of the building is separately analysed using the National House Energy Rating (NHER) program [9]. The single glazed solar panels used in the models have a total area of 20 m^2, with a heat removal factor of 0.93, heat loss coefficient of 7.0 W/m^{2}K and the product of transmittance and absorptance of 0.8. There are four parallel phase change material pipes linked to each solar panel. The phase change material used in this study is calcium chloride ($CaCl_2.6H_2O$) and its properties are shown in table 1 [2].

Case	Solar panel	PCM pipe	Total length (m)	Total volume of phase change material (m^3)
1.	5 m^2 x 4 nos.	3m x 16 nos.	48	0.09
2.	5 m^2 x 4 nos.	6m x 16nos.	96	0.18
3.	5 m^2 x 4 nos.	9m x 16 nos.	144	0.27
4.	5 m^2 x 4 nos.	12m x 16 nos.	192	0.36
5.	10 m^2 x 2 nos.	6m x 8 nos.	48	0.09
6.	10 m^2 x 2 nos.	9m x 8 nos.	72	0.14
7.	10 m^2 x 2 nos.	12m x 8 nos.	96	0.18

Table 2 Case studies

6 Results and discussion

The result from the NHER Program indicates the model room has a space heating load of 13.3 MJ when it is heated for eight hours with average outdoor and indoor temperatures of 21°C and 10°C respectively. The simulated total solar radiation reaching the solar panel on the pitched roof over 24 hour periods for the design days of the six months for SE England, as shown in figure 7, indicates that the available solar energy is well above that required for space heating. However under 2% of the total solar energy is converted into latent heat in the seven case studies.

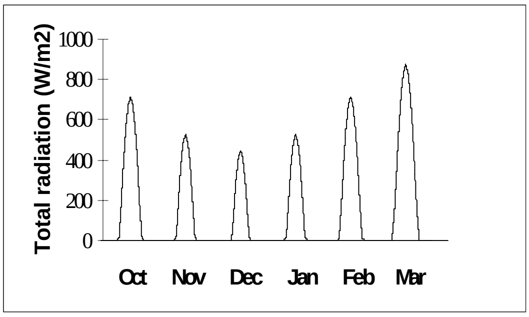


Figure 7 Total radiation on the solar panel

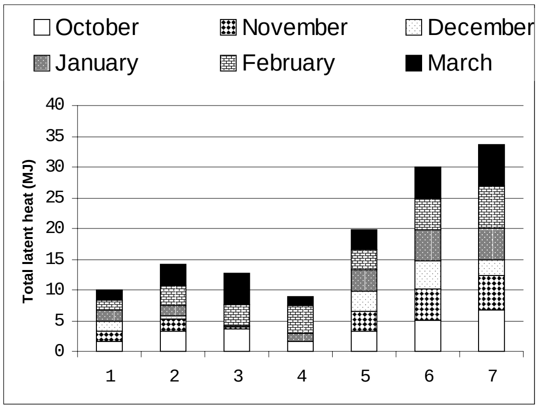


Figure 8 Latent heat captured

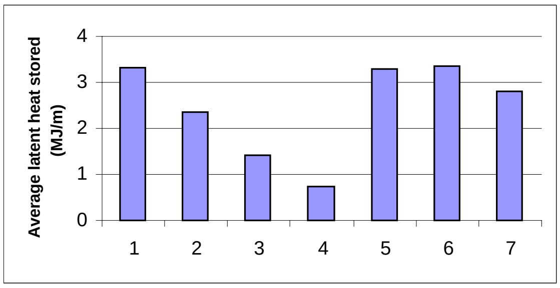


Figure 9 Latent heat stored per unit length

Based on the space heating load established from the NHER program, approximately 70 kg of phase change material is sufficient to provide the space heating requirement by latent heat alone. The amount of phase change material can be used in practice is restricted by the space of the floor void and the area of solar panel that can be mounted on the pitched roof.

Figure 8 shows the amount of latent heat being captured in each of the seven cases (table 1) under investigation. Results indicated that for the same amount of solar radiation, the main factors affecting the efficiency of theses storage systems are water temperature, heat transfer between the pipe walls and phase change process within the material itself. The amount of latent heat stored can vary significantly even when the same amount of phase change material is used in the systems as indicated by case 2 and 7. The use of the larger size solar panel in cases 5 to 7, which results in higher flow temperature, is more favourable for the latent heat storage. Lower water flow rates in return for higher water temperatures could have been used but this would change the heat transfer coefficients and affect the comparisons in the case studies. When evaluating performance per unit length of pipe, it appears that 3 m pipe has the highest latent heat content for cases 1 to 4 and the 6m pipe for cases 5 to 7. Based on the calculated space heating load and excluding the pump and energy, the savings due to solar thermal storage with phase change material are between 18 to 32% (figure 10).

7 Conclusion

Due to the dynamic nature of the solar radiation, the two-dimensional heat transfer and the phase change process, the study of thermal systems involving phase change materials and solar energy is a complex and tedious task. This paper illustrates how such kind of analysis can be performed by means of a modular simulation program.

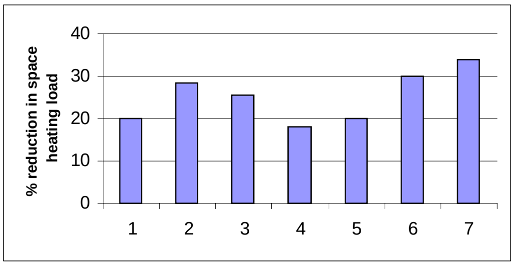


Figure 10 Energy reduction

This study demonstrates not only the viability of incorporating phase change material in domestic buildings to reduce the space heating energy consumption, it also shows that such a system can be constructed using commonly available materials and equipment. Results indicate the performance is affected by the attainment of phase change temperature through heat transfer from the water contained in the pipe to the phase change material. The generation of this phase change temperature is related to the area and efficiency of the solar panel, the temperature gradient along the length of pipe and the heat transfer efficiencies of the equipment. This study has laid the groundwork for further research on the use of phase change material in buildings. As domestic space heating accounts for a large proportion of the energy use in the UK, the exploitation of solar energy in conjunction with the storage potential of phase change material is a design option ought to be explored.

8 References

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