POTENTIAL OF SOLAR THERMAL STORAGE USING PHASE CHANGE MATERIALS IN THE UK

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ABSTRACT

This paper summarises the current research on the application of phase change materials (PCM) for the storage of solar energy in domestic buildings in the UK. A system, which takes into account the constrains of domestic buildings and constructed from common building components, is proposed. Alternative system configurations were modelled analysed and optimised using computer simulation. The space heating load of a typical dwelling was computed and the relative energy saving assessed. Required components for the computer simulation were created and system configurations with different component dimensions were optimised for the best thermal performance. Results showed 18% - 34% of energy saving can be achieved and highlighted the importance of thermal analyses of system configurations.

KEYWORDS

Phase change materials, latent heat, solar space heating, thermal storage, computer simulation.

INTRODUCTION

Thermal storage can take the form of sensible heat storage (SHS) or latent heat storage (LHS). To store the same amount of energy, significantly larger quantities of storage medium are required for SHS in comparison to LHS. In buildings this can be illustrated by the sensible heat capacity of concrete, which is approximately 1.0 kJ/kgK (CIBSE 1999b), whereas calcium chlorine, which during phase transition can store/release 190 kJ/kg of heat (Lane 1983). Solar thermal storage systems in buildings can be a solution to the time-mismatch between the internal space heating demand at night and external solar energy available during the day. When LHS is used to store solar energy it can increase the thermal storage efficiency. This paper introduces and analyse the performance of such a system for use in domestic buildings.

PROPOSED SYSTEM

The proposed thermal storage system aims to provide nighttime space heating by capturing and storing solar energy during the day. Most developed systems rely on the use of centralised storage of phase change materials. Such systems require purpose-built storage equipment (Morrison and Abdel-Khalik 1978, Ghoneim and Klein 1989); hence the implications of cost, space and operation often lead to very few applications in domestic buildings. The proposed system is constructed of commonly available components and can be installed in existing or new domestic buildings. The system consists of solar panels mounted on the southern elevation of a pitched roof. The phase change material (PCM) is contained within the pipe walls of two concentric metal pipes, which are placed inside an insulated floor void (or roof loft), both the pipe and PCM can be recycled at the end of the system's life. Water heated by the solar panel is pumped through the pipes containing the PCM and heat is transferred to the PCM. Heat supply to the room is by means of fan units with air dampers that control the volume of airflow. Heating coils can be placed inside the fan units to supplement any shortfall in space heating demand.

Not all phase change materials can be used in buildings. An ideal candidate should fulfil a number of criteria such as: high heat of fusion, high thermal conductivity, high specific heat capacity, minimal volume change during phase transition, suitable phase change temperature, be non corrosive, non toxic, non flammable and exhibit little or no supercooling or decomposition (Ghoneim, Klein *et al*. 1991). Considering the aforementioned factors and criteria for PCMs, an inorganic compound calcium chloride hexahydrate ($CaCl_2 6H_2 0$) was selected for use in this study.

SYSTEM MODELLING

The simulation model was based on a typical two bedroom bungalow measuring 7m × 10m × 2.4m high. The space heating for the dining/sitting room which measures 3m × 7m is provided by the PCM thermal storage system. The space-heating load of the building was analysed using the National House Energy Rating program (NHER. 1996) and the system simulation was performed by the Bristol Dynamic Modular Simulation program (Ip 1991). Seven different configurations, taking into consideration potential restrictions imposed by building construction and layout, were studied. The number of pipes, diameter and length were optimised for the best thermal performance.

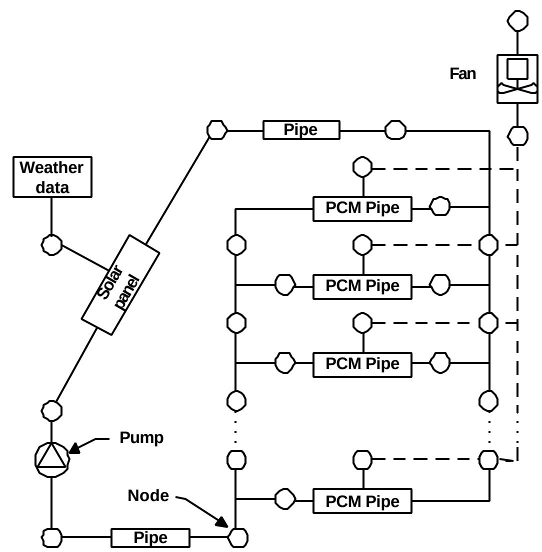

Figure 1

SIMULATION COMPONENTS

The key components used in the simulation programme include: solar panel, water pipe, pipe junction, water pump, air fan, PCM storage pipe and weather. The system network is shown in Figure 1. Dynamic simulation process involved the fluid flow through the network; heat collection by the solar panel; two-dimensional sensible and latent heat transfer processes along the length of pipe containing the PCM and heat transfer from the pipewall to the air. Some of the components' key functions are described below.

The walls of two concentric metal pipes in the “PCM-storage pipe” component are used to encapsulate the PCM. When water from the solar collectors is pumped through the inner pipe, heat is transferred to the PCM which in turn heated the surrounding air. The following processes are performed by this component:

- Radial heat transfer between the water, the pipewalls, the PCM and the external air;
- Heat transfer due to latent heat exchange at phase change temperature;
- Axial heat transfer along the length of the pipe; and
- Water flow generation due to pressure difference exerted at its two ends

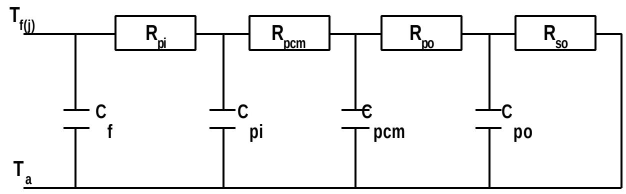

Figure 2

Each pipe component is subdivided into a number of sections along its length in order to take into account the axial temperature gradient that exists in a long pipe. At each time step (dt) this component determines if conditions for phase change process in each section comply.

Figure 2 is the circuit representing the one-dimensional radial heat flow of a section of the pipe based on the lump parameter procedure (Ip, Day *et al*. 1989, Holman 1997). The governing radial heat transfer equations for a unit section j along the length of the concentric pipes containing phase change material are:

$$m_f C_f (T_{f(j-1)} - T_{f(j)}) - \frac{2(T_{f(j)} - T_{pi})}{2R_{si} - R_{pi}} = M_f C_f \frac{dT_{f(j)}}{dt}$$

$$\frac{2(T_{f(j)} - T_{pi})}{2R_{si} - R_{pi}} - \frac{2(T_{pi} - T_{pcm})}{R_{pi} - R_{pcm}} = M_{pi} C_{pi} \frac{dT_{pi}}{dt}$$

$$\frac{2(T_{pi} - T_{pcm})}{R_{pi} - R_{pcm}} - \frac{2(T_{pcm} - T_{po})}{2R_{pcm} - R_{poi}} = M_{pcm} C_{pcm} \frac{dT_{pcm}}{dt}$$

$$\frac{2(T_{pcm} - T_{po})}{2R_{pcm} - R_{poi}} - \frac{2(T_{poi} - T_{a})}{2R_{so} - R_{po}} - = M_{po} C_{po} \frac{dT_{po}}{dt}$$

Where:
m = mass flow rate of fluid [kgs^{-1}]
C = specific heat capacity [$J\ kg^{-1}\ K^{-1}$]
T = temperature [K]
R = thermal resistance of PCM [$K\ W^{-1}$]
M = mass [kg]
Subscripts:
f = fluid
pi = inner pipe
po = outer pipe
pcm = phase change material
si = inside pipe surface
so = outside pipe surface
a = surrounding air

The D'Arcy equation governs the pressure-flow characteristic, which includes the static pressure P_h (Pa) generated by vertical pipes. The flow direction is dictated by the pressure difference P_1 (Pa) and P_2 (Pa) at either ends of the pipe:

$$R_p m^2 = \left| (P_1 - P_2) + P_h \right|$$

Where: R_p = flow resistance of the pipe [$Pa\ s^2\ kg^{-2}$] m = mass flow rate [kgs^{-1}]

The water and air flow rates in the component are kept constant, surface heat transfer coefficients between pipe wall and air h_a ($Wm^{-2}K^{-1}$), and between pipe wall and water h_w ($Wm^{-2}K^{-1}$) are taken from CIBSE guide (CIBSE 1986).

$$Q_{air} = h_a (t_{pos} - t_{air})$$

$$Q_{water} = h_w (t_{pis} - t_w)$$

Where: Q_{air}, Q_{water} = rate of heat transfer to air and water [W]
t_{air}, t_w, t_{pos}, t_{pis} = temperature of air, water, inside and outside pipe surfaces respectively [K]

The basic equation for the solar heat Q_{sol} collected from unit area of the solar panel used in the simulation is (ASHRAE. 1991):

$$Q_{sol} = F[I(t*a) - U(T_i - T_a)]$$

Where: 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}]

RESULTS AND DISCUSSION

Table 1. Optimised system configuration

Case	Solar panel	PCM pipe	Total volume of PCM (m^3)
1	5 m^2 x 4 nos.	3m x 16 nos.	0.09
2	5 m^2 x 4 nos.	6m x 16nos.	0.18
3	5 m^2 x 4 nos.	9m x 16 nos.	0.27
4	5 m^2 x 4 nos.	12m x 16 nos.	0.36
5	10 m^2 x 2 nos.	6m x 8 nos.	0.09
6	10 m^2 x 2 nos.	9m x 8 nos.	0.14
7	10 m^2 x 2 nos.	12m x 8 nos.	0.18

The simulation was carried out over the 24 hour period for each of the design months from October to March using the weather data from the CIBSE guide (CIBSE 1999a). This process identified optimum dimensions for the components and the system configurations that give the best thermal performance. The optimised configurations, with an outer pipe diameter of 65mm and an inner pipe diameter of 15mm, are shown in Table 1. The relative energy saving is shown in Figure 3 which indicates energy savings of 18-34% can be achieved under design conditions, excluding energy required for pumps and fans. The contribution of latent heat is shown in Figure 4. The higher flow temperature resulting from larger solar panel area resulted in higher latent heat storage efficiency as shown in Figure 5. Case 5 and 7 also illustrated efficiency drop due to longer pipe length. The results showed that storage of solar energy by phase change material, using commonly available material, can significantly reduce space-heating load. It highlighted the importance of the study of system configurations and optimum selection of equipment. Current research forms the foundation for further analyses and validation on the application of PCM in domestic buildings.

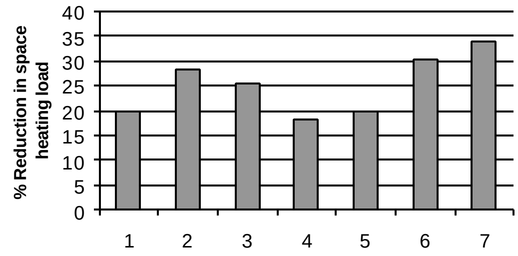

Fig. 3. Energy reduction

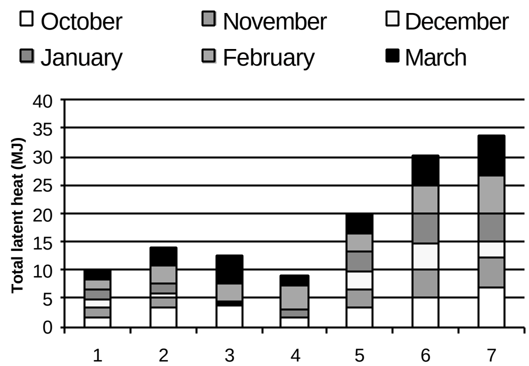

Fig. 4. Latent heat captured

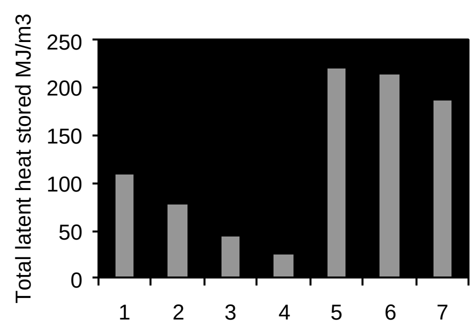

Fig. 5. Latent heat storage efficiency

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