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Selection and performance assessment of Phase Change Materials for heating, ventilation and air-conditioning applications

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ABSTRACT

The rapid commercialization of Phase Change Materials (PCMs) for heating, ventilation and air-conditioning (HVAC) applications, has paved way for effective utilization of ambient thermal fluctuations. However, given a long list of contemporary candidates, it is crucial to select the best material to obtain maximum efficiency for any given application. This article attempts to extend Multiple Criteria Decision Making (MCDM) approach for ranking and selecting PCMs for domestic HVAC application. Firstly, Ashby approach has been employed for determining two novel figure of merits (FOM) to grade PCMs performance. The FOMs thus obtained were subjected to Pareto Optimality test. The graded materials were ranked using Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). The relative weights for the different attributes were calculated using Shannon's entropy method. In order to justify the rankings obtained, the top materials were subjected to a standard simulation study to evaluate their relative performance using PCMExpress with the aim of maintaining human comfort temperature. It was observed that the results obtained by simulation are in good agreement with those obtained using MCDM approach. The candidates with the best ranks showed significant improvement in ameliorating the temperature conditions. Thus it can be concluded that integration of MCDM approach for PCMs selection would prove to an economical and swift alternative technique for ranking and screening of materials.

1. Introduction

Phase Change Materials (PCMs) have been the subject of rigorous investigation in the past few decades [1–8]. These materials have been explored for thermal energy storage (TES) [9–11], heating, ventilation and air-conditioning (HVAC) [12–14], temperature regulation for industrial application [15,16], electricity generation [17] and even soilless crop growth [18]. Recent years have seen significant improvement in terms of material's chemistry [11,19], performance and engineering [15,20]. Techniques like micro-encapsulation [20] and macro-encapsulation [8], have enabled high efficiency versatile operation. This has been followed by rapid commercialization of the technology and is now available for industrial and domestic use at large [21]. These advancements can be credited to the growing awareness towards global climate change and the need to push forward with cleaner and cheaper technology.

PCM as the name implies is a category of various organic or inorganic compounds exhibiting a change of phase within the required operating temperature range [1,8]. As the materials undergo phase transformation, they absorb or release a large amount of thermal energy. Since the energy flow is associated with a change in the physical state of the material, the entirety of the heat exchange is approximately isothermal in nature. Thus, if a suitable material can be fabricated within the required temperature range, a large portion of the thermal energy can be stored in a recoverable manner using PCMs. This concept has been widely employed for thermal energy harvesting and storage for solar energy conversion and space heating applications [1,5,9,10,12]. PCMs also offer an additional advantage of self-sustained and automatic operation. Once a system is installed and operational little or no supervision is required to ensure its working. This coupled with the benefits of solid-state operation, long life, negligible carbon footprints and low operating costs makes PCMs a strong contender for various TES and HVAC applications.

In HVAC applications, PCMs can be integrated into buildings in three ways: (a) PCMs directly used in form of sheets, wallboards etc. [14,22], (b) PCMs integrated into building structure such as facade cement [23] and (c) PCMs used in separate heat and cold devices [24]. The first two systems are passive systems which need no regulation to release or absorb heat. However the third system requires active components such as fan, pumps and a control system [25]. This proposed work primarily focuses on the first two

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systems and compares the various commercially available PCMs to meet the end. The bone of contention lies in selecting the PCMs that marks the strongest candidature in the building applications. Literature is full of excellent reviews articles regarding various grades of pure and commercialized PCMs and their possible applications [6,7,10,21,26]. Reports have also been made proposing various unconventional materials as possible candidates for PCMs applications [19]. However, a direct comparison detailing relative performance of a large number of PCMs for application specific purposes is not yet reported. The primary reason behind the absence of such a study stems from the lack of suitable and complete thermo-physical data for potential candidates. Additionally, it becomes a tedious and cumbersome task to theoretically or experimentally verify the performance of suitable PCMs as the list of potential candidates can run into hundreds or thousands. A similar problem is faced by designers and engineers when selecting optimum material for a particular application. Under such circumstances one is often forced to rely on the availability of experimental data, expert judgment and experience. This can however lead to sub-optimal selection which can adversely affect the vested economic interests of the customers regarding the operation of such installations.

One possible solution to such problems is the use of Multiple Criteria Decision Making (MCDM) approach for selecting the best alternative [27]. The suitability of PCMs and their performance is directly dependent on various thermo-physical properties. Since there are multiple criteria associated with each candidate, such a selection problem is classified under MCDM. MCDM is further subdivided into two separate branches of Multiple Objective Decision Making (MODM) [28] and Multiple Attribute Decision Making (MADM) techniques [29]. MODM approach makes use of various Figures of Merit (FOMs) to numerically identify the relative performance of participating candidates. The FOMs are derived using functional relationship between the various properties of participating contenders, such that maximization of each FOM leads to enhanced fulfilment of a desired objective. Examples of such objectives are: maximum strength per unit weight or minimum cost per unit volume. On the other hand, MADM approach makes use of predefined mathematical models to rank the alternatives based directly on the measure of their associated attributes. A functional relationship is not required to be established between the various properties. A MCDM approach can effectively utilize both MODM and MADM techniques to give a true indicator of the relative performance/ranking of the participating alternatives.

Through this study the authors have attempted to screen and rank various PCMs for domestic HVAC applications using MCDM approach. Two novel FOMs have been proposed for grading various PCMs based on their heat extraction ability and response time. The conflicting nature of the FOM based performance has been resolved by employing Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), a MADM approach. The materials have also been tested for Pareto Optimality and two separate fronts were generated thereof. All these techniques together have been proposed as an efficient selection tool for initial ranking and screening requirements for various PCM applications. To the best of our knowledge, no similar study has been made till date.

2. Materials and methods

2.1. Materials

A large number of materials have been explored and documented as PCM for various applications. Excellent reviews are available in the literature discussing various PCMs and their possible applications [10,21]. The number of documented PCMs, including pure compounds and commercialized products, presently exceed over a thousand. However, for the case study discussed in this report, technologically important materials are listed in Table 1. Indexed in Table 1 are potential PCM materials available for regulating temperature in HVAC applications for human comfort. The important thermo-physical properties considered for this study are phase change temperature (°C), mass density ($\mathrm{kg\,m^{-3}}$), latent heat of fusion ($\mathrm{kJ\,kg^{-1}}$), specific heat capacity at constant pressure ($\mathrm{kJ\,kg^{-1}\,K^{-1}}$) and thermal conductivity ($\mathrm{W\,m^{-1}\,K^{-1}}$).

Since the study in question aims at selecting the best material for regulating temperature within human comfort limits, phase change temperature becomes the single most important screening criterion. Hence, our initial selection of materials was limited to those exhibiting phase change in the temperature range of 17–25 °C. Density, thermal conductivity and latent heat of fusion are the primary factors that determine the performance of a PCM. The higher the density, easier it is to store a larger amount of material in a small volume. Similarly, higher the latent heat of fusion better will be the thermal stability provided by the use of respective PCM. Additional parameter like specific heat capacity, setting and melting enthalpy helps to determine the performance of the PCM in the sensible heating/cooling zone. Hence these parameters have been selected to help in the evaluation process of the candidate materials.

2.2. Methods

2.2.1. Ashby approach and FOMs

A popular MODM tool widely used by the scientific community for various screening and selection problems is the Ashby approach. This technique was first proposed by Ashby [30]. The underlying principle dictates that the performance (P) of any engineered system can be determined as a function of its functional (F), geometric (G) and materials (M) parameters. This statement can be mathematically represented as:

$$P = f(F, G, M) \tag{1}$$

Here, f denotes 'function of'. However, each of the aforementioned parameters operates independently of the rest and their collective output determines the overall performance. Hence, Eq. (1) can be rewritten as:

$$P = f(F) * f(G) * f(M) \tag{2}$$

Since, the aim of this study is to comparatively rank the PCM for generalized operation; we will only concern ourselves with the materials parameters.

The first step towards implementation of the Ashby approach is to determine the screening parameters. In our case, this has been limited to identification of suitable PCMs which are able to operate in the temperature range of 17–25 °C. A list of such potential candidates is listed in Table 1. The second step involves determination of suitable FOMs. Since the primary objective of PCMs is to store maximum amount of thermal energy in a minimum amount of space, the first FOM can be derived as:

$$Q = m * L = \rho * v * L \tag{3}$$

Here, Q represents the total heat extracted during the phase change process. While the symbols m, ρ, v, and L denote mass, density, volume and latent heat respectively. Eq. (3) can be modified to obtain the first FOM by isolating the materials parameters to the right hand side of the equation. Thus, Eq. (3) can be rewritten as:

$$FOM_1 = \frac{Q}{v} = \rho * L \tag{4}$$