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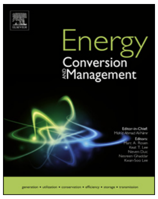

Melting of nano-PCM inside a cylindrical thermal energy storage system: Numerical study with experimental verification

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ABSTRACT

In the current work, the melting process, heat transfer, and energy storage characteristics of a bio-based nano-PCM in a vertical Cylindrical Thermal Energy Storage (C-TES) system are numerically investigated and verified with experimental work. Mathematical models based on non-linear differential equations are developed to study the mass, momentum, and energy transport processes inside the C-TES system. The effects of nanoparticles volume fraction (i.e. ϕ = 0%, 3%, and 5%) and Rayleigh number (i.e. $Ra_{nl} = 10^6$, 10^7, and 10^8) on the melting process are investigated. To compare the numerical results, an experimental setup is developed and transient images are captured to identify the location and shape of solid-liquid interface. To prepare nano-PCM, the copper oxide (CuO) nanoparticles are dispersed into the bio-based coconut oil PCM. The C-TES system is insulated from the bottom, isothermally heated from its lateral walls and the top. Numerically obtained solid-liquid interface locations and melt fractions for base PCM and nano-PCM are compared with experimental analysis and a very good agreement is obtained. The numerical results are further compared with existing numerical and experimental results available in the literature. The work then explains the effects of Rayleigh number and volume fraction of nanoparticles on melt fraction, Nusselt number, and stored energy. The results indicate that adding nanoparticles do not change the patterns of melt fraction, Nusselt number, and energy storage capacity with time compared to the base PCM case. The effects of specific heat capacity of solid nano-PCM, liquid nano-PCM, and latent heat capacity of nano-PCM on energy stored are discussed. The results show that the difference in energy stored with Rayleigh number is less during the beginning of the melting; as melting reaches in the convection dominated regime, a larger difference is observed due to increased melting at larger Rayleigh number.

1. Introduction

The ongoing increase in the worldwide population and industrial units is accompanied by a significant demand for energy. On the other hand, the limitation in the sources of conventional fossil fuels and the environmental issues associated with their uses, have caused several concerns and challenges such as security of energy supply and global climate change [1–4]. To overcome these issues, exploitation of renewable energies (e.g. solar energy, geothermal, wind energy, etc.) has been significantly considered by energy suppliers. However, due to the fluctuations and inability to control the sources of the renewable energies, it is more efficient for these systems to be used with energy storage systems [5]. Thermal Energy Storage (TES) systems are developed with an aim to store thermal energy in an efficient and reliable manner. TES systems have been used in a wide range of applications for heating/cooling purposes including building thermal management, food processing applications, Heating, Ventilation, and Air Conditioning (HVAC) systems, and solar power plants for storing thermal energy during the day and release it during the night and cloudy days. In general, TES systems are divided into three main groups: sensible, latent, and thermo-chemical heat storage. Due to the effective use of Phase Change Materials (PCM) in improving Latent Heat Thermal Energy Storage (LHTES) systems, more impetus has been provided by researchers to develop the LHTES system with PCMs. Utilizing PCMs in LHTES systems have provided advantages of high energy density and an almost constant operating temperature [6]. In these systems, thermal energy is stored during the melting process and released during the solidification process. A wide range of PCMs with various melting temperatures including Paraffin waxes, organic and non-organic compounds, and hydrated salts are available for use in LHTES systems. Comprehensive information regarding different types of PCMs is available in [7]. To select a proper PCM, different parameters including phase change temperature, stability, amount of latent heat, and thermal conductivity should be considered [8]. Although having desirable attributes for storing thermal energy, PCMs suffer from low thermal conductivity, which results in a lower melting/solidification rate and

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Nomenclature

c_p	specific heat at constant pressure [kJ/kg K]
g	gravitational acceleration [m/s^2]
H	height of the filled nano-PCM [cm]
h_{nl}	latent heat of fusion [kJ/kg]
k	thermal conductivity [W/m·K]
R	inner radius of the C-TES system [cm]
T	temperature [°C]

Greek symbols

α	coefficient of thermal diffusivity [m^2/s]
β	coefficient of thermal expansion [1/K]
μ	dynamic viscosity [Pa.s]
ρ	density [kg/m^3]
ϕ	volume fraction of nanoparticles

Subscripts

h	hot
l	liquid PCM
m	melt
n	nanoparticles
nl	liquid nano-PCM
ns	solid nano-PCM
s	solid PCM
0	initial

Abbreviation

C-TES	cylindrical thermal energy storage system
TES	thermal energy storage
LHTES	latent heat thermal energy storage system
MF	melting fraction
PCM	phase change material
RT	Rubitherm (www.rubitherm.eu)
Ra_{nl}	Rayleigh number based on liquid nano-PCM properties, $Ra_{nl} = \frac{g\beta_{nl}H^3(T_h - T_m)}{\nu_{nl}\alpha_{nl}}$

reduction in the efficiency of LHTES systems [9]. Different approaches for enhancing the thermal conductivity of a PCM have been suggested by researchers, which can be categorized into two main groups. The first group is a geometric approach that is related to a modification in the design of the shape of the enclosure or inserting highly conductive fixed materials such as metal fins and porous materials inside the enclosure [10]. The second approach is based on combining PCM with highly conductive nanoparticles (e.g. copper oxide and aluminum oxide particles) to increase the thermal conductivity of the PCM [11–13]. Although using the reported methods can enhance the thermal conductivity of a PCM, some challenges are remained. For instance, by adding high volume/weight fraction of nanoparticles to a PCM, sedimentation occurs, which has a negative effect on the thermal conductivity of nano-PCM after several cycles of operation [14]. On the other hand, inserting conductive materials (e.g. metal fin, porous material) into the PCM reduces the volume of filled PCM. Because of the lower amount of PCM, lower amount of stored energy will be achieved [15,16]. Different types of geometrical configurations including rectangular, spherical, cylindrical, and annular containers have been studied as a TES system. These are necessitated by the different applications and limitations of the occupied space. A complete description of TES systems with different geometries filled with nano-PCMs can be found in [5,6]. Cylindrical containers can be used both horizontally and vertically, which have invoked a significant interest due to the ease of its manufacturing process. Studying vertical cylindrical containers filled with PCM/nano-PCM, which is the primary focus of the present paper, have been investigated by several researchers. A brief review of studying vertical cylindrical containers filled with PCM/nano-PCM is shown in Table 1.

There are other recently published works regarding the use of nanoparticles to enhance the thermal performance of a LHTES system. For instance, the volumetric heat generation effect during melting/solidification process of nano-PCM filled horizontal cylindrical geometries were studied by Bechiri and Mansouri [27]. Several researchers also investigated the thermal performance of a shell and tube LHTES system filled with nano-PCM [28–33]. In general, it is reported that dispersing nanoparticles at low volume fractions increases the heat transfer rate and because of that the time required for melting/solidification process is decreased. Nonetheless, Parsazadeh and Duan [33] have stated that dispersion of nanoparticles into the PCM increases the melting time due to the degradation of natural convection caused by the addition of Al_2O_3 into the paraffin wax. The recent investigations regarding the use of nano-PCM in a rectangular LHTES system revealed that dispersion of highly conductive nanoparticles into the PCM enhances the thermal conductivity of the PCM [34–37]. However, it is mentioned that addition of nanoparticles to the PCM increases the viscosity of PCM, which leads to a decrease in the natural convection that could lower the thermal performance of the LHTES system [35,36]. In addition, nano-PCMs have been also used for several thermal management applications [38–41]. In general, it is concluded that dispersion of nanoparticles at low volume/weight fractions can enhance the amount of removed heat, which can enhance the performance of thermal systems.

According to the published works available in the literature, the melting process of a nano-PCM filled in a vertical C-TES system, which is isothermally heated from its lateral walls and the top and insulated from the bottom, has not been extensively investigated. In the present paper, a numerical investigation on melting process of a bio-based PCM (coconut oil) enhanced with copper oxide (CuO) nanoparticles is performed. Effect of using different volume fractions (ϕ) of nanoparticles (i.e. ϕ = 0%, 3%, 5%), different cylinder heights of filled nano-PCM representing different Rayleigh (Ra) numbers (i.e. $Ra_{nl} = 10^6$, 10^7, and 10^8) on the melting rate, heat and energy transfer characteristics are studied. Moreover, the behavior of solid-liquid interface at different time intervals is studied.

In the authors' opinion, the authors are the first who have studied the melting process of an edible coconut oil PCM with CuO nanoparticles inside a cylindrical enclosure with isothermal surrounding and adiabatic bottom walls. The relatively inexpensive coconut oil PCM is edible, having the melting temperature (≈ 24 °C) close to the typical lab temperature (22 to 23 °C), and exhibits excellent stability and very small sedimentation for longer uses once nanoparticles are incorporated compared to many other commercially available PCMs reported in the literature. Properties of the nano-PCM were measured and compared with the modeled equation, a maximum discrepancy of ± 5% was observed for the thermal conductivity of nano-PCM. Comprehensive numerical simulation is performed to visualize the progression of the melting process with the experimental comparison; and to calculate the melt fraction, Nusselt number, and energy storage rate.

2. Modeling and analysis

A schematic diagram of the vertical C-TES system is presented in Fig. 1. A numerical investigation of the melting process of a bio-based PCM (melting temperature T_m) enhanced with different volume fractions of nanoparticles (i.e. 0%, 3%, and 5% of copper oxide nanoparticles) inside the C-TES system is performed in this work based on