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PHASE CHANGE MATERIALS RANKING BY USING THE ANALYTIC HIERARCHY PROCESS

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Many phase change materials (PCMs) are available with building envelope use potential. PCM in a building envelope stores heat under warm climate as it changes from solid to liquid phase at the melting temperature. Mainly, the latent heat of fusion is stored, which reduces the daily heat flux from the outdoors into the building. Thus, the indoor cooling requirement is reduced. When the outdoor temperature falls, PCM releases the stored heat into the atmosphere over the phase change from liquid to solid that may offset the internal heating needs depending on the design of the PCM application. The PCMs exhibit a great variety in their properties. While many researchers are optimizing the use of PCM for a building application under specific climates, most of them focus on the energy-saving potential of PCMs. Other criteria, such as economic feasibility, environmental hazards, stability, fire resistance, and non-thermal physical properties, should also be considered. Therefore, with many criteria to consider, a sound selection method is necessary for choosing a suitable alternative PCM in an application. Some phase change materials were examined and ranked by taking into consideration their thermal and non-thermal properties. These properties were assessed using a multi-criteria decision-making tool called the Analytic Hierarchy Process (AHP). The results of this paper illustrate a pathway for selecting suitable PCMs and provide support to PCM application in building envelopes.

Keywords: Multicriteria decision analysis, Latent heat capacity, Thermal conductivity, Specific heat capacity, Density, Melting temperature.

1 INTRODUCTION

Phase change material (PCM) is material, with usually a high heat of fusion, which changes its phase from solid to liquid depending on the thermal conditions of the environment. When PCM changes its phase from liquid to solid or vice versa, the latent heat is absorbed or released, respectively. If the material's temperature is within the required working range, then this can be utilized to store and release the energy according to then need.

Use of PCM in buildings may increase thermal comfort, better building envelope, lower power consumption and energy savings. Most of the research on the application of PCM in buildings is focused on the thermal performance of buildings. Several studies have determined suitable PCMs particular for locations or climates. The results of these studies are mostly based on the energy simulation methods, with some studies also performing energy audits and the experimental measurements (Baetens *et al.* 2010). The common criteria, which are considered for the evaluation of PCMs in building applications are the latent heat of fusion, specific heat, thermal conductivity, melting temperature, and the density. Other criteria, such as cyclic stability, degree of supercooling, toxicity, flammability, corrosiveness, recyclability, and embodied energy, are seldom considered (Lizana *et al.* 2017 and Wijesuriya *et al.* 2018). The results of these studies are sometimes complemented by economic analysis using the payback period method, solar radiation, temperature variations, wind speed, elevation, humidity, overcast conditions, building orientation, PCM thickness, PCM placement, and more (Kalnæs and Jelle 2015). The considered criteria are essential for the evaluation of PCMs in the building applications.

The results of thermal and energy performance studies on PCMs are useful for their further evaluation using multiple criteria decision making (MCDM) methods which include Analytic Hierarchy Process (AHP), the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), *VIsekriterijumsko KOmpromisno Rangiranje* (VIKOR), fuzzy-AHP, and fuzzy-TOPSIS, etc. The applications of AHP, TOPSIS, and fuzzy-TOPSIS for the selection of PCM were illustrated by Rathod and Kanzaria (2011). In contrast, Wang *et al.* (2015) employed VIKOR method for the selection of PCMs in thermal energy storage applications.

AHP was developed by Thomas L. Saaty in the 1980s as a decision-making tool in which different alternatives are evaluated based on selected criteria. AHP uses a numerical scale for setting priorities for decision alternatives. According to Rathod and Kanzaria (2011), one of the main advantages of AHP is that it considers both tangible and intangible criteria in the decision-making process. Review of the literature in the field of PCM selection and ranking shows that AHP and related tools are being increasingly applied for ranking PCMs for various purposes, though in most studies, only thermo-physical and economic criteria were considered.
Xu *et al.* (2017) evaluated PCMs using a modified AHP approach to conclude that the selected PCM should be investigated in detail using a proper energy analysis mechanism. The application of AHP for the selection of PCM for building comfort was investigated by Socaciu and Unguresan (2014). Their findings provided weights of thermal conductivity, latent heat of fusion, phase-change temperature, and specific heat as 36%, 36%, 13%, and 7% respectively for the assessment of PCMs.

This paper recognizes the need for a comprehensive PCM evaluation using AHP or any other MCDM method and stresses to fill this gap in the research on PCM selection for building applications. However, for illustration purposes, only a selected list of criteria has been used in the AHP model (Figure 1), which is the method of analysis chosen for this paper. AHP is one of the most established MCDM methods based on the research output in the discipline of operations research. Similarly, not all the possible PCM alternatives have been considered. Only selected PCMs within the suitable comfort and phase change temperature range (21 - 26 °C) have been considered. Thus, the aim of this paper is to illustrate that AHP is a suitable method that can be used to choose the best PCM in addition to the selection based on thermal and energy analyses.

2 METHODOLOGY

More information on the general AHP methodology that has been extensively used in literature can be found in Saaty (2013) and Rathod and Kanzaria (2011). In this paper, five criteria were considered for ranking the alternatives. These criteria are the latent heat capacity (LHC), phase change temperature (PCT), specific heat capacity (SHC), the thermal conductivity of the material (TCM), and density for solids (DFS). Based on these criteria, four commercial PCMs, namely, Climsel C24 (PCM24), PlusIce PCM S23 (PCM23), PlusIce PCM A22H (PCM22), and RT 21 HC (PCM21) were ranked using the AHP method. The AHP model for ranking PCMs is shown in Figure 1, and the properties of the chosen PCMs are given in Table 1.

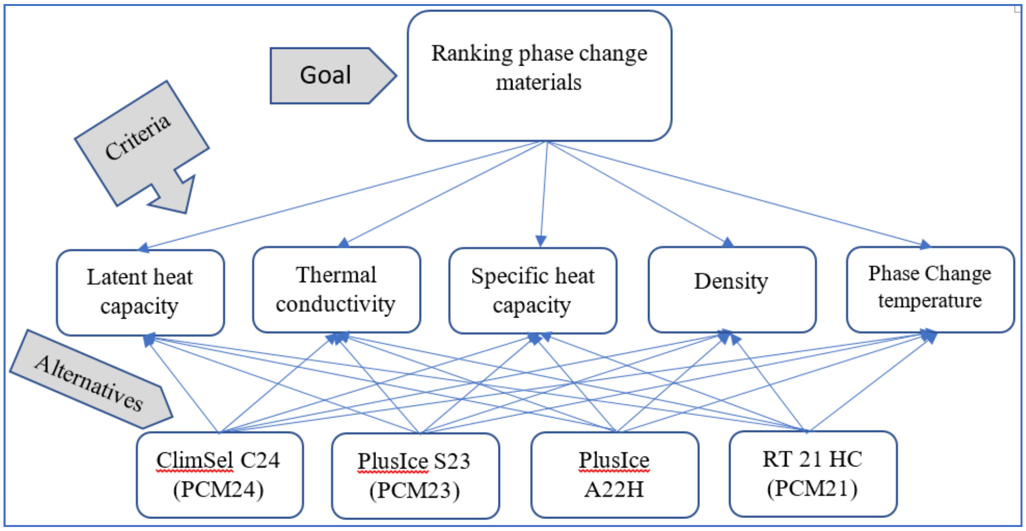

Figure 1. The AHP model for ranking phase change materials.

Table 1. PCM alternatives for evaluation.

PCM Designation	PCM24	PCM23	PCM22	PCM21
PCM Name	Climsel C24	PlusIce PCM S23	PlusIce PCM A22H	RT 21 HC
Manufacturer	Climator	EPS Ltd.	EPS Ltd.	Rubitherm Gmbh
LHC (kJ/kg)	108	175	216	190
SHC (kJ/kg-°C)	3.6	2.2	2.22	2
TCM (W/m-K)	0.7	0.54	0.21	0.7
PCT (°C)	24	23	22	21
DFS (kg/m3)	1380	1530	1530	880
Reference (see reference list)	Climsel C24 (2018), Koekenbier (2011)	PlusIce (2019)	PlusIce (2019)	(Cui and Riffat 2011)

The chosen criteria affect the performance of phase change materials. High latent heat capacity is desired as more heat will be stored without changing the PCM temperature. Although, in practice, there will be a few degrees temperature rise during the latent heat absorption by PCM. High specific heat capacity of PCM is desired as this will lead to more heat absorption with less temperature rise of the PCM outside of its phase-change temperature range. A phase change temperature range coinciding with the human comfort temperature range is desired for the effective operation of the PCM. Typically, a human comfort range between 21 and 26 °C is acceptable for most locations (Navarro *et al.* 2019). All the chosen alternatives are within this range. For further segregation, the alternative with the lower PCT is preferred over higher PCT because the PCM with lower PCT will enter its phase change cycle earlier than other PCMs with higher PCT. High thermal conductivity of the PCM is desired so that PCM is charged and discharged quickly for effective operation (Lizana *et al.* 2017). High-density PCM is desired as more material can be installed in less space, which will increase the storage capacity of PCM.

3 RESULTS AND DISCUSSIONS

Based on the PCM properties given in Table 1 relating to LHC, TCM, SHC, DFS, and PCT, scales of importance values on a scale from one (1) to nine (9) were derived for developing pairwise comparisons in AHP analysis. These scales are shown in Table 2.

Table 2. Scales of criteria importance for pairwise comparisons.

PCM	LHC	TCM	SHC	DFS	PCT
PCM24	1	9	9	7.15	1
PCM23	5.96	6.4	2	9	3.67
PCM22	9	1	2.1	9	6.33
PCM21	7.07	9	1	1	9

Based on how each of the criterion LHC, TCM, SHC, DFS, and PCT affect the performance of PCM, a pairwise comparison can be made among these five criteria, which is shown in Figure 2. For example, LHC is considered strongly important than SHC. A score of five is assigned along the LHC row and SHC column. LHC is rated moderately important than TCM. A score of three is assigned in the matrix at the intersection of the row and column of LHC and TCM, respectively.

Similarly, all other eight scores above the matrix diagonal have been assigned. For reference, a score of seven is rated very strongly important, and nine is rated extremely important of the criterion in the row with respect to the criterion intersecting from the column. The values below the matrix diagonal are reciprocal of the transposed values above the diagonal. It is a standard format for all the pairwise comparison matrices in the AHP analysis.

$$\begin{array}{c} \textbf{Criteria} \\ LHC \\ SHC \\ TCM \\ PCT \\ DFS \end{array} \begin{bmatrix} LHC & SHC & TCM & PCT & DFS \\ 1 & 5 & 3 & 9 & 7 \\ 0.2 & 1 & 0.333 & 5 & 3 \\ 0.333 & 3 & 1 & 7 & 5 \\ 0.111 & 0.2 & 0.143 & 1 & 0.333 \\ 0.143 & 0.333 & 0.2 & 3 & 1 \end{bmatrix}$$

Figure 2. Pairwise comparison matrix for criteria.

$$\begin{array}{c} \textbf{LHC} \\ PCM24 \\ PCM23 \\ PCM22 \\ PCM21 \end{array} \begin{bmatrix} PCM24 & PCM23 & PCM22 & PCM21 \\ 1 & 0.168 & 0.111 & 0.141 \\ 5.96 & 1 & 0.25 & 0.5 \\ 9 & 4 & 1 & 3 \\ 7.07 & 2 & 0.333 & 1 \end{bmatrix}$$

Figure 3. Pairwise comparison matrix for alternatives for latent heat capacity.

The matrix in Figure 3 shows the pairwise comparison matrix for alternatives PCM24 to PCM21 for latent heat capacity. Similar matrices were also prepared for TCM, SHC, DFS, and PCT. The values in these matrices have been developed based on scores in Table 2.

Using the geometric mean methodology for pairwise score aggregation in AHP, criteria weights, and local weights of alternatives for each criterion were calculated. These weights are shown in Figures 4 and 5, respectively. The consistency ratio (CR) for each result is also shown. Several trials for the selection of pairwise comparisons may be needed to achieve the desired CR value, which should not exceed 0.1. Finally, CR values for all cases were less than 0.1.

$$\begin{bmatrix} LHC & SHC & TCM & PCT & DFS \\ 0.510 & 0.130 & 0.264 & 0.033 & 0.064 \end{bmatrix}^T, CR = 0.053$$

Figure 4. Criteria Weight Matrix for Ranking Phase Change Materials.

$$\begin{array}{c} for \\ PCM24 \\ PCM23 \\ PCM22 \\ PCM21 \end{array} \begin{bmatrix} \textbf{LHC} \\ 0.039 \\ 0.159 \\ 0.551 \\ 0.252 \end{bmatrix} \quad \begin{array}{c} for \\ PCM24 \\ PCM23 \\ PCM22 \\ PCM21 \end{array} \begin{bmatrix} \textbf{SHC} \\ 0.729 \\ 0.105 \\ 0.105 \\ 0.061 \end{bmatrix} \quad \begin{array}{c} for \\ PCM24 \\ PCM23 \\ PCM22 \\ PCM21 \end{array} \begin{bmatrix} \textbf{TCM} \\ 0.410 \\ 0.144 \\ 0.036 \\ 0.410 \end{bmatrix} \quad \begin{array}{c} for \\ PCM24 \\ PCM23 \\ PCM22 \\ PCM21 \end{array} \begin{bmatrix} \textbf{PCT} \\ 0.042 \\ 0.100 \\ 0.252 \\ 0.605 \end{bmatrix} \quad \begin{array}{c} for \\ PCM24 \\ PCM23 \\ PCM22 \\ PCM21 \end{array} \begin{bmatrix} \textbf{DFS} \\ 0.165 \\ 0.399 \\ 0.399 \\ 0.036 \end{bmatrix}$$

CR=0.050 CR=0.015 CR=0.041 CR=0.069 CR=0.035

Figure 5. Local Weight Matrices of Alternative PCMs for Each Criterion.

The results of the criteria weights (Figure 4) show that the latent heat capacity has the highest weight at 51%, followed by the thermal conductivity of the material (26.4%), specific heat capacity, density, and the phase change temperature. This hierarchy is reasonable as the thermal performance of PCM is significantly affected by the latent heat and thermal conductivity properties (combined weight 76.4%), while the other three properties combined are less significant (combined weight 23.6%). This finding contrasts with Socaciu and Unguresan (2014), who did not consider density as the criterion in their study. The local weights of four alternatives for each criterion (Figure 5) are according to their properties (Table 1).

The local weights of alternatives were multiplied with their corresponding criteria local weights to obtain the global weights for each alternative. The global weights for each alternative were added together to obtain the overall global weight for each alternative (Table 3).

Table 3. Global Weights of Alternative PCMs.

	Global weights for each criterion					Overall alternative weights	Rank
PCM Alternatives	**LHC**	**SHC**	**TCM**	**PCT**	**DFS**		
Climsel C24 (PCM24)	0.020	0.094	0.108	0.001	0.011	0.234	3
PlusIce PCM S23 (PCM23)	0.081	0.014	0.038	0.003	0.025	0.161	4
PlusIce PCM A22H (PCM22)	0.281	0.014	0.010	0.008	0.025	0.338	1
RT 21 HC (PCM21)	0.128	0.008	0.108	0.020	0.002	0.267	2

The results in Table 4 show that, based on five criteria, the PlusIce PCM A22H (PCM22) has the highest overall weight among four alternatives, followed by RT 21 HC (PCM21), Climsel C24 (PCM24), and PlusIce PCM S23 (PCM23). Looking into the global weights of alternatives for each criterion, the alternative with the highest rating (PCM22) is mainly due to the superior latent heat capacity, which itself is 51% of the criteria weights. It explains why the PCM22 designated alternative is the best among the four evaluated alternatives. LHC contribution is also the highest for second and fourth-ranked alternatives. In contrast, the 3rd ranked alternative has the most significant contributions from thermal conductivity (TCM) and specific heat capacity (SHC) due to superiority in these properties, among other alternatives.

4 CONCLUSIONS AND RECOMMENDATIONS

The main conclusions and recommendations of this paper are as follows.

(i) AHP method can be used to rank the phase change materials for building applications. This paper has only illustrated the effect of five criteria on the ranking of alternatives. With the inclusion of more criteria, a comprehensive analysis can be made.

(ii) Quantitative results of building energy analysis as input to the AHP process can improve the results of this method as then the AHP method can be focused more on the qualitative criteria.

(iii) The outcome of this research is obtained mostly because of priorities set by the authors as decision-makers. However, the results of this research may need a more detailed study for proper weight distributions by other methods such as nominal grouping or Delphi techniques.

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