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Characterization of thermophysical properties of phase change materials for non-membrane based indirect solar desalination application

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ABSTRACT

Phase change material as a thermal energy storage medium has been widely incorporated in various technologies like solar air/water heating, buildings, and desalination for efficient use and management of fluctuating solar energy. Temperature and thermal energy requirements dictate the selection of an appropriate phase change material for its application in various engineering systems. In this work, two phase change materials belonging to organic paraffin wax class have been characterized to obtain their thermophysical properties. The melting/solidification temperatures, latent heat of fusion and heat capacities of the phase change materials have been investigated using Differential Scanning Calorimetry, Thermogravimetric analysis and Temperature History Method. Thermal cycles up to 300 are performed to investigate melting and solidification reversibility as well as degradation over time. It is shown that the selected paraffin waxes have reversible phase change with no degradation of thermophysical properties over time. It is also shown that melting/solidification temperature and thermal energy storage capabilities make them suitable for their application as a thermal energy storage medium, in high temperature vapour compression, multi-stage flash and multi-effect distillation processes of non-membrane based indirect desalination systems.

1. Introduction

Solar energy is an abundant energy source and has been widely incorporated in various desalination technologies. However, inherent incident flux density fluctuations due to varying climate conditions and position of sun present a significant challenge to achieving and maintain stable efficient conversions. Thermal energy storage is a key technology for the efficient use and management of solar energy especially during cloudy days and non-sunlight hours [1] as well as for peak shifting [2]. Among thermal energy storage methods, solid–liquid phase change materials (PCM) are preferred as efficient latent heat, thermal energy storage medium are preferred due to their high storage density per volume/mass [3] and small temperature variation during storage and releasing thermal energy [4]. PCM have been used in several applications such as solar water heating, solar air heating, heat exchangers, buildings and desalination processes [3,5–15]. A PCM stores energy during phase change which results in no change in its temperature during that period [3]. Only after completion of phase change, the temperature of a PCM starts to rise or fall and acts like a sensible heat storage material [16]. Due to this natural buffer effect, latent heat storage is very interesting for applications where a constant temperature is desirable to achieve better conversion efficiency [17,18]. The principle elements of thermal energy storage via PCM, for matching the energy supply and demand requirements for maintaining a constant temperature, are absorption–accumulation, storage and release [6]. These principle elements not only depends on the geometrical configuration of the storage system but on thermophysical properties of a PCM as well. It is numerically demonstrated that the thermophysical properties of PCMs effect the performance of cylindrical latent heat storage tanks for the domestic heating system [15]. While thermal cycling of a PCM should be performed to determine its life cycle prior to the outdoor application [19].

Thermal energy storage not only useful for aforementioned applications but very attractive for solar-driven desalination application as well. Several researchers have undertaken an extensive review of solar energy driven desalination and integration of thermal energy storage for different processes [6,20,21]. Based on the reviews, the classification of solar desalination systems is shown in Fig. 1. Direct desalination systems consist of solar still and solar humidification–dehumidification system while indirect desalination systems consist of the membrane and non-membrane based processes as shown in Fig. 1.

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Nomenclature

A	area, m^2
c_p	heat capacity, J kg^{-1} K^{-1}
DSC	Differential Scanning Calorimetry
HD	humidification–dehumidification
H_f	latent heat of fusion
MD	membrane distillation
MED	multi-effect distillation
MSF	multi-stage flash
m	mass, kg
PCM	phase change material
RO	PV operated reverse osmosis
r	radius, m
SS	solar still
T	temperature, K
TGA	Thermogravimetric analysis
THM	Temperature History Method
VC	vapour compression

Subscripts

i	initial
l	liquid
m	melting
p	PCM
PC	phase change
s	solid
t	tube
w	water

Superscript

$'$	reference material

Application of PCMs for direct desalination systems has been widely researched [18,22–36] and an efficiency improvement of more than 21% has been reported for concentrator-coupled hemispherical and small scale basin type solar stills [23,24]. Increased productivity of freshwater has also been reported for passive solar still [22], cascade solar still [25], continuous single stage solar still [26,27], stepped solar still [28], and weir-type cascade solar still [29]. A single slope solar still having a coupled parabolic concentrator has also reported an increase in productivity when a PCM is added in the basin of the still [31]. A solar concentrating distillation system using a conical solar still with PCM has been designed and tested for desertic conditions [32,33]. It is found that the addition of PCM increases the system working time by 5 h. For humidification de-humidification desalination cycle, PCM produces a consistent air outlet temperature throughout the day or night [18]. An energy saving seawater desalination system employing a hybrid form-stable PCM storage and spray flash evaporation system has also been developed [30]. This system stores thermal energy and uses it on demand for production of fresh water for industrial and domestic usage. Some of the PCM utilized in direct desalination systems are mentioned in Table 1 along with their thermophysical properties. PCM technology is not only appropriate for the low-temperature direct desalination applications mentioned above but also suitable for high-temperature desalination technologies, such as non-membrane based indirect desalination systems [6].

Temperature and thermal energy requirements dictate the selection of suitable PCM for its application in solar desalination systems [18]. There are several PCMs available today to meet the certain temperature and thermal energy storage demand [37–39]. Generally, nominal thermal properties of proprietary commercial PCMs are provided by their manufacturer – including heat of fusion and melting/solidification temperatures. But this information is considered inadequate [40,41] to determine their performance in an application. In-order to design a suitable latent heat storage system, knowledge of the thermophysical properties and thermal reliability of PCM are essential as well as symmetry; considering the variation in these properties under repeated melting/solidification cycles [42]. The desirable properties of PCMs for their applications in different indirect solar desalination systems are reported in Table 2.

For the analysis of PCM to determine their thermophysical properties, the techniques used are; Differential Scanning Calorimetry (DSC), Differential Thermal Analysis, Thermogravimetric analysis (TGA) and Temperature History Method (THM) [43,44]. Several studies have been performed to characterize

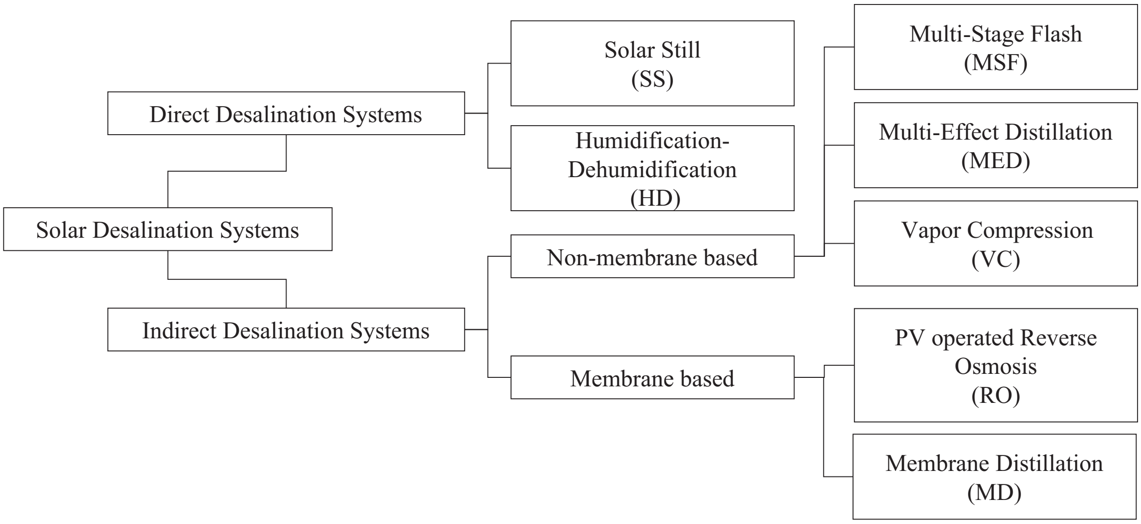

Fig. 1. Classification of solar desalination systems [17].