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Selection of Phase Change Material for Thermal Energy Storage in Solar Air Conditioning Systems

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Abstract

The selection of Phase change materials (PCMs) is crucial in the design of Latent Heat Thermal Energy Storage (LHTES) system in solar air conditioning applications. This study performs a systematic selection procedure of PCMs for LHTES in a typical solar air conditioning system. Comprising prescreening, ranking and objective function examination based on multi-criteria decision making (MCDM) tools, this procedure is able to reflect the system goals of LHTES, as well as to take into account designer’s subjectivity. Results indicate the proposed approach to be a highly applicable and efficient tool in the LHTES design process.

Keywords: Phase change material; Thermal storage; Selection methodology; Solar air conditioning; Multi-criteria decision making

1. Introduction

There is a growing interest in the solar air conditioning systems due to the increasing demand for space cooling in solar abundant areas [1] [2]. However, the intermittency characteristic of solar energy presents a challenge to downstream applications that require a steady energy supply. In recent years, Thermal Energy Storage (TES) has drawn the attention of researchers owing to its capability of resolving the intermittency of renewables [3]. Compared with other types of TES systems, Latent Heat Thermal Energy Storage (LHTES) system charges and discharges the heat power by utilizing phase transformation of Phase Change Materials (PCMs). Being able to provide high storage density and constant temperature output, LHTES is regarded as a very promising energy storage technique [4].

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Literatures show that incorporating LHTES into the solar air conditioning system was crucial in maximizing the solar harness, and to provide a reliable and steady output of air conditioning system subject to the building’s requirements. In 2012, Kantole [5] investigated a numerical model of a LHTES system used in a solar driven ammonia absorption refrigeration system. Agyenim et al. [6] explored the system configuration of a LHTES using erythritol to power a LiBr/H₂O absorption chiller. In another study, Noro et al. [7] simulated the effect of using PCM in either hot tank or cold tank of an integrated solar absorption air conditioning system. He pointed out that only when the mean temperature of the storage is around the melting temperature of the PCM that the LHTES can outperform the sensible storage.

Among all the design aspects, selection of the right PCM stands out as the first important step. To select the proper PCM candidates, engineers need to consider a set of criterion. Firstly, the phase change temperature of this material should satisfy the operating temperature range of LHTES. Secondly, the PCM should possess high latent heat of fusion and large specific heat, to ensure high storage density of system. Thirdly, the material is required to have high thermal conductivity, in order to achieve high discharge power. Lastly, material with large density is favored when the volume reduction is considered in the system design. Besides the abovementioned merits, the material is favored if it is at low cost with a high availability. Since none of the PCMs has a perfect property profile, and each application has unique thermal boundaries and operation goals, the good variety of PCMs makes it difficult to select one to match the thermal conditions and requirements in LHTES design.

Regarding selection of PCM in LHTES, only a few papers covered this in detail. Rathod and Kanzaria [8] adopted two Multi-Attribute Decision Making (MADM): Techniques for Order Preference by Similarity to Ideal Solutions (TOPSIS) and Analytical Hierarchy Process (AHP) to evaluate PCMs in solar hot water application. Similarly, another MADM tool VIKOR (acronym from the original Serbian: Vise Kriterijumska Optimizacija I Kompromisno Resenje) was applied to deal with selection of low temperature PCM [9]. In a passive storage case, the authors used MADM method to rank objective functions instead of material properties. This approach was compared with building simulations and received positive compliance [10]. However, the previous two approaches did not attempt to validate the consistency between selected PCMs and their ability to fulfill system requirements. The last approach gave up the design engineer’s subjectivity of altering the weights of different properties in the decision making process. Apparently, a more thorough and practical selection procedure should be brought out to overcome the shortcomings discussed above.

Considering the variety of PCMs and the complexity of material selection, this study presents a systematic selection procedure of PCMs for LHTES in typical solar absorption cooling applications. The procedure takes into account both design engineers’ preference and also explicitly reflects the system design objectives. Results after performing each step and the final PCM candidate are clearly illustrated, followed by detailed discussion and conclusion.

2. Selection Procedure of PCMs

2.1 Definition of LHTES system scope and goals

A typical solar driving absorption chilling system in building applications is considered here. First of all, the system’s goals and requirements are clearly defined and translated into the selection objectives. In the integrated system, LHTES buffers the hot water tank from being overheated, and charges with excess
solar irradiance during daytime. In the nighttime, LHTES discharges to drive an absorption chiller directly to meet the cooling demand. The overall performance of LHTES in integrated solar system depends on the solar collector field size and characteristics, the phase change temperature, the supply temperature of heating appliances, and the storage volume [7]. Therefore, the system goals and requirements might include a specific temperature range of PCM and volume constraint, which will thus be reflected in the corresponding selection objectives.

2.2 Prescreening of PCM from database

After the selection objectives become clear, an initial prescreening will be performed based on some key criterion of the material. For instance, the materials whose melting temperature is not within the desired temperature range will be subsequently screened out.

2.3 MADM ranking

In the third stage, Multi-Criteria Decision Making tools are employed to rank the pre-screened material candidates. Table 3 presents the typical MADM performance matrix composed of all alternatives and their attributes, as well as the weights for each attribute. In the context of material selection, alternatives denote material candidates, while attributes refer to the quantitative properties. The $X_{ij}$ from the matrix illustrates the value of property “$j$” possessed by material alternative “$i$”. The weights determine the importance of each attribute relatively to each other, assigned by the design engineer by a certain technique. Weightage can be determined either subjectively or objectively. In the context of selection of materials, design engineer’s preferences should be taken into consideration in most real situations. Therefore, AHP in subjective weighting is preferable in this study. Literature revealed that if one single method is to be used for the sake of both accuracy and efficiency, TOPSIS and AHP is able to provide the closer results to real decisions made [11]. Therefore, this study adopts AHP and TOPSIS for weighting and ranking, respectively. With the performance matrix available, design engineers can thus run through AHP and TOPSIS algorithm to sort out the ranking.

Table 1. MADM performance matrix [12]

<table>
<thead>
<tr>
<th>Attribute 1</th>
<th>Attribute 2</th>
<th>…</th>
<th>Attribute n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material alternative 1</td>
<td>$X_{11}$</td>
<td>$X_{12}$</td>
<td>…</td>
</tr>
<tr>
<td>Material alternative 2</td>
<td>$X_{21}$</td>
<td>$X_{22}$</td>
<td>…</td>
</tr>
<tr>
<td>…</td>
<td>…</td>
<td>…</td>
<td>…</td>
</tr>
<tr>
<td>Material alternative m</td>
<td>$X_{m1}$</td>
<td>$X_{m2}$</td>
<td>…</td>
</tr>
<tr>
<td>Attribute weights</td>
<td>$W_1$</td>
<td>$W_2$</td>
<td>…</td>
</tr>
</tbody>
</table>

The AHP algorithm is clearly explained by Hotman [13]. In this paper, TOPSIS algorithm is presented to demonstrate the ranking steps [14]. Step (i): Construct the performance matrix, which is displayed in Table 1. Step (ii): Perform the column normalization of matrix $[X]_{mn}$, obtaining a new matrix $[N]_{mn}$. Then multiply the normalized matrix with weights obtained by AHP.

$$N_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \quad i = 1, 2, \ldots, m; \quad j = 1, 2, \ldots, n$$  \hspace{1cm} (1)
Step (iii): Calculate the ideal solution and the negative ideal solution with the equations below.

\[
R^+ = \left\{ \frac{\max_i (R_{ij}/J)}{\min_i (R_{ij}/J')} / i = 1, 2, ..., m \right\} = \{R_1^+, R_2^+, ..., R_n^+\} \quad (3)
\]

\[
R^- = \left\{ \frac{\min_i (R_{ij}/J)}{\max_i (R_{ij}/J')} / i = 1, 2, ..., m \right\} = \{R_1^-, R_2^-, ..., R_n^-\} \quad (4)
\]

Where \(J = (1, 2, \ldots, n)/j\), associated with the beneficial attributes. While \(J' = (1, 2, \ldots, n)/j\), associated with the non-beneficial attributes. Step (iv): Compute the separation distances of each alternative to the ideal and negative ideal solutions with the Euclidean distance equations.

\[
D_i^+ = \left\{ \Sigma_{j=1}^{n} (R_{ij} - R_{ij}^+)^2 \right\}^{0.5} / i = 1, 2, ..., m \quad (5)
\]

\[
D_i^- = \left\{ \Sigma_{j=1}^{n} (R_{ij} - R_{ij}^-)^2 \right\}^{0.5} / i = 1, 2, ..., m \quad (6)
\]

Step (v): Obtain the relative closeness of all alternatives to the ideal solution. Then rank all the closeness in the descending order to find the ranking of the alternatives.

\[
C_i = \frac{D_i^-}{D_i^+ + D_i^-} \quad (7)
\]

2.4 MODM examination

Whether the collective effect of all properties necessarily produces good output in the system is not explicitly illustrated in MADM procedure. Henceforth, the objective functions of Ashby’s approach, a popular MODM tool, are considered to examine if the system objectives are in good agreement with the ranking goal. The relative performance of material in objective functions can be analysed qualitatively by plotting the results of two conflicting objective functions in one chart. As both two functions are intended to be maximized, the materials with material index lying within the outer boundary of the chart are preferred.

In typical solar air conditioning system, LHTES serves as a buffer between solar energy and thermal energy provided to the absorption system, meaning a good response of the LHTES is required. Besides, the storage volume is usually sought to be minimized due to space constraints. Considering these two system requirements, two objective functions are therefore proposed. The first function is the thermal energy stored per unit of volume.

\[
f_1 = (L + C_p \cdot \Delta T) \cdot \rho \quad (8)
\]
where \( L \) (kJ/kg), is the latent heat of fusion, \( C_p \) (kJ/(kg·K)) its specific heat capacity, \( \Delta T \) the temperature interval of charge/discharge, and \( \rho \) (kg/m\(^3\)) is the material density. The second function, denoting the equivalent PCM thermal diffusivity, can be expressed as:

\[
 f_2 = \frac{k}{(L + C_p \Delta T)/\Delta T \rho} \tag{9}
\]

where \( k \) (W/(m·K))is the thermal conductivity. An initial outcome of this first part of the analysis is that design engineers are able to assess if the material is performing well enough to keep it on the list. If the ranking result overlaps with the objective function examination result, the overlapping solutions will be kept forward. If they undoubtedly go against each other, design engineer should check the system goals, repeat the process again from the pre-screening list, while be careful deciding the relative weights of different properties. The loop will continue until a good alignment is confirmed from both the ranking and the objective function examination. After the main selection process, the top selected materials will be subject to case studies, no matter whether in analogy to old cases, or in simulation, or in experiments. Final choice will be made based on the judgements from all above considerations.

3. Results and discussion

The selection algorithms explained in section are executed in the Matlab environment, with the results presented in this section. In the prescreening stage, a temperature range from 90 to 120 °C is used as the constraint to prescreen a database of available materials, producing a list of PCMs as displayed in Table 2. Then, MADM techniques based on TOPSIS and AHP are employed to rank the list of PCMs. Table 3 shows the relative importance of thermo-physical properties, as well as their weights based on AHP method, whereas Table 2 illustrates the materials and their thermo-physical properties in the ranked order.

<table>
<thead>
<tr>
<th>PCM</th>
<th>( T_{mp} ) (°C)</th>
<th>( L ) (kJ/kg)</th>
<th>( k ) (W/mK)</th>
<th>( C_p ) (kJ/kgK)</th>
<th>( \rho ) (kg/m(^3))</th>
<th>Ranking by MADM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Erythritol</td>
<td>117.7</td>
<td>339.8</td>
<td>0.579</td>
<td>2.61</td>
<td>1450</td>
<td>1</td>
</tr>
<tr>
<td>PlusICE-S117</td>
<td>117</td>
<td>160</td>
<td>0.7</td>
<td>2.61</td>
<td>1450</td>
<td>2</td>
</tr>
<tr>
<td>MgCl(_2)-6H(_2)O</td>
<td>116</td>
<td>167</td>
<td>0.57</td>
<td>2.61</td>
<td>1450</td>
<td>3</td>
</tr>
<tr>
<td>PlusICE-H120</td>
<td>120</td>
<td>120</td>
<td>0.506</td>
<td>1.51</td>
<td>2220</td>
<td>4</td>
</tr>
<tr>
<td>PlusICE-H115</td>
<td>114</td>
<td>100</td>
<td>0.503</td>
<td>1.505</td>
<td>2200</td>
<td>5</td>
</tr>
<tr>
<td>PlusICE-H105</td>
<td>105</td>
<td>125</td>
<td>0.5</td>
<td>1.5</td>
<td>1700</td>
<td>6</td>
</tr>
<tr>
<td>PlusICE-X120</td>
<td>120</td>
<td>180</td>
<td>0.36</td>
<td>1.5</td>
<td>1245</td>
<td>7</td>
</tr>
<tr>
<td>PlusICE-A95</td>
<td>95</td>
<td>205</td>
<td>0.22</td>
<td>2.2</td>
<td>900</td>
<td>8</td>
</tr>
<tr>
<td>PlusICE-X95</td>
<td>95</td>
<td>140</td>
<td>0.36</td>
<td>1.51</td>
<td>1215</td>
<td>9</td>
</tr>
<tr>
<td>PlusICE-X90</td>
<td>90</td>
<td>135</td>
<td>0.36</td>
<td>1.51</td>
<td>1200</td>
<td>10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>L ( L ) k</th>
<th>C_p</th>
<th>( \rho )</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>K</td>
<td>1</td>
<td>1</td>
</tr>
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</table>
The objective function examination is performed by plotting $f_2$, the equivalent diffusivity against $f_1$, the volume energy density, as displayed in Figure 1. The operating temperature interval $\Delta T$ is assumed to be 10 °C. Clearly, PCM No.1 has the highest performance of $f_1$, while PCM No.2 has the highest performance of $f_2$. On the left side of line A, PCM No. 5, 6, 7, 9 and 10 perform worse of $f_1$ than PCM No.2, indicating that these PCMs are overall less competent and thus will not be considered as first group of choice. Similarly, on the bottom side of line b, there is PCM No.8, indicating that No.8 is less competent than No.1 in terms of function $f_2$. So it will not be considered as well. Based on the analysis, the first group of choice arises with PCM No. 1, 2, 3 and 4. No preference between them is indicated by this figure since no material maximizes both two functions. In order to decide upon the final choice, designers may refer back to the MADM ranking in Table 3. Two conclusions are thereupon drawn.

- The top ranked materials No.1, 2, 3 and 4 from MADM do have first class performance of objective function examinations, meaning they are the better choice to achieve system goals compared with the rest of the list.
- Under the circumstances that no preference is given according to the objective functions, designer may retain the ranking order and select material No. 1, 2 and 3 for further design purpose.

In summary, Erythritol, PlusICE-S117, and MgCl$_2$·6H$_2$O will be recommended for further consideration in the next design stage of the LHTES system.

![Fig. 1. Objective function performance of nine prescreened PCMs](image-url)
4. Conclusions

Conventional way to select PCMs for solar air conditioning applications is mostly based on the design engineers’ experience or material availability. Recent studies in PCM ranking neither had no successful attempt to address the system goals explicitly, nor did they account for the subjective choices of designers. This paper seeks to overcome the existing limitations, and proposed a more comprehensive approach to select PCM for LHTES in solar air conditioning applications. This approach suggested a clear definition of system objectives and prescreening criteria, and integrated successive complementary Multi-Attribute Decision Making with Multi-Objective Decision Making to ensure the explicitly alignment of system objectives with ranking. The selection procedure of PCMs for LHTES in a typical solar air conditioning scenario was demonstrated. Two objective functions were suggested as an example of ensuring the system goals. Final candidates for solar-LiBr absorption chilling system were recommended for future references. In conclusion, the proposed procedure has been revealed to be an applicable and competent tool to effectively select PCM.

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References


**Biography**

The corresponding author, Asst. Prof. Alessandro Romagnoli’s research activity in Nanyang Technological University encompasses several aspects related to propulsion energy efficiency and waste heat recovery. Examples of his current research include the study of waste heat recovery for ships propulsion, turbomachinery design and optimization. Alessandro also acts as reviewer for several engineering journals (ASME, SAE, IMechE, Elsevier).