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Research Paper

Experimental assessment on thermal storage performance of beeswax in a helical tube embedded storage unit

Abhay Dinker [a], Madhu Agarwal [a,*], G.D. Agarwal [b]

[a] Department of Chemical Engineering, MNIT Jaipur, 302017, India
[b] Department of Mechanical Engineering, MNIT Jaipur, 302017, India

HIGHLIGHTS

- Beeswax has been introduced as natural phase change material.
- Beeswax was characterized for its thermal properties.
- Shell and tube type unit with embedded helical coil for thermal storage is proposed.
- Increase in inlet temperature of heat transfer fluid decreased charging time.
- Increase in flow rate of heat transfer fluid decreased efficiency of thermal storage unit.

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ABSTRACT

In the present study beeswax is considered as a natural latent heat storage material. A novel rectangular shell and tube type geometry is introduced as a thermal storage unit (TSU), in which copper helical coil carrying hot heat transfer fluid is embedded in the beeswax filled in rectangular shell. Thermal performance study of beeswax is carried out in a series of charging and discharging experiments with water as a heat transfer fluid (HTF). Temperature profiles along the axial and vertical direction of helical coil have been recorded by measuring nine temperatures to understand the mode of heat transfer within the beeswax. Effect of flow rates (0.25 LPM, 0.5 LPM, 0.75 LPM, 1.0 LPM) and inlet temperatures (60 °C, 70 °C, 80 °C) of HTF on charging time and thermal storage efficiency of beeswax is analyzed. It is observed that increase in fluid flow rate reduced the charging time and storage efficiency of the system, however increase in fluid inlet temperature increased the charging time of the system. Maximum efficiency of TSU during charging was 84% when HTF at 80 °C flows through TSU at 0.5 LPM. Results of the study prove beeswax as low cost and naturally available phase change material (PCM) performance wise better than conventional PCMs in lower temperature range.

1. Introduction

Our society is facing energy crisis due to rapidly depleting fossil fuels and environmental problems like global warming, climate change, loss of biodiversity, deforestation and ozone layer depletion. Studies revealed a sharp increase in greenhouse gases in environment. It is estimated that by the year 2400 there is about 5000 gigatonnes of carbon will be released in environment starting from industrial revolution keeping rates of fossil fuel consumption and carbon-sequestration constant [1]. Due to enhanced greenhouse effect average rise in temperature occurred globally at the rate of 0.15–0.20 °C [2,3]. Another concern with rise in greenhouse gases is the depletion of ozone layer led to increased environmental and health problems [4,5]. To address the above problems there is need of energy storage to reduce fossil fuel consumption and burden on environment. Renewable source of energy is intermittent in nature and dependent on weather conditions and therefore required some sort of energy storage systems like photo-voltaic systems [6–8], photovoltaic/thermal hybrid system, sensible energy storage through solar ponds [9,10], latent energy storage [11–13], concentrated solar plant [14,15] and hydrogen storage system [16–18].

Latent energy storage systems are one of the promising technologies available at present to meet world's energy crisis. These systems uses phase change material to store heat as latent heat of melting during their phase transition i.e. from solid to liquid.

* Corresponding author.
E-mail addresses: madhunaresh@gmail.com, magarwal.chem@mnit.ac.in (M. Agarwal).

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Nomenclature

Dimensional variables

d_i	inner diameter of tube (m)
d_o	outer diameter of tube (m)
C_{ps}	heat capacity of solid (J kg^{-1} K^{-1})
C_{pl}	heat capacity of liquid (J kg^{-1} K^{-1})
T_w	wall temperature (K)
T_b	bulk temperature (K)
T_{out}	fluid outlet temperature (K)
T_{in}	fluid inlet temperature (K)
T_m	melting temperature (K)
T_i	initial temperature of PCM (K)
T_f	final temperature of PCM (K)
ΔT_m	least mean temperature difference (K)
$\dot{m}$	mass flow rate of HTF (kg s^{-1})
m_w	mass of PCM (kg)
ρ	density of water (kg m^{-3})
v	velocity (m s^{-1})
$\dot{Q}$	instantaneous energy (kJ/s)
Q_a	available energy (kJ)
Q_w	energy required by wax (kJ)
L	latent heat of fusion (kJ/kg)
U_o	overall heat transfer coefficient (W m^{-2} K^{-1})
h_i	internal heat transfer coefficient (W m^{-2} K^{-1})
h_o	external heat transfer coefficient (W m^{-2} K^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
β	thermal expansion coefficient (K^{-1})
g	acceleration due to gravity (m s^{-2})
D_c	diameter of curvature (m)
L	length of tube (m)
b	pitch length (m)
A_s	total surface area of tube (m^{-2})
A_o	outer surface area of the coil (m^{-2})
A_i	inner surface area of the coil (m^{-2})

Dimensionless numbers

Nu_i	inside Nusselt number
Nu_o	outside Nusselt number
R_e	Reynolds number
D_e	Dean number
Pr	Prandlt number
γ	dimensionless pitch
Ra	Rayleigh number
Gr	Grashof number
N	total number of turns

Abbreviations

PCM	phase change material
HTF	heat transfer fluid
LPM	liter per minute
TSU	thermal storage unit

A latent heat storage system stores heat at a constant temperature and therefore has high energy storage density (5–10 times more as compared to sensible energy storage) [19]. High energy density, isothermal energy storage, low volume change, low vapor pressure, no super cooling and choice of temperature range are important properties of phase change materials for domestic and industrial applications like domestic solar water heater [20,21], temperature control of buildings [22] and electricity generation through concentrated solar power [23,24] respectively.

A variety of organic and inorganic phase change materials (PCMs) are available for the development of an efficient thermal energy storage system. Selection and use of an appropriate PCM is dependent on factors like melting point, stability after thermal cycles, toxicity and corrosive nature [25,26]. Inorganic phase change materials like sodium nitrate [27], sodium carbonate/lithium carbonate [28], sodium carbonate/sodium chloride binary mixture [29], lithium nitrate/potassium chloride mixture [30], Magnesium nitrate/magnesium chloride mixture [31], etc. with their high melting point temperature range are suitable for higher temperature heat storage applications like concentrated solar power plant [32,33], however, most of them are highly corrosive in nature [34,35] which reduces the life of thermal storage units and therefore needs special handling [34]. Organic phase change materials like Paraffin [14,36–38] and fatty acids [39–41] with low melting point range like paraffin, fatty acids, and fatty alcohols are commonly being used for lower temperature applications. These organic materials offer a wide possibility in solar thermal applications for heating water and for maintaining the indoor building temperatures [42]. Paraffin is the most commonly used PCM for lower temperature applications; however, being a derivative of petroleum product its production process involves the use of various toxic catalysts and follows the pathway where various byproducts of carcinogenic nature are produced [43] which make its promotion as promising PCM unsustainable for the environment. Fatty acids and their esters due to their higher cost of production are not recommendable for thermal energy storage applications [39]. These limitations of synthetic organic phase change materials restrict their use and demands for the identification and introduction of new phase change materials which are technically and economically feasible, easily available for different applications.

In this work natural beeswax is introduced as a new phase change material for latent heat storage. Beeswax is obtained from honey bees consisting of fatty acids (mainly palmitic acid, tetracosanoic acid and oleic acid), long chain of alkanes, monoesters (C_{24} to C_{34}), diesters, and hydroxyl-monoesters [44] and mainly used for making sculptures, candles and also in food and medical industries for surface coatings [45–49]. Beeswax also finds potential application in the field of drug delivery and proved more efficient as compared to other waxes in faster release of drugs [50,51]. Despite of its wide applications in the food, medical and other sectors the application of beeswax as thermal storage material is not reported much.

Natural beeswax is non-toxic, non-corrosive, having low melting point (60–68 °C), high latent heat of transition (145–395 kJ/kg) [52,53], small volume change, low vapor pressure and long term chemical stability almost similar to conventional paraffin [54,55]. Being a natural product its cost is quite less as compared to other organic materials and its production and degradation does not involve any toxic byproduct which makes it a sustainable product [56] and can be used in place of paraffin and other organic PCMs as latent heat storage material.

For an efficient thermal storage system an effective PCM as well as an efficient geometrical configuration is required for faster heat transfer. Various numerical and experimental thermal performance studies have been performed on shell and tube type thermal storage units using straight tube configuration for different organic PCMs [57–59]. These storage units are generally consisting of cylindrical shell encapsulating the PCM with straight tube carrying HTF. There are different geometries of shell and tube