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RESIDENTIAL THERMAL ENERGY STORAGE DEVELOPMENT

Roger A. CRANE[a], José L. F. PORTEIRO[a], and Ivan KLEVTSOV[b]

[a] Department of Mechanical Engineering, University of South Florida, 4202 Fowler Avenue, Tampa, Florida 33620-5350, USA
[b] Department of Thermal Engineering, Tallinn Technical University, Kopli 116, EE-0017 Tallinn, Estonia

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Abstract. A residential thermal energy storage device has been developed to facilitate shifting of electric utility heating loads. This device provides for the electric heating of phase change media during periods of low electric demand for utilization during periods of peak demand. By producing electric power during off peak periods, minimum costs of generating facilities may be used more effectively, and peak electrical generation requirements may be reduced. Previous analysis has shown a potential for significant economic savings for an efficient low cost energy storage system.

Key words: energy storage, phase change material, residential heating, smoothing of electric loads.

1. INTRODUCTION

Large peak heating loads are a common problem for electric utilities. This may be particularly acute in warmer regions where short or mild winters have encouraged extensive use of low heaters for residential heating. Florida utilities have reported peak loads in excess of 1000 MW during winter storms.

Traditionally, electric utilities have provided for these intermittent periods by adding peaking units. Alternatively, methods of load shifting or peak shaving may provide a cost effective option. Figure 1 indicates a typical daily generation load during a typical winter cold period. Two peaks are observed, one in the early morning as large numbers of households arise and another in the late afternoon as workers and children return home at the end of the day. The period between 5 and 11 a.m. represents a prime opportunity for load shifting. If the energy consumed during this peak could be produced between 11 a.m. and

6 p.m., peak loads are seen to be reduced by about 20%. The purpose of this paper is to present a thermal storage device suitable for a load shifting application in the average home environment.

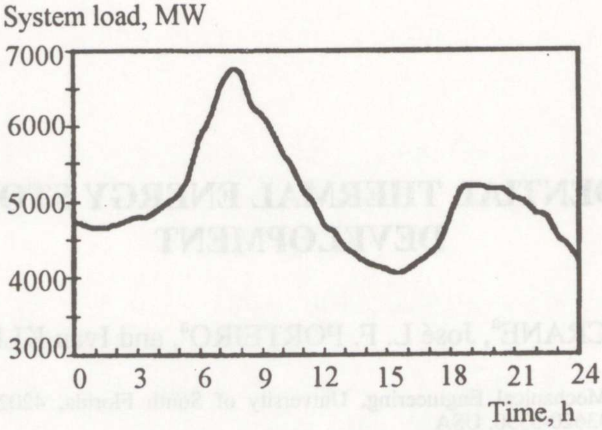

Fig. 1. Typical system peak load [1].

2. PERFORMANCE CRITERIA

The system proposed here provides for a residentially installed thermal energy storage unit. In order to be economically competitive, manufacturing and installation costs must be carefully controlled. Remote installation and intermittent operation will dictate reliable operation with minimal planned or unscheduled maintenance. A single model, suitable for a large number of traditionally built or pre-manufactured homes and adaptable to a variety of installation conditions, would be highly desired. Further considerations would include a simplified control systems to limit the complexity of centralized remote control. Finally, there should be a complete absence of any hazardous materials or environmentally unsafe materials so as to limit risk within the community. This should be accomplished with a final product which individual homeowners would elect to have installed within their own homes, based on whatever incentives the utility might choose to provide.

Among performance criteria, the following are included: initial charging time is not judged as critical given advanced warning of impending storms. However, because severe cold periods may last for several days, it is important that the unit, once initiated, be capable of recycling within a 24-hour period. An acceptable cycle has been assumed to consist of a thermal charging period not to exceed eight hours, a thermal storage period up to ten hours and a discharge period not to exceed five hours. Shorter discharge periods may be desired, which offer the utility an opportunity to stagger use patterns for individual residences to achieve a more efficient overall load pattern. Total thermal storage capacity has been, somewhat arbitrarily, set at kW_e-hr, this value being considered appropriate for short-term heating needs for typical single residences.

3. SYSTEM DESCRIPTION AND OPERATION

A schematic of the prototype device is shown in Fig. 2. The system includes a total of seven cylinders for thermal storage, arrayed in the lower right of the drawing. Each cylinder is filled with pentaerythritol as thermal storage material. Pentaerythritol belongs to the polyalcohols that offer the unique advantage of undergoing a solid/solid phase transformation with a relatively high enthalpy of transformation. Alternative storage materials include various organics (paraffin, polyethylene glycol, and cross-linked polyethylene) and salt hydrates. The decision to select one of the polyalcohols was primarily to utilize the design advantages of a solid phase material. Pentaerythritol was chosen for considerations of: a) low cost, b) a significantly higher enthalpy of transformation than the other polyalcohols, and c) non-toxic characteristics.

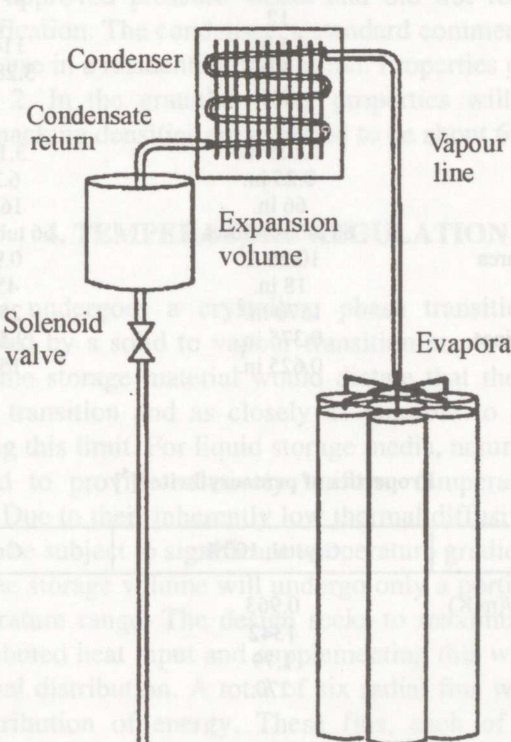

Fig. 2. Arrangement of a thermal storage system.

Cylinders may be situated as shown in a close packed array to minimize thermal loss, or alternate arrangements may be used to fit available space in specific applications. The cylinders are electrically heated by internal helical coils passing through the mass of the phase change material. A cooling tube runs centrally through each of the storage cylinders. These tubes contain R-134a which, when evaporated, is used to transport energy from the top of the storage cylinders, through a vapour line to the inside of the condenser. The condenser is situated in the same residential circulating air duct used for normal heating, ventilation, and air conditioning.

Table 1

Dimensions of major components

Component dimension	USA Units	SI Units
Storage cylinder height	54 in.	1372 mm
Storage cylinder diameter	6 in.	152.4 mm
Empty cylinder weight	49 lb.	22.2 kg
Pentaerythritol weight per cylinder	42 lb.	19 kg
Overall heater length	141 in.	3581 mm
Heater spirals	12	12
Heater spiral pitch	4.5 in.	114.3 mm
Heater resistance, ohm/ft.	1.0	3.28 ohm/m
Fin spacing	60°	60°
Number of fins	6	6
Fin thickness	0.125 in.	3.175 mm
Central tube I.D.	0.25 in.	6.35 mm
Central tube length	66 in.	1676 mm
Condenser arrangement	66 tubes/3 rows	66 tubes/3 rows
Condenser heat transfer area	10.26 ft^2	0.953 m^2
Duct diameter	18 in.	457 mm
Expansion tank volume	1570 $in.^3$	25.7 dm^3
Diameter of condensate lines	0.375 in.	9.525 mm
Diameter of vapour lines	0.625 in.	15.9 mm

Table 2

Properties of pentaerythritol [3]

	Crystal, 100%	Granular, 60%
Thermal conductivity, W/(m K)	0.963	0.16
Density, kg/m^3	1342	805
Specific heat, kJ/(kg K)	1.79	1.79
Heat of transition, kJ/kg	270	270

The system is sized and designed to operate in an average-sized home. The operating cycle for a typical household begins with the storage of thermal energy in the pentaerythritol-filled cylinders during off-peak hours, mostly at night. The following morning, the storage system is shut off and the stored energy is used to heat up the house by circulating cold house air over the condenser situated in the air-conditioning ductwork. A fan circulates room air through the air duct, passing it over the outside surface of the condenser. As the air is heated, energy is extracted from the R-134a, causing it to condense. The condensate returns to the cylinders through a solenoid valve. The system is turned off by closing the valve, blocking the path of heat removal. It is restarted when the valve is reopened reestablishing a heat removal path. An expansion tank, appearing adjacent to the condensate return line, is included in the system to accommodate vapour expansion during heating. In residential applications, the solenoid valve and the electric heaters inside the cylinders will be remotely controlled. In this way, the system operation is designed to be transparent to the residential customer.

Final system design specifications for the thermal storage canisters are shown in Table 1 and correspond to the conditions used for the reported test results. It may be noted that, in general, weights have been directly measured except for the pentaerythritol weight, which is calculated. The expansion tank used in these tests is considered to be considerably larger than required, but was found to meet the need for an approved pressure vessel and did not require special manufacturing or certification. The condenser, a standard commercially available unit, was designed for use in a residential installation. Properties of pentaerythritol are shown in Table 2. In the granular form, properties will vary with packing density. Typical packing densities are assumed to be about 60%.

4. TEMPERATURE REGULATION

Pentaerythritol undergoes a crystalline phase transition at about 360 °F (182.2 °C) followed by a solid to vapour transition at about 510 °F (265.6 °C). Efficient use of the storage material would dictate that the material be heated beyond the first transition and as closely as possible to the second, without actually exceeding this limit. For liquid storage media, natural convective effects may be expected to provide relatively uniform temperature throughout the storage material. Due to their inherently low thermal diffusivity and solid phase, polyalcohols will be subject to significant temperature gradients. The implication is that much of the storage volume will undergo only a portion of the theoretical maximum temperature range. The design seeks to maximize thermal usage by providing a distributed heat input and supplementing this with heat transfer fins to enhance thermal distribution. A total of six radial fins were used to assist in the uniform distribution of energy. These fins, each of 3.2 mm thickness, extended the entire length of the cylinder and across the entire radial gap between the inner cooling cylinder and the outer cylindrical containment wall. The utilization efficiency was used here as an indicator of the success in distributing stored energy uniformly and in effectively using the capacity of the storage material. It is defined as the ratio of the energy storage capacity achieved to that of a uniformly heated, ideal system heated to the same peak temperature.

The temperatures encountered in the phase change material are well above those considered desirable or safe for room heating. These temperatures have been moderated through the vapour transport system and expansion tank. The vapour lines were initially evacuated and filled with R-134a so that the liquid level would occur immediately above that of the storage cylinders when the R-134a temperature was at the minimum operational temperature, 125 °F (51.7 °C) selected in this case. The expansion tank was sized so that if 100% of the refrigerant were vapourized, the saturation pressure would not exceed that corresponding to the maximum operational temperature, 150 °F (65.6 °C) selected

$$\rho_{v,125} \cdot V_v + \rho_{l,125} \cdot V_l = \rho_{v,150} \cdot (V_v + V_l),$$

where V_v corresponds to the vapour volume at 125 °F and V_l to the liquid volume at 125 °F. When the vapour temperature drops below the minimum temperature, the condensate level rises to cover the entire heated surface on the inside of the storage cylinders, maximizing the rate of heat removal. When the vapour temperature exceeds the maximum operational value, the liquid level drops below that of the storage elements, effectively ending the energy transfer. Other important factors effecting vapour temperatures will include the temperature distribution within the thermal storage media. If the latter effects can be minimized, the design will provide for an extremely simple and reliable temperature regulation. The extent to which this control system is effective in maintaining uniform air duct exit temperatures is considered to be of prime importance in evaluating the overall system performance.

R-134a [2] has been selected as an energy transport medium. This provides an environmentally acceptable, non-toxic, non-flammable, readily available, and stable material. It provides a positive vapour pressure for temperatures down to –15 °F (–26.1 °C), helping to ensure against air infiltration. The saturation pressure corresponding to an average temperature of 150 °F (65.6 °C) is 278 psia (19.5 kgf/cm^2), allowing for the use of standard HVAC components.

5. TEST CONDITIONS

Experimental evaluation of the system was conducted over a period of about nine months. Initial runs were conducted with a relatively low charge of R-134a, and this was increased gradually as a way of adjusting the condensation temperature. Alternate series and parallel wiring arrangements for the seven cylinders provided for individual heater voltage drops of 73, 110 and 220 V using a standard 220 V source. These arrangements provided for differing power levels for the heating of the system and could be used to regulate temperature differences within the storage medium. The 73 V arrangement was selected for the initial test, corresponding to 3.14 kW input. In order to limit thermal losses, insulation using an overall rating of R40 was installed. Particular care was taken to insulate the cylinders from the support structure, using ceramic spacers, and to ensure that free circulation paths were obstructed.

6. TEST RESULTS

Initial test showed that, even with the low initial power level, a faint aroma of pentaerythritol would permeate the laboratory shortly after the heaters were switched on. Temperatures measured at the heater surface indicated levels slightly above those of the pentaerythritol but well below the published values for sublimation. Based on this observation and on those in parallel experiments, it was concluded that the material actually begins to sublimate at relatively low temperatures. After several thermal test cycles, a white powdery residue appeared around cylinder thermocouple penetrations, and later internal inspections indicated that the material had coalesced, possibly as a result of internal vapour recondensation. Clearly, a vapour tight system is required to prevent gradual depletion of the storage material. There was, however, no indication of measurable deterioration through the range of experiments, and thermal storage capability appeared undiminished through the series of the test.

During all the experiments, the storage cylinders were arranged in a hexagonally closely packed pattern. The complete system has been operated through seven complete cycles and five partial cycles. Temperature histories for the storage cylinders during the last test of the series are presented in Fig. 3. The output shown is from a total of seven thermocouples. Locations correspond to mid-height positions within the storage material. During the final heating phase, these were arrayed from highest to lower in the following order. The peak temperature occurred adjacent to the heater element in the interior cylinder. The next probes were adjacent to the central coolant pipe, at mid-radius and adjacent to outer for the interior and a peripheral cylinder, respectively. The temperatures are shown passing through a complete heat-up cycle.

The system was preheated for seven hours before power was shut off. Throughout the high temperature storage phase, the temperature readings do not differ significantly between the various regions of the phase change material. It may be noted that the curves begin to change slope prior to power shut-off, indicating that the material is beginning phase transformation. Power is reinitiated at 24 h and about one hour is required to recover the energy lost overnight. At 33 h, all thermocouples indicate that the pentaerythritol has passed through the phase transition. At this time, measured temperature differences from the seven thermocouples differ by a maximum of 28 degrees (15.6 °C), indicating that relatively uniform thermal storage had been achieved in the design. At this point, power was cut to the system, air circulation was initiated through the duct system and the condensate return line valve was opened. This initiated the cool-down phase. Within 5.5 h, all thermocouples within the storage media had readings below 150 °F (65.6 °C), indicating that the storage system was exhausted. This is comfortably within the design range of six hours for energy removal.

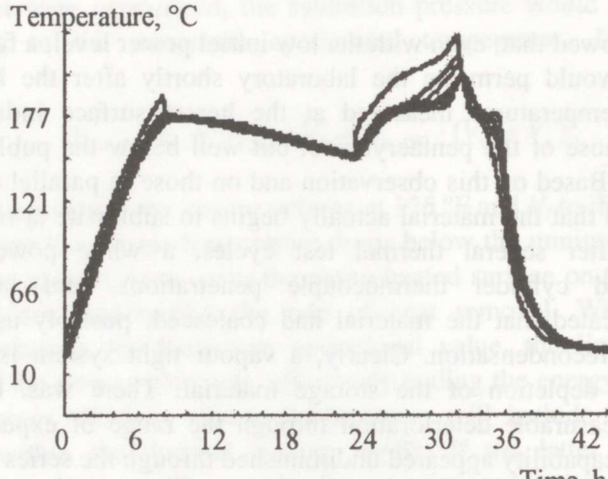

Fig. 3. Transient response in storage media.

Figure 4 shows the temperatures measured in the circulating air. Since these will remain near room temperature through the heating phase, the major focus will be on times after 33 h. The two lowest temperature readings were measured at room ambient and at the air duct inlet. The room temperature probe was placed physically closer to the thermal storage cylinders, resulting in a slightly higher temperature, but both remained very close to a constant 73 °F (22.8 °C). The remaining probes were situated inside the air duct, downstream of the condenser. The probe placed to measure temperatures in the upper 1/3 of the duct immediately downstream of the condenser resulted in the highest readings, one placed in the central 1/3 gave nearly identical results to another downstream probe, intended to measure temperatures after the stream had become well mixed. A probe immediately downstream of the condenser, situated in the lower 1/3 of the duct, yielded slightly lower readings.

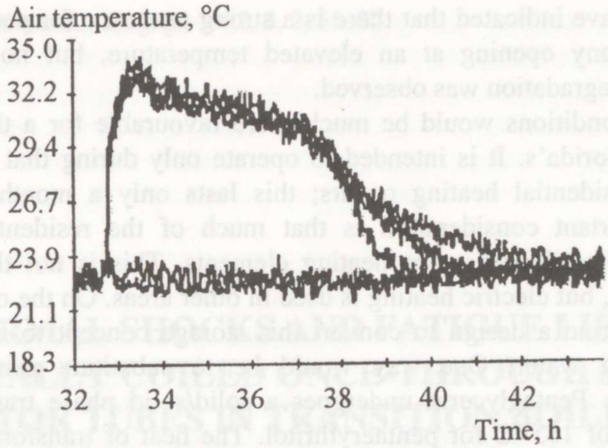

Fig. 4. Transient response in an air handling system.

The temperature variations with elevation downstream of the condenser were judged to be the result of initial superheating of the refrigerant as it enters the condenser and subcooling before exiting the bottom. After opening the control valve, air temperatures rise sharply as the transport loop and the condenser rise to operational temperature. Air temperatures quickly rise to about 92 °F (33.9 °C) and gradually drop toward 86 °F (30 °C) over the next 4.5 h as energy is drawn from the systems. After 4.5 h, a sudden change in slope is observed, corresponding to about the time that storage temperatures drop to below 150 °F (65.6 °C). At this point, the system is judged to be depleted and substantial refrigerant subcooling is observed in the lower portions of the condenser.

7. CONCLUSIONS

The proposed system has been tested and shown capable of being heated and of being discharged within appropriate periods. Temperature profiles within thermal storage material indicated relatively uniform heating with maximum measured temperature variations of under 60 °F (15.6 °C). This would provide for an energy utilization efficiency of better than 88%. Energy extraction was seen to be completed well within the design interval. Outlet air temperatures were observed to degrade somewhat during this period, indicating that the temperature control method, while working as intended and adequate for the application, was not able to provide the highly stable temperatures desired. Overall, the system has been shown to be capable of operating within the design range and no unusual safety or operational problems were encountered.

Within the literature [4] there has been concern expressed that a degree of thermal degradation may occur in the pentaerythritol with thermal cycling. These experiments have indicated that there is a strong tendency for pentaerythritol to escape from any opening at an elevated temperature, but no indication of performance degradation was observed.

Estonian conditions would be much more favourable for a thermal storage device than Florida's. It is intended to operate only during that portion of the year when residential heating occurs; this lasts only a month or two here. Another important consideration is that much of the residential heating in Florida uses electric resistance heating elements. This is not the case in the Estonian cities, but electric heating is used in other areas. On the other hand, it is quite easy to find a design to convert this storage concept to a system using circulating hot water. One way would be to substitute pentaglycerin for pentaerythritol. Pentaglycerin undergoes a solid/solid phase transformation at 81 °C instead of 185 °C for pentaerythritol. The heat of transformation is only 46 cal/gm as compared to 72.5 cal/gm for pentaerythritol. The storage volume would need to be larger, but hot water coils might be substituted for the electric heating elements and a much smaller condenser could be substituted. It would probably be desirable to construct one large storage system to serve an entire apartment building, perhaps even several such apartment buildings. This would allow for the power stations to supply hot water during that portion of the day when it is most convenient or economical to do so, but the residential users would be able to use the energy when it is most convenient for them.

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ERAMU SOOJUSSALVESTI

Roger A. CRANE, José L. F. PORTEIRO ja Ivan KLEVTSOV

On välja töötatud soojussalvestid, mis aitavad ühtlaselt jaotada eramajade elekterküttesüsteemide energiatarbimist. Soojusenergia salvestamiseks on kasutatud faasimuutusega materjale. Salvesti võimaldab koguda soojust energiasüsteemist minimaalse tarbimise ajal ja kasutada seda küttesüsteemis elektrienergia maksimaalse tarbimise perioodil. Sellega tagatakse energia ühtlasem tarbimine. Esialgne analüüs näitas, et selle odava ja efektiivse salvestussüsteemi kasutamine tagab üsnagi suure kokkuhoiu.