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Research Paper

Thermal energy storage system operating with phase change materials for solar water heating applications: DOE modelling

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HIGHLIGHTS

- Phase change materials play a vital role in heat energy conservation.
- A design of experiment modelling is applied to thermal energy storage system.
- Artificial neural network model revealed good agreement with experimental results.

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ABSTRACT

Phase change materials have gathered wide acceptance globally due to its effective and economically efficient storage properties. It is emerging to find potential applications in both renewable and fossil energy systems. This paper analyzes the performance and models an experimental design for heat transfer enhancement of a thermal energy storage system by using honey and paraffin waxes. Experiments were conducted in a fabricated thermal energy storage cylindrical tank embedded with copper tubes that in turn filled with these waxes in a liquid state. This non-isothermal system was fabricated to improve the water heat transfer rate from the solar tank unit to waxes in the thermal chamber. The conservation of heat energy was achieved through implementation of this system, this offer a better solution to a conventional storage tank. Performance appraisal of results from experimentation during the processes of charging and discharging of phase change materials has been performed and examined. Good thermal energy storage characteristics of heat transfer, absorption and rejection were observed. The design of experiments modelling work- artificial neural network showed good agreement with experimental results. Mainly, it was found that the factor time has contributed more than 40% of the heat improvement in this storage system during charging and discharging process of paraffin and honey waxes. On the other side, the least number of residuals was observed for the honey wax heat absorption during charging process.

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1. Introduction

The thermal energy storage system can be operated by changing the material's internal energy in the form of latent, sensible, and both. Thermal energy storage plays a significant role in the conservation of available energy, and illuminating a new way for energy optimization. PCM are materials in either liquid or solid state with good thermal characteristics like fusion in high heat energy. PCM is highly non-equilibrium materials, which means it can solidify and melt at a specific temperature. Latent heat storage is dependent on the absorption or release of heat when a material under storage go through from the liquid state to solid state or gaseous state to liquid state or vice versa. In the case of sensible heat storage, the heat energy is stored through the liquid or solid rising temperature. This paper employs honey and paraffin waxes phase change materials and in our scenario a combination of both latent and sensible heat storages play a vital role in TES system and heat transfer process. Latent and sensible heat storage avails the heat capacity and temperature change of the PCM during the charging and discharging processes. Enhancements of heat transfer processes in both experimental and analytical works have been stated and presented in the literatures extensively, in accordance with industrial and domestic applications. This literature review is con-

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Nomenclature

TES	thermal energy storage
Cu	copper
PCM	phase change materials
DOE	design of experiment
ANN	artificial neural network
LHS	latent heat storage
SHS	sensible heat storage
HTF	heat transfer fluid
MAPE	mean absolute percentage error
RMSE	root mean square error
CPPW	charging process of paraffin wax
DPPW	discharging process of paraffin wax
CPHW	charging process of honey wax
DPHW	discharging process of honey wax
O_i	observed values
E_i	expected values
n	number of iterations used in the calculation
χ^2	chi-square test

fined to the design of experiment modelling work, which is ultimately relevant to the theme of this paper. Lamberg et al. [5], examined the phase change materials, in which the storage materials are used to balance the temporary temperature alternations. Validation obtained through a comparison of experimental data and numerical results. The numerical results are compared with the FEMLAB simulation software.

The final results show a good estimation of the temperature distribution of the storage in both the melting and freezing processes. Benmansour et al. [2], developed a numerical analysis of the transient response of a cylindrical packed bed thermal energy storage system, this system is randomly packed with spheres has uniform size and encapsulated the paraffin wax as a phase change material (PCM), with air as a working fluid flowing through the bed. The fluid energy equation was transformed by finite difference approximation and solved by alternating direction implicit scheme. While the PCM energy equation was solved using the explicit system. This analysis is valid for fluids of various Prandle numbers. It can be applied for both charging and recovery modes and for a broad range of Reynolds numbers. Qarnia [4], developed a number of rectangular channels for the flowing heat transfer fluid. The velocity profile of the rectangular channel is given by an exact analytical solution. A numerical code based on the finite difference method was developed and validated by comparing numerical predictions with an exact analytical solution. Banaszek et al. [1], used two-dimensional computer simulation conjugate heat transfer method to solve the phase changing problem. The numerical model is based on local energy balances in a set of curvilinear control-volumes and the enthalpy approach to account the latent heat effect. Gairaa et al. [3], evaluated the global solar radiation on a daily basis using a combined approach of ANN and Box-Jenkins Models. The authors have analyzed the worldwide solar radiation data documented in 2012 and 2013. They have taken two different climate locations in Algeria. The results revealed that, the combined models indicated an improvement in terms of absolute and root mean square error for both sites.

Sharma et al. [6], made an extensive and critical reviews on different types of thermal energy storage systems and critically analyzed the applications and importance of the phase change materials. Thus, their review helps a researcher to pursue in depth research and development of thermal energy storage process and phase change material properties. Some literature studies regarding heat transfer, numerical and analytical modelling were described above. The rapid growth of global literatures in this area shows that transfer of heat, energy storage, and PCM are a main ultimate field in the research and development of heat and mass transfer. As material and energy scarcity become top priority factors on the whole thermal engineering systems, the enhancement implementation of these applications in the industry will gradually increase. Hence, a reader can observe this paper innovation in the separate attachment consisting of experimental testing and values. We used paraffin and honey waxes to enhance the heat transfer in the thermal energy storage system for solar water heating applications. We applied ANN models to this work for optimization and identification of best parameter or factor for the improvement of this thermal system. However, ANN is not a new technique and it is an existing model. This work has analyzed the variations in ANN network structure with different input and output parameters for charging and discharging processes of honey and paraffin waxes.

2. Thermal energy storage system: Design and development

Thermal energy storage systems have an enormous potential to make the function of thermal energy equipment more effectively and to facilitate large-scale energy substitutions. They are highly valuable from an economic perspective. It is an advanced energy technology that has recently attracted increasing interest for thermal applications such as space and water heating, cooling and air-conditioning. It appears to be the most appropriate method for balancing the mismatch between the energy supply and demand. It is therefore a very captivating technology for meeting community needs and desires for more efficient and environmentally friendly energy use. This TES system uses two phase change materials such as paraffin and honey wax for heat enhancement testing. The normal paraffin of type C_nH_{2n+2} is a family of saturated hydrocarbons with very similar properties. Paraffin between C_5 and C_{15} are liquids, and the rest is waxy solids. Paraffin wax is the mostly used commercial organic heat storage PCM. It consists of straight chain hydrocarbons, which have melting temperatures from 23 °C to 67 °C. Its major advantages are no segregation, recyclable, safe, freeze without high super-cooling, large temperature range availability etc. Honey wax can be softened by adding vegetable oils so that it can be made workable at room temperature. It is a tough, complex mixture of a number of chemical compounds. It contains hydrocarbons (14%), monoesters (35%), diesters (14%), triesters (3%), hydroxyl monoesters (4%), hydroxy polyesters (8%), acid esters (1%), acid polyesters (2%), free acids (12%), free alcohols (1%) and unidentified matter (6%). It has a high melting point of 62–64 °C and if the honey wax is heated over 85 °C its discoloration begins.

2.1. Design and fabrication of chamber

The fabricated TES storage chamber has been designed and developed to enhance the heat transfer rate from the state of HTF to PCM. The fabricated TES storage chamber inserted with a number of copper tubes filled with PCM materials. The copper tube arrangement has kept in well insulated storage tank. It carries a minimum of 45 l capacity of water with glass wool insulation. Cu

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