The use of phase change material (PCM) to improve the coefficient of performance of a chiller for meeting domestic cooling in Wales

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ABSTRACT

This paper investigates the possibility of integrating thermal energy storage to the hot side of LiBr/H₂O absorption cooling system to cover 100% of peak cooling load for a three bedroom house on the hottest summer day in Cardiff, Wales. A shell and tube experimental system was designed to conduct charging and discharging experiments using Erythritol (melting point 117.7°C) as a phase change material, considered to have the highest energy density in the temperature range investigated (90°C to 120°C). The results show that Erythritol meets the requirement of an appropriate temperature range of application for the hot side of an absorption air-conditioning system. Erythritol store of 100 litres would provide approximately 4.4 hours of cooling at peak load based on the optimum COP of 0.7 for LiBr/H₂O absorption cooling system.

1 INTRODUCTION

Households consume 31% of the final energy usage in the UK, with cold appliances accounting for about a fifth of all domestic electricity consumption (Anon, 2004). Based on current climate change scenarios, Wales is expected to experience a rise in average annual daily temperature of between 2°C and 4°C by 2080 (UKCIP) due mainly to the environmental problems associated with conventional energy generation and the worldwide increasing demand for energy. The energy demand for domestic air conditioning in Europe is likely to increase during the peak cooling demand in summer, as indicated by the increase in air conditioned floor space from 30 million in 1980 to over 150 million in 2000 (Balaras et al, 2007). The quest for new technologies to avert the growing concern about environmental problems, the imminent energy shortage and the expected increase in average daily temperatures provide a strong motivation for a much-expanded clean energy supply for air conditioning applications. Renewable energy technologies offer a solution to many environmental and social problems associated with the conventional energy technologies indicating a clear environmental incentive to reduce the dependence on conventional energy sources. Solar energy is one of the most promising alternative energy options in the future because it is known to be non-polluting, inexhaustible, and clean. The fact that peak cooling demand is in phase with peak solar radiation offers the opportunity to optimise the solar thermal energy technology for heat-driven cooling applications. This paper assesses how the COP of a chiller can be improved using a phase change material with a solar collector at the hot side of an absorption chiller in order to meet the cooling needs of a selected modern three bedroom house in Wales during the summer period.

<table>
<thead>
<tr>
<th>Dwelling Type</th>
<th>Age of Dwelling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purpose-built Flat</td>
<td>Pre-1850</td>
</tr>
<tr>
<td>Purpose-built Low-rise Flat</td>
<td>1851-1919</td>
</tr>
<tr>
<td>Converted Flat</td>
<td>1920-1944</td>
</tr>
<tr>
<td>End-terrace Detached Flat</td>
<td>1945-1964</td>
</tr>
<tr>
<td>Semi-detached Detached Flat</td>
<td>1965-1980</td>
</tr>
<tr>
<td>Detached Detached House</td>
<td>1981-1999</td>
</tr>
<tr>
<td>End-terrace Semi-detached House</td>
<td>2000-2002</td>
</tr>
<tr>
<td>Detached House</td>
<td>Post-2000</td>
</tr>
</tbody>
</table>

Table 1: Dwelling categories in Wales based on age and type of building (Rhodes, 2007)

2 DWELLING CATEGORIES IN WALES

The selection of dwelling type to study was based on the classification of dwelling categories in Wales (Rhodes et al, 2007). A copy of the classification is reproduced in Table 1. The ranges of age used in Table 1 were selected based on building regulations passed at the time, which
changed building specifications. Out of the 69 dwelling types in Wales, a post 2000 modern three bedroom semi detached house was selected for study as part of a large study to characterise the energy needs of dwelling types in Wales. A post 2000 three bedroom semi detached house was initially selected because the modern houses are known to have higher indoor summer temperatures. Among the reasons assigned are the lower floor to ceiling height which reduces circulation of air, the high levels of insulation, the air-tight construction methods imposed by the latest building regulations and the excessive internal gains due to increased number of appliances used by occupants (Rhodes et al, 2007).

3 THERMAL COMFORTS

The purpose of cooling buildings is to provide indoor thermal conditions that are acceptable to the occupants of the building. The issue of thermal comfort therefore determines the cooling requirements. Indoor temperature is one of the four factors which define what most people consider a comfort zone. The rest are the relative humidity, the amount of air movement and the mean radiant temperature. Assuming mean radiant temperature and modest air movement with between 20% and 80% relative humidity, the comfort zone temperature in the summer months is estimated at between 20°C and 25°C (Hestnes, 1994). The energy demand for air conditioning to reach acceptable thermal comfort in the summer season has been experiencing a rapid growth in recent times and constitutes a very important component of the potential overall energy demand in the building sector, accounting for about 40% of primary energy demand in Europe. The need for air conditioning in the summer months for a three bedroom semi detached house has been demonstrated by Ampatzi and Knight (2007), using the weather data from Cardiff. The improvement in thermal comfort during the summer months using a 9m² vacuum tube solar collectors and a 4.5KW chiller, assuming a COP of 0.7 were suggested.

4 IMPROVEMENTS IN COP USING PCM

Of the air-conditioning alternatives, the LiBr/H₂O absorption system has been reported to have one of the most promising methods. A plot of COP as a function of heat supply temperature for single, double and triple-effect LiBr/H₂O solar absorption air conditioning in Europe by Balaras (2007) shows that the single effect system gives the best results in the temperature range 80°C to 100°C. The improvement in thermal comfort can be achieved using solar thermal powered LiBr/H₂O absorption cooling system. Among companies which currently produce small scale solar absorption chillers (2KW to 10KW capacity), powered by hot water is Rotatica in Spain. A key parameter used to measure the performance of any such thermally driven air conditioning system is the coefficient of performance (COP), defined as the useful cold produced per unit of driving heat, given by equation 1 (Henning, 2007).

\[
COP = \frac{Q_{\text{cold}}}{Q_{\text{heat}}}
\]

Single effect LiBr/H₂O absorption systems are generally limited to a COP of 0.7, requiring a large solar collector area to supply the heat needed for proper operation. The collector area can be reduced if system is capable of storing a higher temperature heat source for example, using a phase change storage system. A schematic representation of the underlying concept of integrating thermal energy storage and solar collection system to the hot side of an absorption cooling system is illustrated in Figure 1. The possibility of employing a phase change material with appropriate melting temperature to improve the COP is assessed by investigating into phase change materials.

The development of an effective thermal energy storage system utilising the process of phase change between solid and liquid to store and release energy at nearly constant temperature is of great scientific interest due to the potential improvement in temperature related COP that may be realised.

\[
\text{Figure 1: Schematic diagram of the underlying concept showing solar energy collection, thermal energy storage and its integration to air conditioning system (Alizadeh et al, 1979).}
\]
5 PCM SELECTIONS

The selection of an appropriate PCM requires the PCM to have a melting temperature within the practical range of application; in this case the selection was dictated by the temperature required for efficient operation of an hot side absorption air conditioning system. More than 90% of the literature on previous studies conducted on phase change materials relate to phase change materials in the lower temperature range between 0°C to 60°C, including palmitic acid, 57.8-61.8°C (Hasan, 1994), n-octadecane, 27.7°C (Lacroix, 1993), water-ice, 0°C (Laoudi et al., 1998), CaCl₂·6H₂O, 29.9°C (Zivkovic and Fujii, 2001), Na₂SO₄·10H₂O, 32°C (Ghoneim, 1989) and Paraffin wax, 44°C and Stearic acid, 58.1°C (Bansal and Budhi, 1992). Studies into medium temperature latent heat thermal energy storage system operating above 90°C suitable for use as hot-side storage for example in a LiBr/H₂O absorption air conditioning system are lacking (Agyenim et al., 2005).

Table 2: The thermophysical properties of the phase change materials selected for investigation.

<table>
<thead>
<tr>
<th>Deposit</th>
<th>Phase Change Material of PCM</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Erythritol</td>
<td>( \Delta H_\text{fus} (\text{kJ} \cdot \text{kg}^{-1}) )</td>
<td>117.7</td>
<td>116.7</td>
</tr>
<tr>
<td>PCM mass fraction</td>
<td>99</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CaCl₂·6H₂O</td>
<td>33.8</td>
<td>108.6</td>
<td></td>
</tr>
<tr>
<td>Specific heat of PCM solid, ( C_{p,\text{solid},\text{PCM}} ) (kJ kg(^-1) K(^-1))</td>
<td>2.7</td>
<td>2.8 (29°C)</td>
<td></td>
</tr>
<tr>
<td>Specific heat of PCM solid, ( C_{p,\text{solid},\text{PCM}} ) (kJ kg(^-1) K(^-1))</td>
<td>1.8</td>
<td>2.55 (29°C)</td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity of PCM solid, ( k_\text{solid,PCM} (\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}) )</td>
<td>0.326 (10°C)</td>
<td>0.371 (29°C)</td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity of PCM solid, ( k_\text{solid,PCM} (\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}) )</td>
<td>0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density of PCM solid, ( \rho_\text{solid,PCM} (\text{kg} \cdot \text{m}^{-3}) )</td>
<td>1300 (10°C)</td>
<td>1400 (29°C)</td>
<td></td>
</tr>
<tr>
<td>Density of PCM solid, ( \rho_\text{solid,PCM} (\text{kg} \cdot \text{m}^{-3}) )</td>
<td>0.9</td>
<td>775 (29°C)</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: The thermophysical properties of the phase change materials selected for investigation.

LiBr/H₂O absorption systems operate with generator inlet temperatures of less than 120°C, typically 75 to 88°C whilst water/ammonia units require temperatures of 90 to 180°C (Li and Sumathy, 2000). For these operating temperatures, Erythritol \( (C_{6}H_{12}O_{6} \cdot \text{melting point } 117.7^\circ \text{C}) \), RT 100 \( (C_{n}H_{2n+18} \cdot \text{melting point } 99^\circ \text{C}) \) and Magnesium chloride hexahydrate \( (\text{MgCl}_2\cdot6\text{H}_2\text{O} \cdot \text{melting point } 116.7^\circ \text{C}) \) were identified as having suitable melting temperatures to provide heat to drive the air conditioning system. The thermophysical properties of the three PCMs identified are detailed in Table 2. In addition to the PCM having a melting temperature that is within the practical range of application, the selection is also guided by the two most important advantages realisable by using PCMs:

- high energy density and
- the delivery ability to effect near constant temperature heat source.

The maximum energy density per given mass of Erythritol, magnesium chloride hexahydrate and RT100 were calculated using equation 2.

\[
\text{Q}=m[C_{f}(T - T_{\text{m}}) + C_{p}(T_{\text{w}} - T_{\text{ref}})] \quad (2)
\]

Erythritol would store 20% more energy than magnesium chloride hexahydrate (MCHH) and 32% more energy than RT100. The highest energy density of Erythritol combined with the fact that it is commercially available makes Erythritol suitable to be considered as energy storage material for the STACS project at the Welsh School of Architecture, Cardiff University.

6 EXPERIMENTAL RESULTS FROM CHARGING AND DISCHARGING ERYTHRITOL

An experimental system designed to test the suitability of Erythritol as a TES material consisted of a 54mm outer diameter horizontal copper cylinder embedded in Erythritol PCM within a one-metre long aluminium tubular container of 146mm inner diameter. Results obtained from experimental results were assessed to determine the suitability of Erythritol for use in the STACS project in The Welsh School of Architecture, Cardiff University.

Figure 2: Temperature profile along the length of the of a shell and tube phase change material storage system with an average HTF inlet temperature of 140°C and mass flow rate of 30 kg min\(^{-1}\).

Heat charging and discharging experiments were conducted to determine the quantitative information relating to the transient change in temperature in five different locations along the length of the PCM store. Figure 2 shows the time variation of measured temperatures at a heat transfer inlet fluid temperature of 140°C and a flow rate of 30 kg min\(^{-1}\). Thermocouples employed in the analysis (A, B, C, D and E) were located at 20mm from the heat transfer tube and at axial distances of 30mm, 250mm, 500mm, 750mm and 970mm from the inlet respectively.
The shapes of the temperature curves in Figure 2 illustrate temperature distribution in three different regions during the charging of Erythritol:

1. in the solid region below the lower limit of the melting temperature (115.6°C) of Erythritol,
2. in the solid-liquid phase transition region within the melting temperature range and
3. in the liquid region above the upper limit of the melting temperature (119.7°C).

The first period of heating involved the transfer of heat from the heat transfer fluid to the PCM. This energy was absorbed by the PCM in the form of sensible heat and increased the temperature of Erythritol from 20°C to 115.6°C. The temperature increased nearly linearly with time during the sensible heat addition but tended to asymptote after reaching a temperature of 115.6°C within 160 minutes. Complete melting was achieved at location A within 195 minutes into the phase transition period indicated by the rise in temperature above the upper phase transition temperature of 119.7°C. The melting temperature range for Erythritol was taken to be between 115.6°C and 119.7°C. Location B achieved a temperature above 119.7°C within 295 minutes into the phase transition period. This meant the formation of solid liquid interface proceeded down across the length of PCM with time. The final melt temperatures achieved at A, B, C, D and E (20mm away from the heat transfer tube) along the length of the store are given in Table 3.

<table>
<thead>
<tr>
<th>Thermocouple Location</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final melt temperature (°C)</td>
<td>125.8</td>
<td>122.4</td>
<td>118.6</td>
<td>120.2</td>
<td>120.2</td>
</tr>
</tbody>
</table>

Table 3: Final melt temperatures measured along the length of the PCM store ($T_s=140°C, m=30kg min^{−1})$.

At the very beginning of the discharge process, the temperature of the PCM at locations A and B dropped rapidly. Natural convection controlled the heat transfer in the liquid state at the very beginning and the heat dissipated from locations A and B were mainly sensible heat, accounting for the rapid temperature drop. Location A recorded a subcooling temperature at 114.8°C but rebounded to 117.4°C. Location B recorded a reduced temperature of 116.6°C and rebounded to 118.9°C. Locations C, D and E did not experience any temperature drop at the very beginning of the discharge process. Conduction controlled heat transfer at these locations because complete melting did not occur in these areas. Temperatures remained constant for approximately 110 minutes during the solidification process. As complete PCM solidification approached, progressively less and less latent heat energy was discharged until the temperature started to decrease more quickly to dissipate sensible heat from the solid PCM.

7 ENERGY STORAGE CAPACITY OF ERYTHRITOL TES SYSTEM.

The amount of energy needed to cover the annual cooling demand of a post 2000 three bedroom house in Cardiff has been estimated at 1472kWh with a peak of 2.1 kW (Ampatzi and Knight, 2007). Assuming no solar radiation for a day, Erythritol store of 100 litres would provide approximately 13.2kWh heat with 4.4 hours of cooling at peak load based on the optimum COP of 0.7 for LiBr/H$_2$O absorption cooling system.

8 CONCLUSIONS

The experiments show that Erythritol meets the temperature requirements of a PCM suitable to provide improvements in COP of LiBr/H$_2$O solar absorption cooling system. Preliminary evaluations show that Erythritol has a high storage capacity and would be suitable for use a TES for the STACS project. Study is ongoing at the Welsh School of Architecture, Cardiff University, Wales to identify other potential PCMs in the temperature range of between 90°C and 120°C to integrate the phase change material with a Thermomax vacuum tube solar collector at the hot side of a LiBr/H$_2$O absorption cooling system.

NOMENCLATURE

- $C_p$: Specific heat capacity of liquid PCM (kJ/kgK)
- $C_{ps}$: Specific heat capacity of solid PCM (kJ/kgK)
- $k_l$: Thermal conductivity of liquid PCM (W/mK)
- $k_s$: Thermal conductivity of solid PCM (W/mK)
- $m$: Mass of PCM (kg)
- $Q$: Energy or Heat flow (J)
- $Q_{cold}$: Useful cold produced (J)
- $Q_{heat}$: Heat input (J)
- $Q_{pc}$: Cooling peak load (kWh)
- $T_m$: Melting point of PCM (°C or K)
- $T$: Temperature (°C or K)
- $T_{ref}$: Reference temperature (°C or K)
- $V$: Volume (m$^3$)
- $\lambda$: Latent heat of fusion of PCM (kJ/kg)
ρ \quad \text{Density (kg/m}^3\text{)}

\rho_f \quad \text{Density of liquid PCM (kg/m}^3\text{)}

\rho_s \quad \text{Density of solid PCM (kg/m}^3\text{)}

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Further information on the project will be made available on the STACS project website: http://www.cf.ac.uk/archi/research/stacs/STACS.html.