

## Characterization of Alkanes and Paraffin Waxes for Application as Phase Change Energy Storage Medium

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**Abstract** Latent thermal energy storage is one of the favorable kinds of thermal energy storage methods considered for renewable energy source utilization, as in solar photothermal systems. Heat is stored mostly by means of the latent heat of phase change of the medium. The temperature of the medium remains more or less constant during the phase transition. A large number of materials have been identified for low, intermediate, and high operating temperatures for application as latent thermal energy storage media. In the present paper a method for characterization of alkanes ( $C_1$ - $C_{100}$ ) and paraffin waxes for application as the low-temperature (298-323 K) phase change energy storage medium is introduced. A computational technique is introduced by which the alkanes and paraffin waxes could be evaluated, and possibly upgraded, as the phase change energy storage media. It is demonstrated that the family of n-alkanes has a large spectrum of latent heats, melting points, densities, and specific heats so that the heat storage designer has a good choice of n-alkanes as storage materials for any particular low-temperature thermal energy storage application. As an example of the proposed method, a particular paraffin wax for which appropriate experimental data are available is analyzed and the results of the analysis are presented.

**Keywords** alkanes, paraffin waxes, energy storage medium

### Introduction

For uninterrupted utilization of the intermittent renewable energy sources, such as the solar energy, it is necessary to develop a storage medium. Phase change (latent) thermal energy storage is one of the three kinds of thermal energy storage methods (sensible heat, latent thermal energy, and chemical energy) used for this purpose. In phase change thermal energy storage, heat is stored by means of the latent heat of phase change of the medium. The temperature of the phase change material

(PCM) remains more or less constant during the phase transformation (Abhat 1983; Batlet et al. 1979; Garg et al. 1985; Gomez and Mansoori 1983; Mansoori 1976; Mansoori and Patel 1979). Heat storage through phase change materials has the advantage of compactness because the heat of fusion (melting) of PCMs is very much larger than their specific (sensible) heats. PCMs such as *n*-alkanes and paraffin waxes appear to have some attractive features as a medium for storage of thermal energy, especially in direct photothermal solar energy utilization through flat-plate collectors.

For application of a material as a phase change thermal energy storage medium, information about its latent heat of phase transition as well as densities and specific heats is necessary. High latent heat is required to provide a higher thermal storage per unit weight. High density is desirable to allow a smaller size of storage container, and higher specific heat is preferred to provide for better sensible heat storage. In selecting a PCM for a particular application, the operating temperature of the heating and cooling systems must be matched with the melting temperature of the PCM. The PCM melting point range must be chosen at a temperature interval above the operating temperature. This range must be large enough to provide a sufficient temperature gradient for a satisfactory heat withdrawal rate. But the temperature range should not be excessive, since the heat loss will increase and the system efficiency will decrease. Generally, for PCMs the higher the thermal conductivity the more efficient is the rate of heat transfer, and the higher the density the larger is the heat of melting per unit volume.

There are four possibilities in changes of phase: solid-gas, liquid-gas, solid-solid, and solid-liquid. The absolute value of latent heat of phase change for a solid-solid transition is usually less than that of solid-liquid conversion. Solid-gas and liquid-gas transitions are generally not employed for energy storage, in spite of their high latent heat, because gases occupy large volumes, requiring a big space for storage. Solid-liquid transition has comparatively smaller latent heat than solid-gas; however, solid-liquid transition involves only a small change in volume and therefore it is quite promising for phase change energy storage. The candidate PCMs are generally divided into two groups: organic and inorganic compounds. Inorganic compounds show a volumetric latent thermal energy storage capacity twice that of organic compounds. But the organic substances could serve as important heat storage media because of their several advantages, including their ability to melt congruently, their self-nucleation, and the noncorrosiveness of the conventional materials of construction. Alkanes and paraffin waxes are in the latter category.

In comparison to inorganic PCMs, paraffin wax PCMs have no problems of phase separation on melting and have good self-nucleating properties on freezing, so that nucleating agents are not required. They also do not have corrosion problems of the conventional materials of construction, so that they have long-term performance.

A large number of PCMs have been identified for low, intermediate, and high operating temperatures for application as latent thermal energy storage (Batlet et al. 1979; Abhat 1983). The present report is intended to discuss the characterization of alkanes and paraffin waxes for application as low-temperature phase change energy storage medium. A low-temperature PCM should operate in the 273–393 K temperature range.

In the first part of this report we present and characterize the peculiar thermophysical properties of paraffin hydrocarbons (alkanes), which comprise the paraffin waxes. In the second part of this report we introduce a method to analyze

and characterize paraffin waxes from the point of view of their use as PCMs. Then we introduce a computational technique by which the paraffin waxes can be evaluated, and possibly upgraded, as PCMs. As an example of the proposed method, a particular paraffin wax for which appropriate experimental data are available is analyzed and the results of the analysis are presented.

### **Paraffin Hydrocarbons (Alkanes)**

Paraffins are mineral oil (petroleum) products, consisting mostly of the organic family of heavy hydrocarbons called alkanes, with the chemical formula  $C_nH_{2n+2}$ , with  $n \geq 16$ . Presence of paraffins in crude oil could cause plugging problems due to wax buildup inside conduits (well, pipeline, etc.) during production, transportation, and storage of petroleum crude (Kawanaka et al. 1991). However, paraffin and microcrystalline waxes are important petroleum refinery products. According to the statistics published by the petroleum industry, demand for these products continues to increase (International Petroleum Encyclopedia 1993). As a result, paraffin hydrocarbons can be a primary product rather than a by-product of a refinery. Pure paraffins contain only alkanes. The first four alkanes of the series (from methane,  $CH_4$ , up to butane,  $C_4H_{10}$ ) are gaseous at room temperature and atmospheric pressure. The compounds between  $C_5H_{12}$  and  $C_{17}H_{36}$  are liquids and compounds with more than 17 carbon atoms per molecule are waxy solids at room temperature. The melting points and the heats of fusion of alkanes increase with their number of carbon atoms. In Table 1 we have compiled the data on molecular weights, melting points, latent heats of fusion, densities (at 20°C), specific heats in solid and liquid states, and boiling points of the normal alkanes from  $C_1$  to  $C_{100}$ , all at atmospheric conditions. Most of the property data in this table are from Domalsky et al. (1984), Garge et al. (1985), Lane (1986), Marsh et al. (1988), and Timmermans (1965). For alkanes for which these experimental data were not available, they were estimated using estimation techniques (Chorn and Mansoori 1988), discussion of which is beyond the scope of the present report.

Because of "steric" effects, caused by the arrangement of atoms in the molecule, there is a difference between alkanes with odd and even numbers of carbon atoms. The even-numbered homologs have higher latent heat than the odd-numbered homologs. Humphries (1974) showed that alkanes with an even number of carbon atoms (between 20 and 32) and alkanes with odd number of carbon atoms (higher than 7) exhibit a lattice transition in the solid state. The even-numbered carbon atom alkanes exhibit this transition closer to their melting point than the odd-numbered alkanes as demonstrated in Figure 1. Also shown in Figure 1 is the boiling point of normal alkanes for the temperature range of the figure.

The lattice transition in alkanes is accompanied by the release of heat of transition. Generally, lattice transition occurs in the solid state at about 2–5 K below the melting point. The difference between the transition temperature and melting temperature becomes smaller with increasing molecular weight and finally disappears for alkanes with more than 36 carbon atoms (Mozes 1982), as demonstrated in Figure 1. The heat associated with this solid-solid transition is subtracted from the latent heat of melting.

Figures 2 and 3 show variations of the latent heat of melting, melting point, and density of normal alkanes versus increasing number of carbon atoms in their structures. According to these figures, while the melting point and density versus

**Table 1**  
**Thermodynamic Properties of *n*-Alkanes**

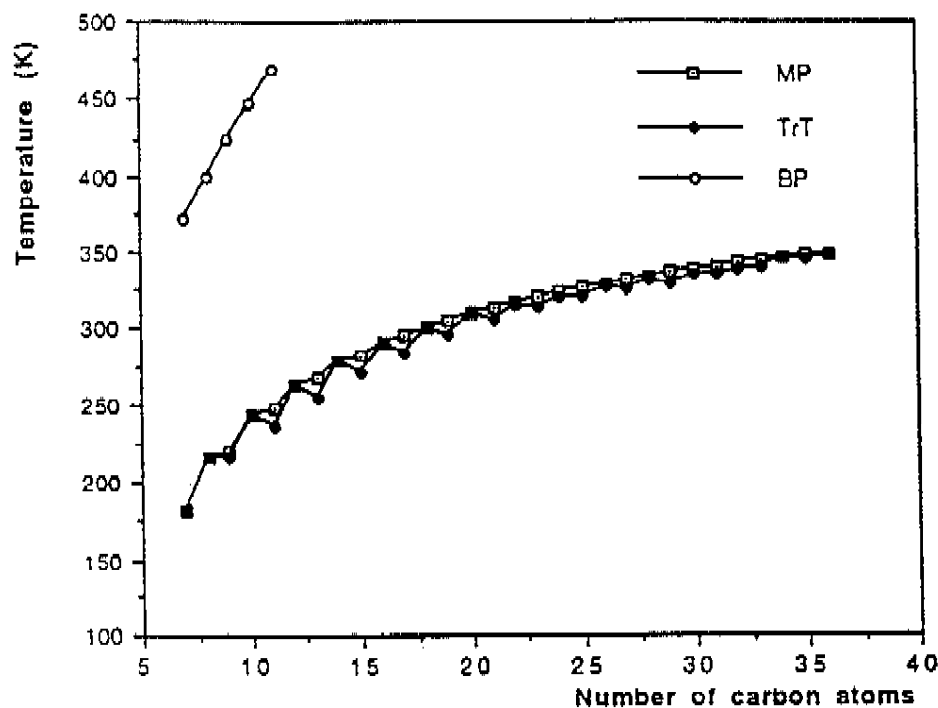
<i>n</i> -Alkanes	No. of C Atoms	Mol. Weight	Melting Point (K)	Latent Heat of Fusion (kJ/kg)	Density at 20°C (kg/m <sup>3</sup> )	Specific Heat		Boiling Point (K)
						Solid (J/mol.K) at 298 K	Liquid (J/mol.K) at 353 K	
Methane	1	16	90.68	58	0.658 (g)	—	—	116.6
Ethane	2	30	90.38	95	0.124 (g)	—	—	184.6
Propane	3	44	85.47	80	1.834 (g)	—	—	231.1
Butane	4	58	134.79	105	2.455 (g)	—	—	272.7
Pentane	5	72	143.45	117	621 (l)	—	167.2	309.0
Hexane	6	86	177.83	152	655 (l)	—	195.4	341.9
Heptane	7	100	182.55	141	649 (l)	—	225.0	371.6
Octane	8	114	216.37	181	699 (l)	—	254.2	398.8
Nonane	9	128	219.65	170	714 (l)	—	284.5	424.0
Decane	10	142	243.50	202	726 (l)	—	314.5	447.3
Undecane	11	156	247.55	177	737 (l)	—	345.0	469.1
Dodecane	12	170	263.55	216	745 (l)	—	376.0	489.5
Tridecane	13	184	267.75	196	753 (l)	—	406.9	508.6
Tetradecane	14	198	278.95	227	759 (l)	—	438.5	526.7
Pentadecane	15	212	283.05	207	765 (l)	—	470.0	543.8
Hexadecane	16	226	291.25	236	770 (l)	—	501.5	560.0
Heptadecane	17	240	295.05	214	775 (s)	—	534.3	575.2
Octadecane	18	254	301.25	244	779 (s)	—	564.4	589.5
Nonadecane	19	268	305.15	222	782 (s)	—	618 <sup>a</sup>	603.1
Eicosane	20	282	309.75	248	785 (s)	—	658 <sup>a</sup>	617.0
Heneicosane	21	296	313.35	213	788 (s)	—	698 <sup>a</sup>	629.7
Docosane	22	310	317.15	252	791 (s)	—	739.0	641.8
Tricosane	23	324	320.65	234	793 (s)	—	625.0 <sup>a</sup>	653.4

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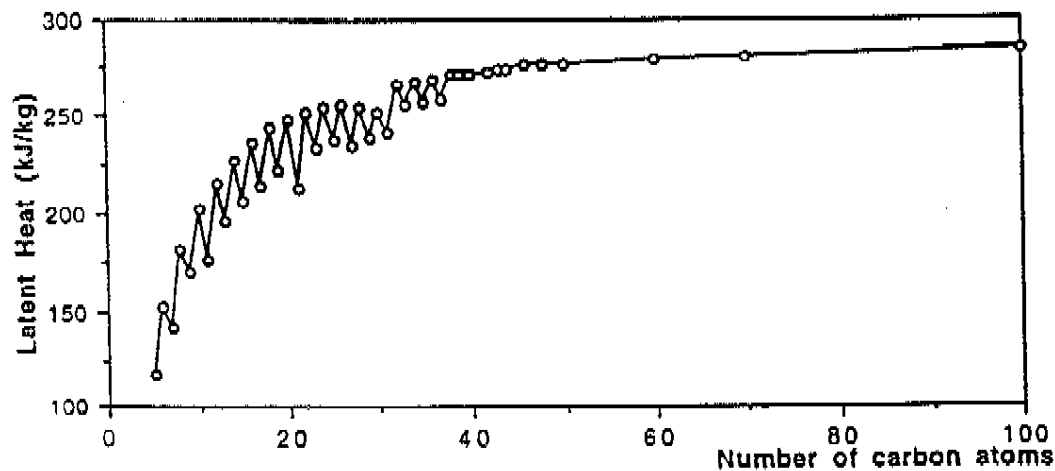
Tetracosane	24	338	323.75	255	796 (s)	651.4 <sup>a</sup>	805.0	664.5
Pentacosane	25	352	326.65	238	798 (s)	670.4 <sup>a</sup>	815.9	675.1
Hexacosane	26	366	329.45	250	800 (s)	677.8	870.0	685.4
Heptacosane	27	380	331.95	235	802 (s)	728.1 <sup>a</sup>	928 <sup>a</sup>	695.3
Octacosane	28	394	334.35	254	803 (s)	752.8 <sup>a</sup>	937.0	704.8
Nonacosane	29	408	336.35	239	805 (s)	777.2 <sup>a</sup>	1001 <sup>a</sup>	714.0
Triacosane	30	422	338.55	252	806 (s)	801.2 <sup>a</sup>	1037 <sup>a</sup>	722.9
Henriacontane	31	436	341.05	242	808 (s)	824.5 <sup>a</sup>	1073 <sup>a</sup>	731.2
Dotriacontane	32	450	342.85	266	809 (s)	867.4	1095	740.2
Trtriacontane	33	464	344.55	256	810 (s)	871.0 <sup>a</sup>	1113	748.2
Tetraacontane	34	478	346.25	268	811 (s)	887.4	1149	755.2
Pentatriacontane	35	492	347.85	257	812 (s)	916.0	1210 <sup>a</sup>	763.2
Hexatriacontane	36	506	349.35	269	814 (s)	937.5 <sup>a</sup>	1206	770.2
Heptatriacontane	37	520	350.85	259	815 (s)	959.1 <sup>a</sup>	1276 <sup>a</sup>	777.2
Octatriacontane	38	534	352.15	271	815 (s)	980.4 <sup>a</sup>	1305 <sup>a</sup>	784.2
Nonatriacontane	39	548	353.45	271 <sup>a</sup>	816 (s)	1001 <sup>a</sup>	1341 <sup>a</sup>	791.2
Tetracontane	40	562	354.65	272	817 (s)	1022 <sup>a</sup>	1411	795.2
Dotetracontane	42	590	357.32	273	817 (s)	1062 <sup>a</sup>	1435	804.2
Tritetracontane	43	604	358.65	273 <sup>a</sup>	819 <sup>a</sup> (s)	1085 <sup>a</sup>	1465 <sup>a</sup>	813.2
Tetrateracontane	44	618	359.55	274	820 <sup>a</sup> (s)	1102 <sup>a</sup>	1495 <sup>a</sup>	818.2
Hexetracontane	46	646	361.45	276	822 <sup>a</sup> (s)	1140 <sup>a</sup>	1553 <sup>a</sup>	829.2
Octetracontane	48	674	363.45	276	823 (s)	1177	1595	838.2
Pentacontane	50	702	365.15	276	825 <sup>a</sup> (s)	1213 <sup>a</sup>	1665 <sup>a</sup>	848.2
Hexacontane	60	842	372.15	279	831 <sup>a</sup> (s)	1380 <sup>a</sup>	1916 <sup>a</sup>	888.2
Heptacontane	70	982	378.65	281 <sup>a</sup>	836 <sup>a</sup> (s)	1526 <sup>a</sup>	2131 <sup>a</sup>	919.2
Hectane	100	1402	388.40	285 <sup>a</sup>	846 <sup>a</sup> (s)	1869 <sup>a</sup>	2598 <sup>a</sup>	935.2

<sup>a</sup> Estimated values --- experimental data not available.

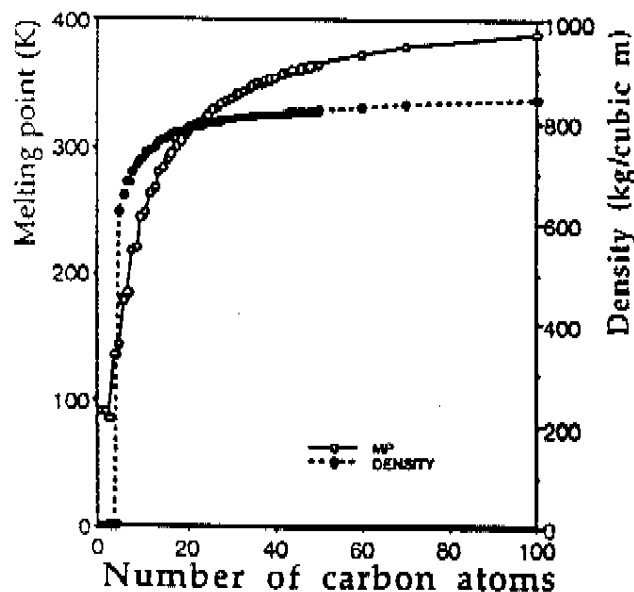


**Figure 1.** Variation of melting point (MP), transition temperature (TrT), and boiling point (BP) of normal alkanes with their number of carbon atoms.

the number of carbon atoms have a smooth variations, the latent heat of melting goes through fluctuations. Because of the steric effects (the solid-solid phase transitions mentioned above) the latent heats of melting of two consecutive alkanes do not always increase with increasing number of carbon atoms, as demonstrated in Figure 2. Each even-numbered alkane (with 8 carbon atoms or higher) exhibits a lower latent heat than the odd-numbered alkane having one carbon less than it. This fluctuation of latent heat of melting vanishes as the number of carbon atoms



**Figure 2.** Variation of the latent heat of melting of normal alkanes with the number of carbon atoms in alkanes and exhibition of the steric effect.



**Figure 3.** Variation of the melting point and density (at 20°C) of normal alkanes with the number of carbon atoms in alkanes.

approaches 40, and after that the latent heat of melting increases with increase of the number of carbon atoms.

### Paraffin Wax

Paraffin waxes consist of mixtures of mainly normal alkanes. The amount of normal alkanes in a paraffin wax usually exceeds 75% (and may reach almost 100%), with the rest consisting of mostly iso-alkanes, cyclo-alkanes, and alkyl benzene (Turner et al. 1955). The molecular weight of hydrocarbons in a paraffin wax is in the range of about 280–560 ( $C_{20}$ – $C_{40}$ ), with each specific wax having a range of about 8 to 15 carbon numbers (Encyclopedia of Polymer Science and Technology 1971). There exists a wealth of information on the thermophysical properties of paraffin waxes (Haji-Sheikh et al. 1983; Melpolder et al. 1964; Mozes 1982; Timmermans 1965). As an example, a wax sample produced by the Sun Refining and Marketing Company (Suntech P116) which contains almost 100% normal alkanes is used here for analysis. The thermophysical properties and chemical composition (Haji-Sheikh et al. 1983) of Suntech P116 are presented in Table 2. According to this table, the hydrocarbons with carbon chain lengths of 20 to 32 constitute 99% of the mixture. The hydrocarbons with carbon chain length longer than 32 constitute the remaining 1% with exponentially reducing fraction.

Paraffin waxes are generally polydisperse compounds for which polydisperse-solution theories must be used for characterization (Mansoori et al. 1989). We have constructed the distribution of *n*-alkanes in Suntech P116 paraffin wax as a function of the number of carbon atoms using the data of Table 2. This distribution is shown in Figure 4. With knowledge about the thermophysical properties of pure alkanes and paraffin waxes, it is possible to design a thermal energy storage medium comprising these compounds.

**Table 2**  
Chemical Composition and Thermophysical Properties of  
Suntech P116 Paraffin Wax

Hydrocarbon	Weight (%)
<i>n</i> -C-20	2.0
<i>n</i> -C-21	5.5
<i>n</i> -C-22	14.0
<i>n</i> -C-23	23.0
<i>n</i> -C-24	22.0
<i>n</i> -C-25	14.0
<i>n</i> -C-26	6.5
<i>n</i> -C-27	3.0
<i>n</i> -C-28	2.5
<i>n</i> -C-29	2.0
<i>n</i> -C-30	1.7
<i>n</i> -C-31	1.5
<i>n</i> -C-32	1.3
Melting range	316–329 K
Heat of fusion	266 kJ/kg
Liquid specific heat	2.51 kJ/kg K
Solid specific heat	2.95 kJ/kg K
Liquid thermal conductivity	0.24 W/m K
Solid thermal conductivity	0.24 W/m K
Liquid density	760 kg/m <sup>3</sup>
Solid density	818 kg/m <sup>3</sup>
Liquid viscosity	1.90 kg/m s
Molecular weight	332 g/mol

### Latent Thermal Energy Storage

In latent thermal energy storage (LTES) systems, thermal energy is stored by means of phase change in the storage medium (PCM). Two thermal processes which are relevant to phase change storage are melting and freezing phenomena. During the melting process, added heat is stored as latent heat of fusion, and during the freezing process this latent heat is liberated. In melting and freezing cycles, a circulating fluid, such as air or water, stores (and extracts) heat to (and from) the storage unit, causing the storage medium to exhibit a change in phase. Any LTES system must possess the following three components: (1) a heat storage material (PCM), (2) a container for holding the PCM, and (3) a heat-exchanging surface for transferring heat from the heat source to the PCM and from the PCM to the required point of use. In storing heat, the LTES utilizes some sensible heat storage below and above the PCM melting temperature. The total heat  $Q$  stored by material can be calculated from the following equation:

$$Q = m \left[ \int_{T_1}^{T_m} C_{ps} dT + L + \int_{T_m}^{T_2} C_{pl} dT \right] \quad (1)$$

where  $m$  is the mass of the PCM;  $L$  is its latent heat of melting;  $T_1$ ,  $T_2$ , and  $T_m$  are

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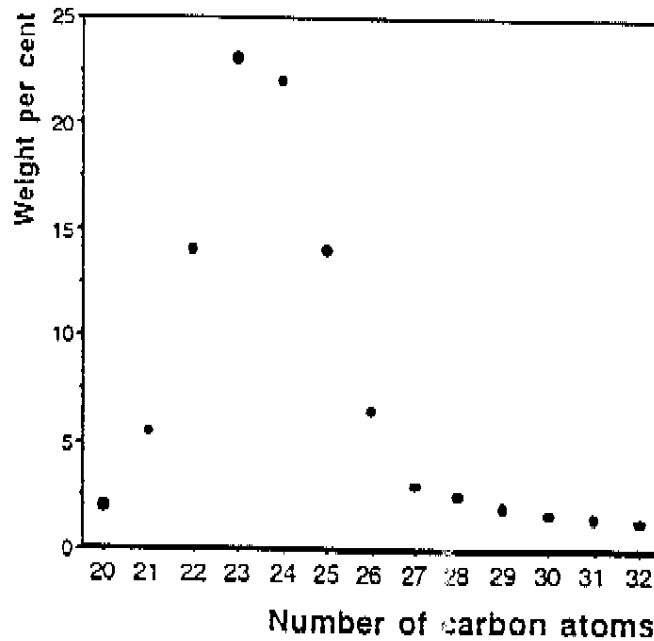


Figure 4. Distribution of *n*-alkanes in Suntech P116 paraffin wax as a function of the number of carbon atoms.

the initial, final, and melting absolute temperatures; and  $C_{ps}$  and  $C_{pl}$  are the specific heats of solid and liquid PCM phases, respectively. The first term of Eq. 1 represents the sensible heat of the solid PCM phase (below its melting point), the second term is the PCM latent heat of melting, and the third term is the sensible heat of the liquid PCM phase (above its melting point). In practical LTES systems, the latent-heat term predominates.

Using Eq. 1 and the data of Table 1, we have calculated the thermal energy stored per unit volume of the storage,  $Q/V$ , in the family of pure *n*-alkanes ( $C_6$ - $C_{100}$ ). The calculations reported are for three heating temperatures of 323, 348, and 373 K (with the reference temperature of 298 K).

The results of calculation are presented in graphical form in Figure 5. This figure shows, for example, that at 323 K the *n*-alkanes in the range of  $C_{18}$  through  $C_{33}$  store a higher amount of thermal energy (about  $226 \text{ MJ/m}^3$ ) than the rest of the *n*-alkanes. This is due to the fact that their melting transition occurs in the temperature range  $298 \text{ K} \leq T_{MP} \leq 323 \text{ K}$ . At 348 K the *n*-alkanes in the range of  $C_{18}$  through  $C_{35}$  still store a larger amount of thermal energy than the rest of the *n*-alkanes (about  $279 \text{ MJ/m}^3$ ). At the temperature of 373 K the series  $C_{18}$  through  $C_{40}$  can store even more thermal energy (about  $331 \text{ MJ/m}^3$ ). According to this figure, every alkane hydrocarbon is useful as a PCM material for a rather narrow temperature range. This figure also indicates that the amount of energy stored in alkanes (due to phase change and/or sensible heat) is a rather weak function of alkane molecular weight.

In order to calculate the total heat stored in a paraffin wax, assuming that the alkanes present in paraffin wax form an ideal solution, Eq. 1 will assume the following form:

$$Q = \sum_i m_i \left\{ \int_{T_i}^{T_m} C_{ps,i} dT + L_i + \int_{T_m}^{T_2} C_{pl,i} dT \right\} \quad (2)$$

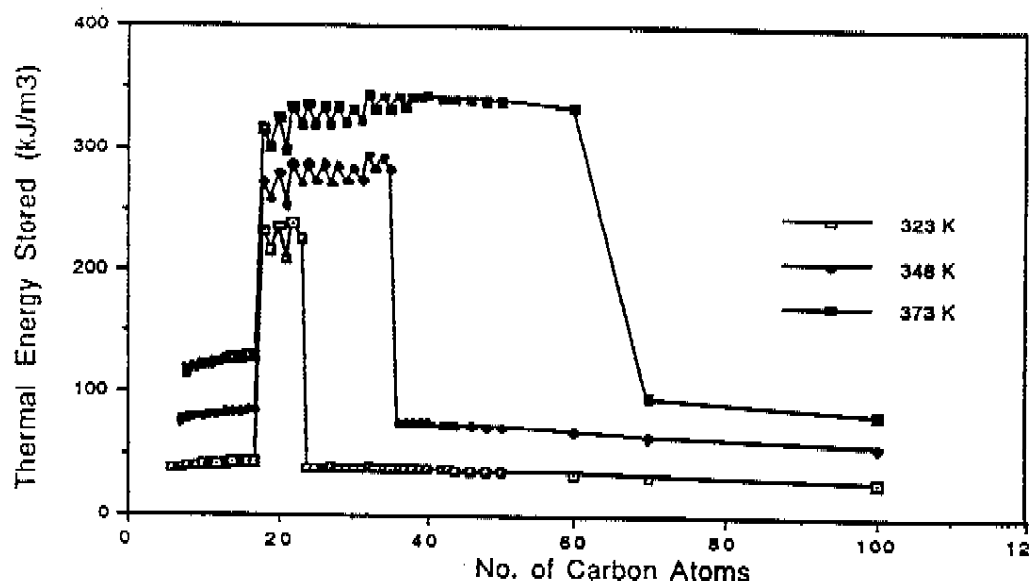


Figure 5. Variation of the thermal energy stored in *n*-alkanes with their number of carbon atoms and temperature with a reference temperature of 298 K.

In this equation the summation is over the components of the paraffin wax and every term with subscript *i* stands for properties of the *i*th component (alkanes) of the paraffin wax.

An important thermal energy storage characteristic of a paraffin wax is its "cumulative thermal energy storage." Cumulative thermal energy is defined as the thermal energy stored in a wax by raising its temperature from a reference temperature (298 K in the present case) to a higher temperature, taking into account the composition effects of all the hydrocarbons present in the wax. By using Eq. 2, the composition distribution data of P116 paraffin wax, and the thermophysical properties of alkanes reported in Table 1, we have calculated the cumulative latent heat,  $(1/v)\sum m_i L_i$ , and the cumulative heat stored,  $Q/V$ , at different temperatures in P116 paraffin wax, considering 298 K as the reference temperature. The results of these calculations are shown in Figure 6. At present, no experimental data for cumulative thermal energy of paraffin wax are available to compare with the theoretical values reported here. The difference between the cumulative latent heat and cumulative heat stored in this figure is due to the sensible heat stored in the wax. According to this figure, the sensible heat contribution to the heat stored could reach as much as the 30% of the total heat stored in a paraffin wax and it must be taken into account for any design calculation.

### Discussion

In this report thermophysical properties of *n*-alkanes ( $C_1$ – $C_{100}$ ) and paraffin waxes are analyzed and characterized from the point of view of their use as low-temperature phase change energy storage media. It is demonstrated that the family of *n*-alkanes have a large spectrum of latent heats, melting points, densities, and specific heats so that the heat storage designer has a good choice of *n*-alkanes as storage materials for any particular low-temperature (298–323 K) thermal energy storage application.

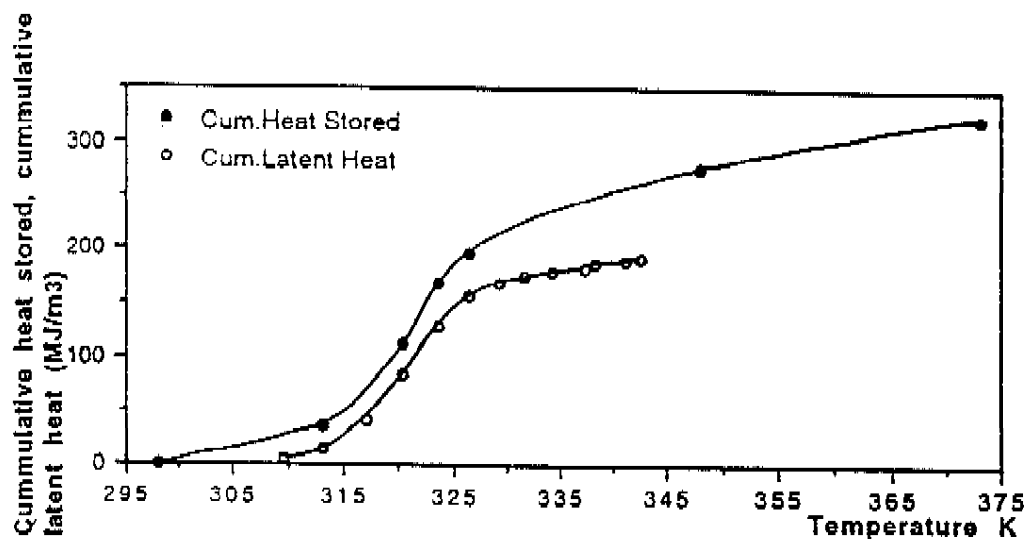


Figure 6. Variation of the cumulative heat and latent heat stored in P116 paraffin wax with temperature with a reference temperature of 298 K.

Although paraffin waxes exhibit desirable properties as PCMs, they have rather low thermal conductivity. This may reduce the rate of heat storage and extraction during melting and solidification cycles. In order to compensate the low thermal conductivity of an alkane-based PCM, its container must be designed with an adequate surface-to-volume ratio and container material must have a suitable heat transfer coefficient. The paraffin wax low thermal conductivity can also be enhanced by embedding a metal matrix structure in it. It is also possible to choose the container and heat transfer system configuration to ensure more efficient extraction (or addition) of heat from (or to) alkane/paraffin wax PCMs.

Another undesirable characteristic of alkane/paraffin wax material is their potential hazard because of being flammable materials. However, a fire barrier-rated container would be sufficient to remedy this problem.

Because the melting points of *n*-alkanes are higher than those of iso- and cyclo-alkanes with the same carbon numbers, the melting point of waxes tends to rise with the increase of *n*-alkane components in paraffin wax (Melpolder et al. 1964). The melting point of waxes can also be increased, even with a low content of *n*-alkanes, if the iso- and cyclo-alkane components are present in large amounts at the higher carbon atom number.

The data, analysis, and characterization reported here are the basic information with regard to computational sources necessary for the design of a PCM storage system based on paraffin wax and generally heavy alkane hydrocarbon blends. Depending on the specific need for the energy storage, the present procedure can be used for selecting the appropriate composition of the alkane/paraffin wax mixture to achieve a suitable PCM.

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## References

- Abhat, A. 1983. Low temperature latent heat thermal energy storage: Heat storage materials. *Solar Energy* 30(4):313-332.
- Asinger, R. 1968. *Paraffins, chemistry and technology*. Elmsford, NY: Pergamon.
- Batlet, A. G., R. Viskanta, and W. Leidenfrost. 1979. Heat transfer from cylinders during melting of a thermal energy storage material. *Journal of Heat Transfer* 101:179-184.
- Chorn, L. G., and G. A. Mansoori (Eds.). 1988. C<sub>7</sub> + fraction characterization. *Advances in thermodynamics*, Vol. I. New York: Taylor & Francis.
- Domaisky, E. S., W. H. Evans, and E. D. Hearing. 1984. Heat capacities and entropies of organic compounds in the condensed phase. *Journal of Physical and Chemical Reference Data* 13 (Suppl. 1). New York: American Chemical Society and the American of Physics for the National Bureau of Standards.
- Encyclopedia of polymer science and technology*. 1971. Vol. 14, pp. 768-769. New York: Wiley.
- Garg, H. P., S. C. Mullick, and A. K. Bhargava. 1985. *Solar thermal energy storage*. Dordrecht: Reidel.
- Gomez, A. L., and G. A. Mansoori. 1983. Thermodynamic equation of state approach for the choice of working fluids of absorption cooling cycles. *Solar Energy* 31:557-566.
- Haji-Sheikh, A., J. Eftekhari, and D. Y. S. Lou. 1983. Some thermophysical properties of paraffin wax as a thermal storage medium, spacecraft thermal control design and operation. *Progress in Astronautics and Aeronautics* 86:241-253.
- Humphries, W. F. 1974. *Performance of finned thermal capacitors*. NASA TN D-7690. Washington, DC: NASA.
- International petroleum encyclopedia*. 1993. Tulsa, OK: PennWell Publishing Co.
- Kawanaka, S., S. J. Park, and G. A. Mansoori. 1991. Organic deposition from reservoir fluids. *SPE Reservoir Engineering Journal* May: 185-192.
- Lane, G. A. 1986. *Solar heat storage: Latent heat materials*, Vols. I and II. Boca Raton, FL: CRC Press.
- Mansoori, G. A. 1976. Prospects for solar energy utilization. *Iranian Journal of Science and Technology* 5(2):55-73.
- Mansoori, G. A., and V. Patel. 1979. Thermodynamic basis for the choice of working fluids for solar absorption cooling cycles. *Solar Energy Journal* 22(6):483-491.
- Mansoori, G. A., P. C. Du, and E. Antoniadou. 1989. Equilibrium in multiphase polydisperse fluids. *International Journal of Thermophysics* 10(6):1181-1204.
- Marsh, K. N., E. B. Gammon, and C. R. Wilhoit. 1988. *TRC thermodynamic tables: Hydrocarbons*, Vols. I and III. College Station, TX: Thermodynamics Research Center, Texas Engineering Experiment Station.
- Melpolder, F. W., W. R. Turner, and B. C. Wilbur. 1964. A nomograph for the estimation of paraffin wax composition. *Tappi* 47(5):283-285.
- Mozes, G. Y. (Ed.). 1982. *Paraffin products: Properties, technology, applications*. New York: Elsevier Scientific Publishing.
- Timmermans, J. 1965. *Physico-chemical constants of pure organic compounds*, Vol. 2. New York: Elsevier Publishing Company.
- Turner, W. R., D. S. Brown, and D. V. Harrison. 1955. Properties of paraffin waxes: Composition by mass spectrometer analysis. *Industrial and Engineering Chemistry* 47:1219-1226.