Applied Thermal Engineering 123 (2017) 614–624

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

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.

ARTICLE INFO

Article history:
Received 15 October 2016
Revised 20 April 2017
Accepted 23 May 2017
Available online 25 May 2017

Keywords:
Phase change materials
Heat transfer
Artificial neural network
Residuals
Model verification

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.

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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http://dx.doi.org/10.1016/j.applthermaleng.2017.05.122
1359-4311/

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

Table 1
Thermo-physical properties of paraffin and honey waxes.

Properties		Paraffin wax (R40)	Honey wax
Melting point		54 °C	58 °C
Latent heat		203 kJ/kg	217 kJ/kg
Density		912 kg/m^3	953 kg/m^3
Heat capacity	Solid	1.8 kJ/kg·K	2.2 kJ/kg·K
	Liquid	2.7 kJ/kg·K	3 kJ/kg·K
Thermal conductivity		0.3–1.8 W/m·K.	0.6–2.1 W/m·K.

having high thermal conductivity hence in order to increases enhancement of heat, bundle of copper tubes is used to transfer heat from solar panel to TES storage chamber, it receives Heat Transfer Fluids (hot water) from solar tank. Solar tank, which is integrated with evacuated glass tube collector. Solar energy has absorbed and stored in a PCM storage chamber as latent heat. Large quantities of solar energy can be stored in a day time and same heat can be retrieved for later use. The tank was instrumented to measure the HTF and PCM temperature. Valves are used to vary the mass flow rate at different interval. Paraffin and honey waxes were used as Phase change materials. A good design of latent heat thermal energy storage requires the knowledge of selection of materials and the heat exchange processes. The following Table 1 shows the thermo-physical properties of paraffin and honey waxes.

In this experiment, two circular plates are provided to arrange the copper tubes. The circular plates have 30 cm diameter and 1.5 mm thickness. 50 numbers of holes are provided concentrically on the surface of the circular plate; through the holes copper tubes exactly fit with less clearance. While the copper tubes are arranged vertically in the circular plates, the higher and lower level difference between the circular plates is 35 cm. Fig. 1(a) shows the circular plate with the arranged copper tubes. In which the length of the copper tube is 65 cm, diameter of the copper tube is 1.8 and this design is based on the outside diameter, its thickness is 1.5 mm, and number of tubes in the arrangement is 50. Fig. 1(b) and (c) shows the filling process of PCM in Cu tube and the tube arrangements was kept inside the thermal chamber. Fig. 2 presents the solar panel collectors.

Fig. 2. Solar collectors.

2.2. Experimental procedure

The experimental set-up has three storage tanks, the first one is a cold water tank with a capacity of 500 l, the second one is a solar tank with a capacity of 100 litres, and the third one is the PCM storage tank with a capacity of 45 litres. The tank was instrumented to measure the HTF and PCM temperatures with a thermometer arrangements. Flow meters were fitted across the pipeline to measure the flow rates by adjusting the valve position, proper inlet and outlet pipe connections are ensured, as shown in Fig. 3(a). Here, water is used as HTF and paraffin and honey waxes are used as phase change materials. To analyze the temperature variation of the HTF and PCM in the copper tube, the length of the copper tube

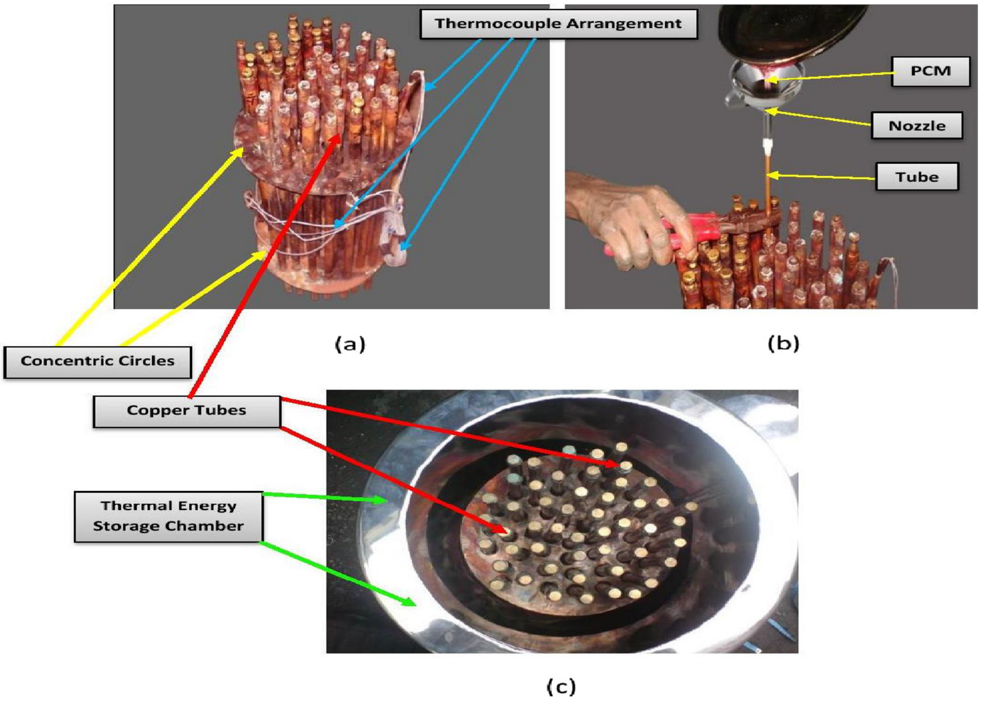

Fig. 1. (a) Cu tubes embedded in concentric circles and thermocouples arrangements, (b) filling of PCM, and (c) Cu tubes arrangements kept in a thermal energy storage chamber.

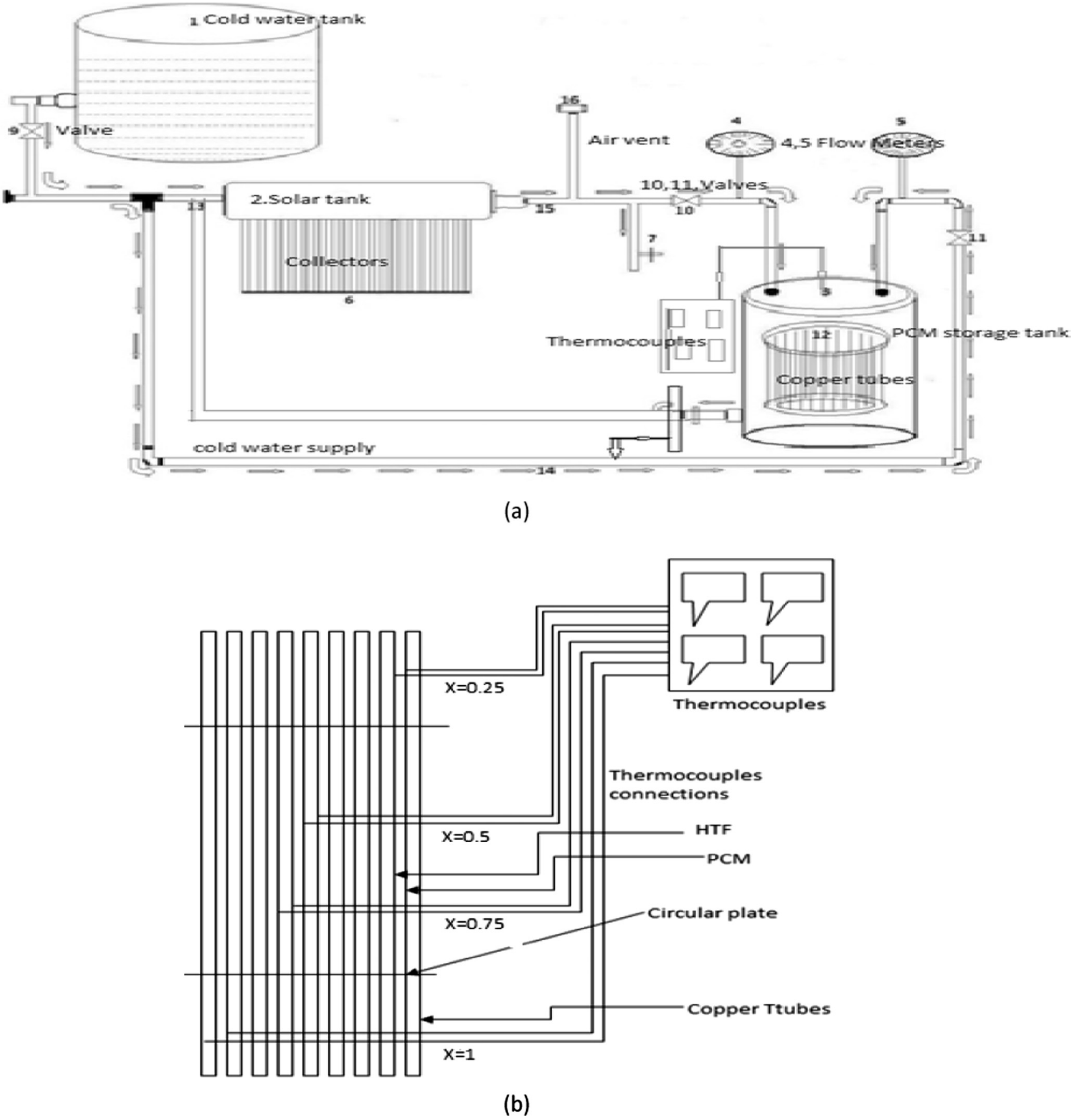

Fig. 3. (a) Experimental setup line diagram, (b) thermocouple levels around copper tubes.

is divided into four divisions or segments (levels) from the base, each division of which in and out of the copper tubes is connected to thermometers with sensors. Inside the copper tube the PCM is presented, and outside the copper tube the HTF water is circulated. Hence, we can read the temperature for both the HTF and the PCM at all levels. Fig. 3(b) shows the thermocouple wiring arrangement levels around the copper tube.

The flow starts from cold water storage tank, then it goes to the evacuated solar tube collector area with 1.5 m^2 and is saved as hot water in the solar tank, then it passes to PCM storage tank while adjusting the valve position. In the charging process, during the active phase of the sun light the heat energy can be stored in the solar tank through the evacuated glass tube collector. Then the heat transfer fluid from the solar tank is allowed at 76 °C with a flow rate of 6 kg/min to the PCM storage tank. Then the PCM and HTF temperature are noted every 10 min at four levels, the experiment is carried for nearly 160 min for the charging process. For the discharging process, the cold water is allowed in the PCM tank with a flow rate of 6 kg/min, 4 kg/min, and 2 kg/min at 40 °C. Then the HTF and PCM temperature are noted every 10 min at four levels, the cold water absorbs heat from the PCM, and releases hot water continuously.

The experiment is completed when the PCM and water temperatures are the same. The experiment is done nearly for 200 min for the discharging process. The same procedure is repeated for different mass flow rates, and the heat transfer rate and heat absorption

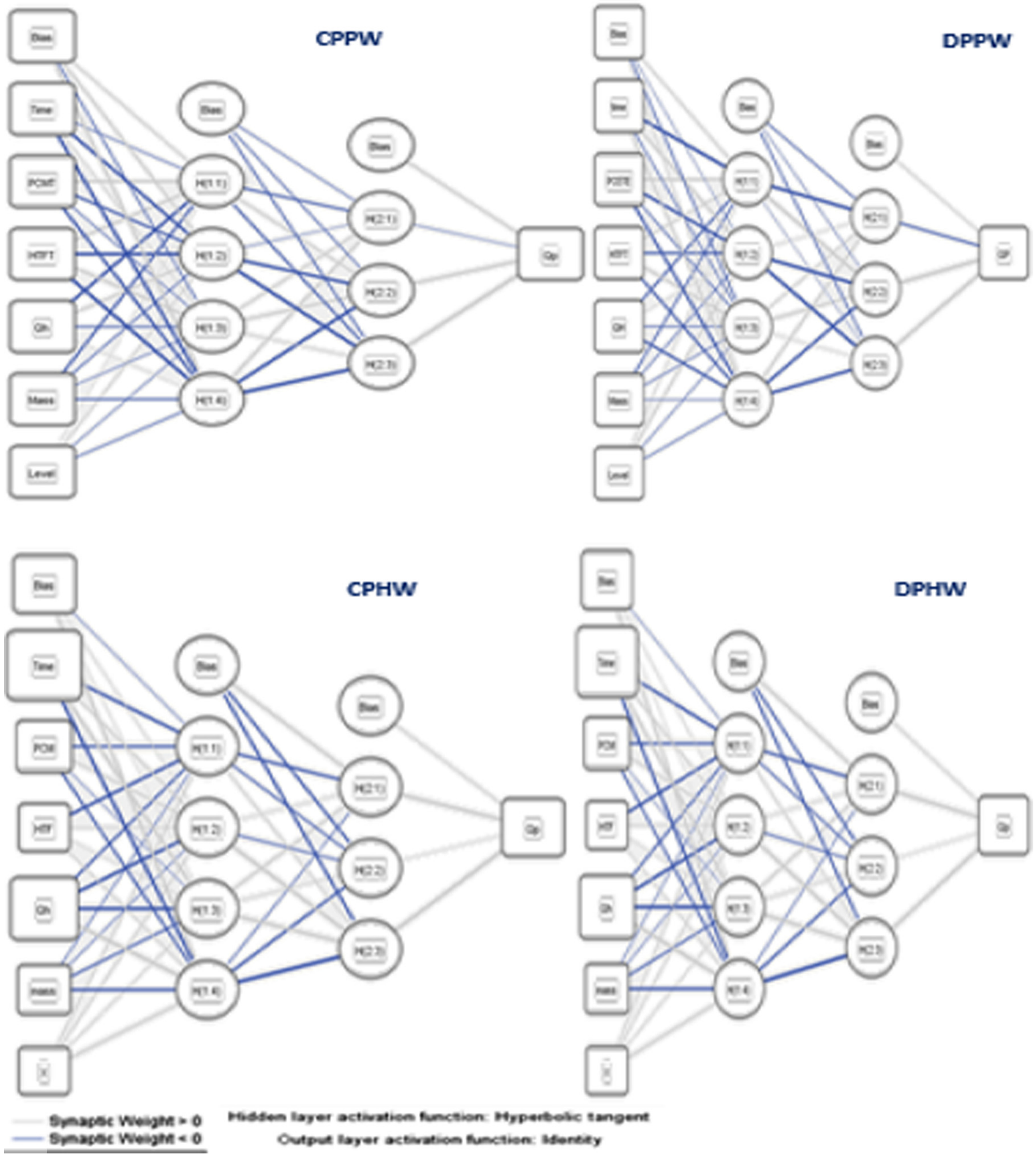

Fig. 4. ANN model for charging and discharging processes for paraffin and honey waxes.

are calculated. The observed data for the charging and discharging processes at different mass flow rates for both paraffin and honey waxes were not presented in this paper. This paper only focuses on the design of experiment modelling part. Those experimental values weren't mentioned due to its extensive length and the percentage of uncertainties associated with the physical experimental work is ±3.52% and its calculation is presented in appendix E, which can be found in a separate attachment. Once the experiment was over for paraffin wax at different mass flow rates, the packed paraffin in the copper tubes is taken out of the insulation tank. All the paraffin wax is removed from the copper tubes, and honey wax is refilled. Again the insulation is set up and the same procedure is repeated.

3. Design of experiment modelling

This section discusses the modeling analysis with the obtained experimental results, in which the observed values are arranged into a set of data to develop the model using a statistical software tool of "Statistical Package of Social Science" (SPSS). In which ANN model is described in detail. The developed models are compared with the experimental results and validated with Chi-Square Test, Mean Absolute Percentage Error (MAPE) and Root Mean Square Error (RMSE). Also flow chart for ANN model, residuals, and dendrogram have been developed.

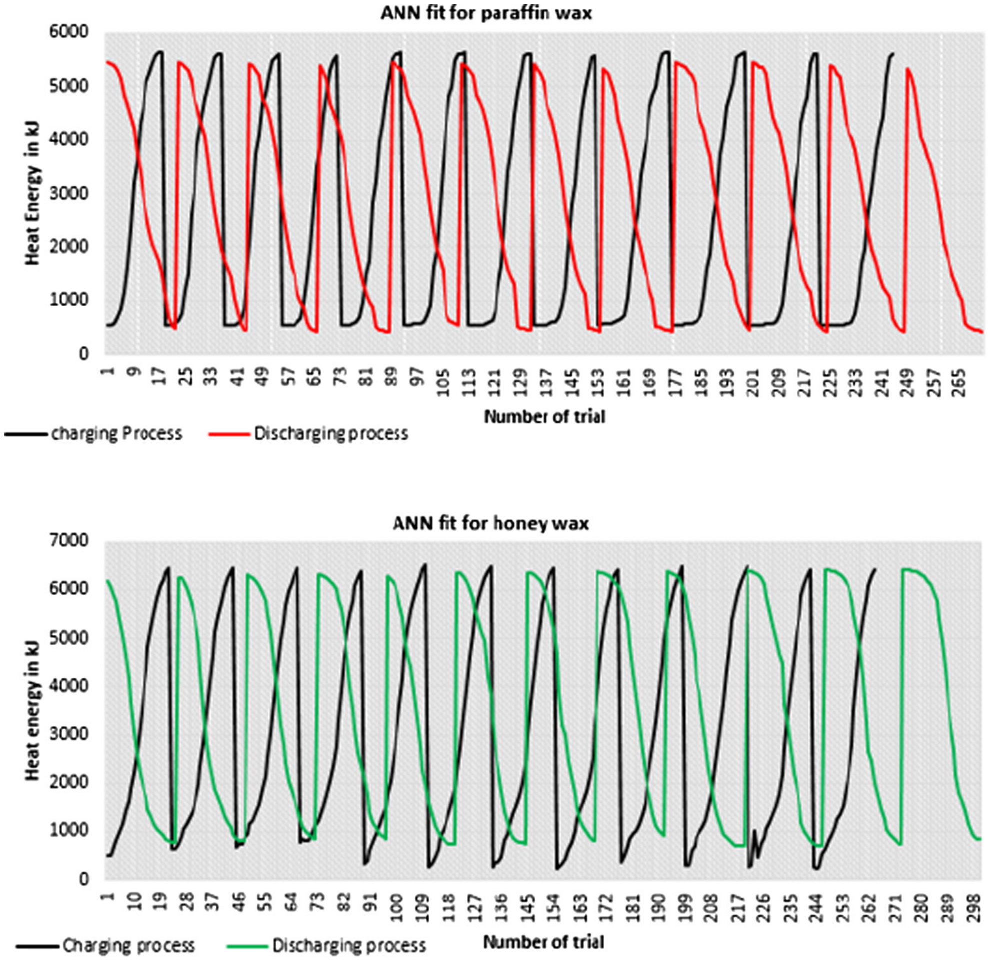

Fig. 5. ANN fit for charging and discharging processes of paraffin and honey waxes.

3.1. ANN modelling

An artificial neural network is based on the principle of the back propagation algorithm. The ANN model constructs a model based on examples of data with known outputs. A back propagation network typically comprises three types of neuron layers, an input layer, one or more hidden layers and an output layer. Each layer includes one or several neurons. The flow diagrams of the ANN model for the charging and discharging processes are shown in Fig. 4. The principle behind this normalization process is:

$$\text{Normalized value (N)} = \frac{(\text{Original value} - \text{minimum Value})}{(\text{Maximun value} - \text{Minimum value})} \quad \text{Where, } 0 \leqslant N \leqslant 1$$

ANN learns to solve specific problems without the need for specific algorithms. The learning strategy incorporates the minimization of mean square error across all training patterns. The user can set a desirable result and compare the network's performance with the target training set. The model output gives the results that the nodes from one layer are connected to all nodes in the following layer, but no lateral connections within any layer, nor feedback connections are possible. Six input neurons are used. The output layer comprises one neuron, indicating the presence or absence of a heat absorption value. The net input for each neuron is the sum of all input values x_n, each multiplied by its weight w_{jn}, and a bias term z_j, which may be considered as the weight from a supplementary input that is equalling one.

The module learns the underlying latent function through an error gradient-descent method and the training stops when the RMSE for output-target values fall below 0.0001%. More iteration in the training of data improves convergence. Each hidden node (that is H_1 to H_4) receives a set of feed in signals (or values) from which an output value is generated. Finally, all nodes in the hidden-layer are fully connected to the output node. The model value for (ANN) through the analysis are mentioned in Fig. 5. It can be observed from this Fig. 5 that we have conducted a total of 265 trials for both paraffin and honey waxes charging and discharging processes to quantify the heat energy in the thermal energy storage system. Both figures indicate a sinusoidal behaviour or variation. For charging process for both phase change materials, at the first trial the ANN fit for heat energy is 500 kJ and reaches a maximum peak of 5500 kJ for paraffin wax and 6500 kJ for honey wax and after that the sinusoidal behaviour continues. In the case of discharging process the ANN fit of heat energy for paraffin wax is 5600 kJ and 6200 kJ for honey wax and then, it exhibits sinusoidal characteristics.

3.2. Residuals of the models

There are many statistical tools for model validation, but the primary tool for most modeling applications is graphical residual analysis. Different types of plots of the residuals from a fitted model provide information on the adequacy of different aspects of the model. The deviation from the fitted line to the observed values gives the residuals for the charging and discharging processes

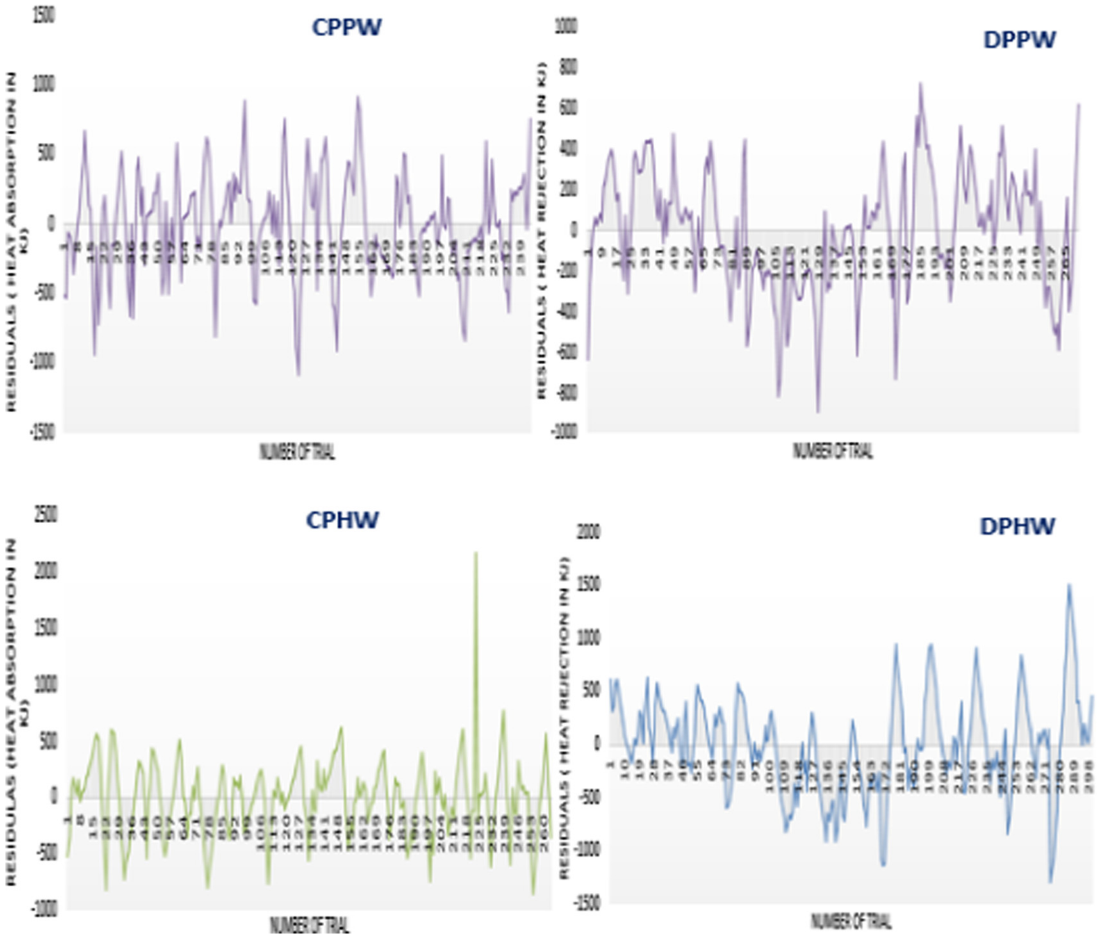

Fig. 6. Residual for the charging and discharging processes of paraffin and honey waxes.

of paraffin and honey waxes. Plotting the residuals on the y-axis against the explanatory variable on the x-axis reveals the possible non-linear relationships among the variables are presented in Fig. 6. It can be observed from the figure that the residual charging and discharging process for paraffin and honey waxes shows a behavior of Fourier continuous or series curve. The positive and negative variations in residuals of heat absorption in KJ are observed in all trials. It can be seen from the bottom left figure that the charging process for honey wax shows the least residuals.

3.3. Dendrogram

Dendrogram is generated through a mathematical process based on Ward Method. It is a graphical representation of the results of hierarchical cluster analysis. This is a tree-like plot, where, each step of hierarchical clustering is represented as a fusion of two or more branches into a single one. Each branch represents as a cluster and the set of clusters joined together is called the tree of hierarchical clustering. The purpose of a dendrogram is to display the relationships among distinct units by grouping them into smaller and smaller one. The present model represents the relationship among the selected variables. The first branch represents the phase change temperature and heat transfer fluid temperatures are based on the mass flow rate. The second branch represents the level differences acting on the first three factors (first branch variables). So, first and second branches are clustered, and then these two branches are acting on the third branch. In which the final output of heat absorption based on all other factors, including time and heat transfer rate as shown in the Fig. 7.

Using a design expert software package the percentage of factor or parameters contribution is acquired. The design expert is an efficient tool for statistical analysis, Taguchi and multi-response optimization processes. In this paper, this technique was used to identify the dominating factors on the performance of the fabricated thermal energy storage system. Fig. 8 presents the factors% contribution for charging and discharging processes. It can be observed from both figures that, the factor time has the significant effect on the model and the other factor has some considerable effect.

4. Model validation

The numerical values for the model validation tend to be narrowly focused on a particular aspect of the relationship between the model and the data and often try to compress that information into a single descriptive number or test result. The performance of the model is examined using standard measures, such as chi-square test, mean absolute percentage error and root mean squared percentage error. The Chi square test is a useful measure of comparing the observed results with expected theoretical values based on the hypothesis. It is used to determine whether there is a significant difference between the expected frequencies and the observed frequencies in one or more categories. The following standard formula used to calculate the measure of the Chi-Square value is given in Eq. (1).

$$\chi^2 = \sum_{i=1}^{n}\left(\frac{(O_i - E_i)^2}{E_i}\right) \tag{1}$$

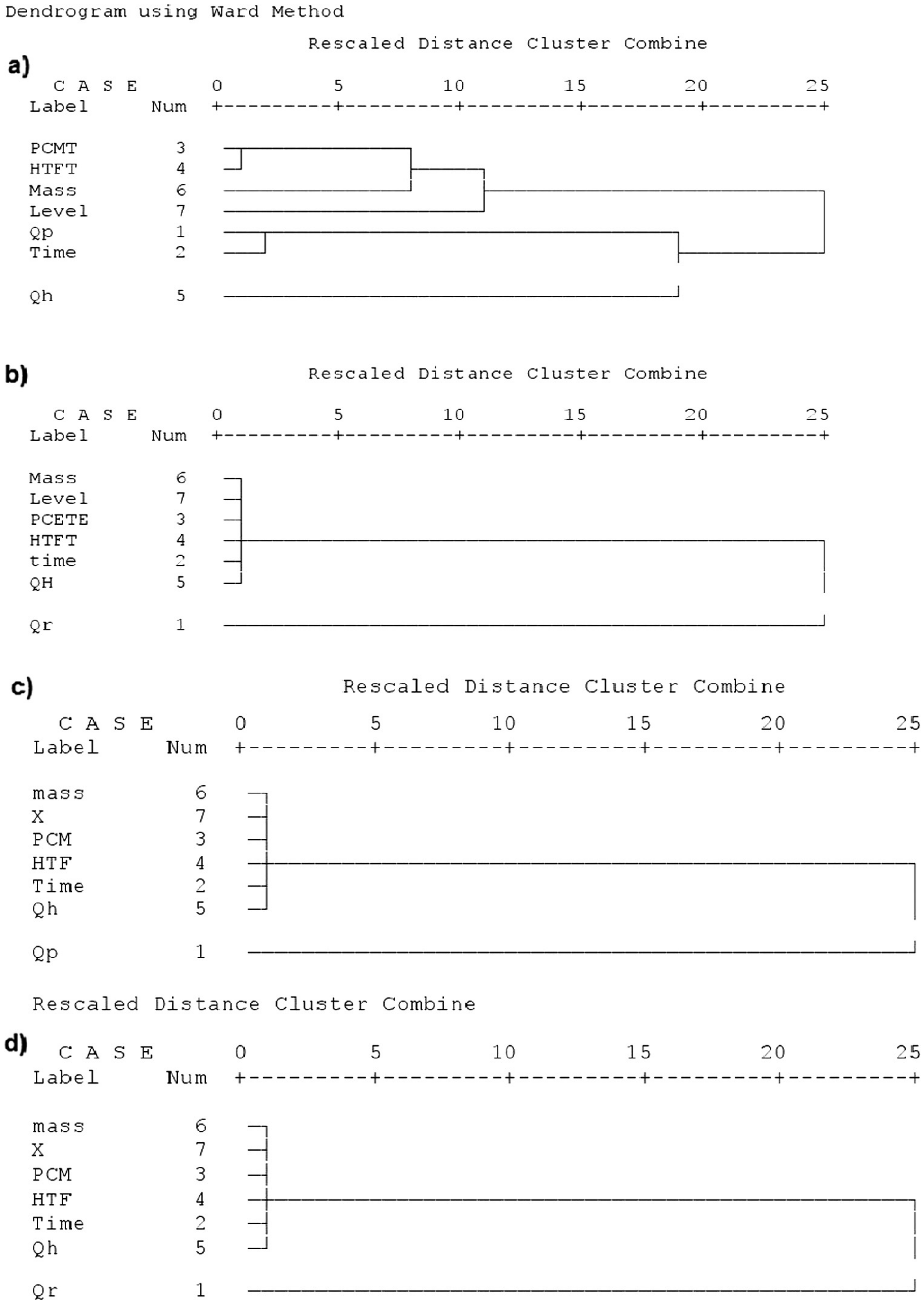

Fig. 7. Dendrogram models: (a) CPPW, (b) DPPW, (c) CPHW and (d) DPHW.

Null hypothesis are assumed in the test that there is no significant difference between the observed and expected values in the model. The χ^2 values are obtained for all the processes. The table value of χ^2 is 13 with 5% level of significance. It can be seen that the χ^2 values are lower than the table value, so the null hypothesis is accepted and proved that the models developed are significant. MAPE is commonly used in quantitative forecasting methods, because it produces a measure of relative overall fit. The absolute values of all the percentage errors are summed up and the average is computed. The MAPE is computed through a term-by-term comparison of the relative error in the prediction with respect to the actual value of the variable. Thus, the MAPE is an unbiased statistic for measuring the predictive capability of a model. The standard formula for mean absolute percent error is given in the (2)

$$MAPE = 1/n\sum_{i=1}^{n}|(Ei - Oi)/Ei| \tag{2}$$

Usually, a MAPE of 10% is considered very well, a MAPE in the range of 20–30% or even higher is quite common. In this investigation it is observed that the MAPE values obtained from SPSS tool is less than 15% and the same from ANN model is lesser than 5%. This

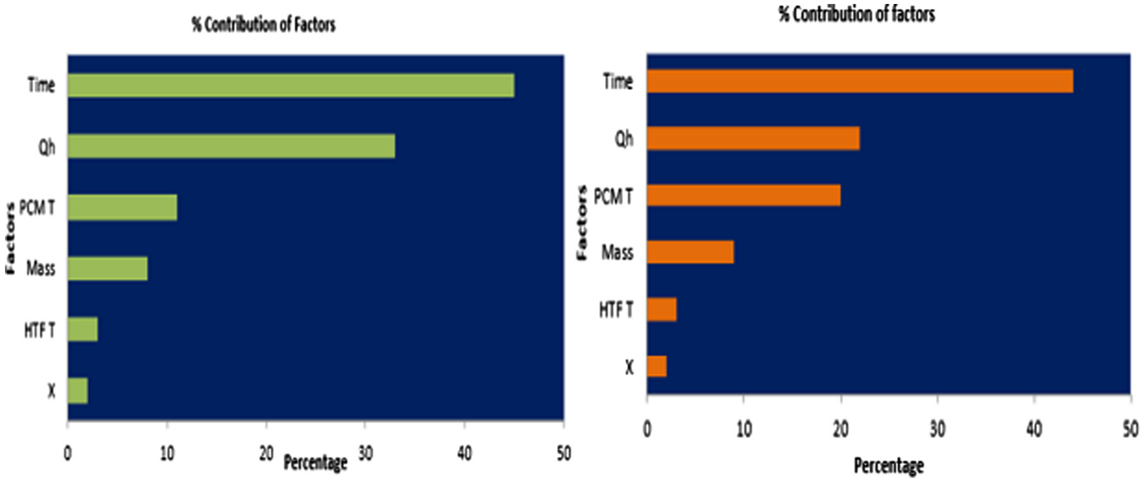

Fig. 8. Ranking factors by statistical method for charging process (left) and discharging process (right).

Table 2
Model evaluation outcome.

Analysis	Chi-square test ANN	MAPE ANN	RSME ANN
Charging process of paraffin wax	1.5	2.5	0.75
Discharging process of paraffin wax	2.25	8.5	0.65
Charging process of Honey wax	4.8	11.4	1.1
Discharging process of Honey wax	2.3	2.6	1.9

observation reveals that both the models are found good for the prediction of heat absorption and heat rejection. RMSE model is used to measure the difference between the values predicted by a model and actually observed values. It is one of the commonly used error index statistics and is defined in Eq. (3)

$$RMSE = \left(1/n\sum_{i=1}^{n}\left(\frac{Ei - Oi}{Ei}\right)^{2}\right)^{1/2} \quad (3)$$

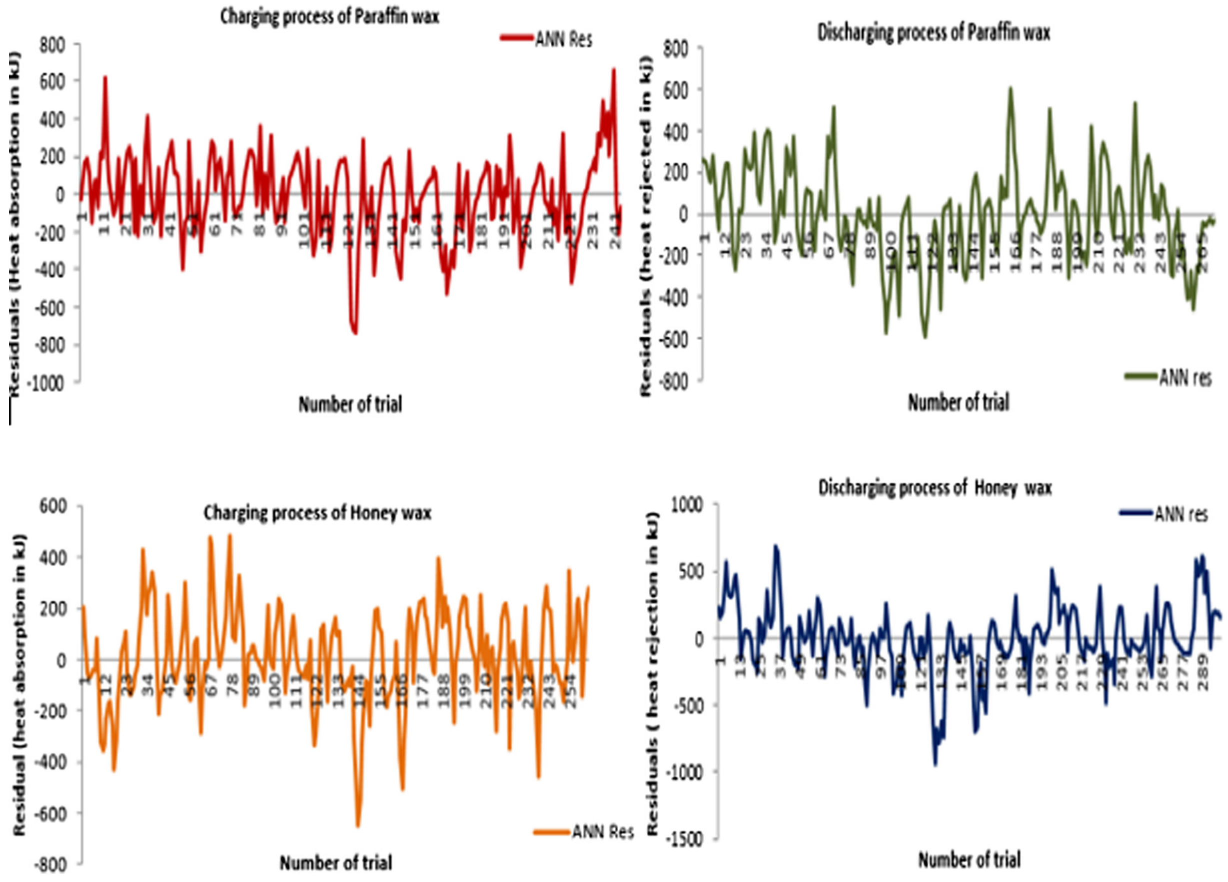

Fig. 9. ANN residuals for the charging and discharging processes of paraffin and honey waxes.

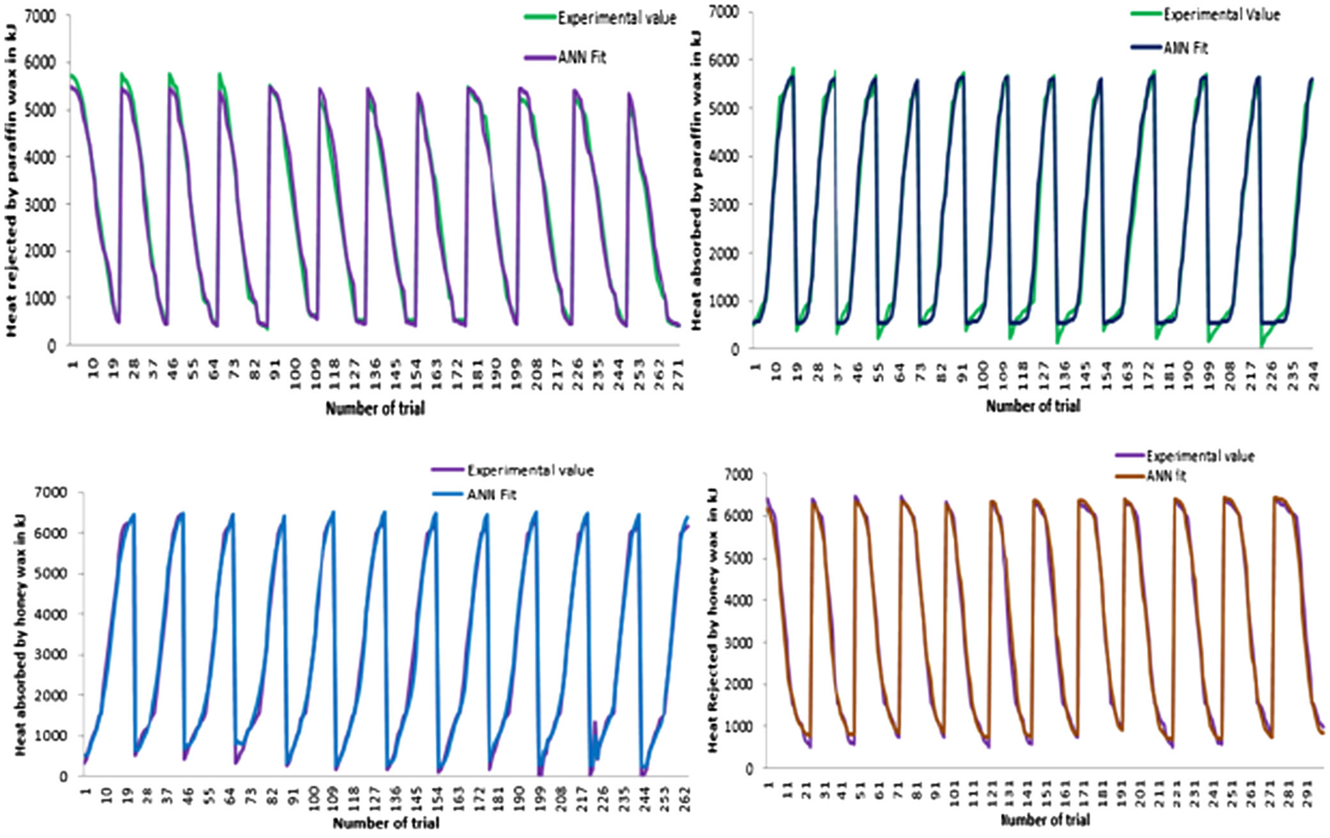

Fig. 10. Comparison of modelling results for the charging and discharging processes of paraffin and honey waxes.

RMSE is also known as the fit standard error and the standard error of the regression, where MSE is the mean square error or the residual mean square. An RMSE value closer to 0 indicates a better fit. Both regression and ANN models show errors less than 15%, which demonstrates the significance of the modelling methods. Table 2 shows the outcome of model evaluation.

Therefore, the flow diagram of the ANN model for the charging and discharging processes of paraffin and honey waxes is good.

5. Discussions

The residuals from a fitted model are the differences between the responses observed at each combination values of the explanatory variables and the corresponding prediction of the response computed using the regression and neural network function. Mathematically, the definition of the residual for the *i*th observation in the data set is written in Eq. (4).

$$e_i = y_i - f(x) \quad (4)$$

where y_i denoting the *i*th response in the data set and x_i is the explanatory variables, each set at the corresponding values found in the *i*th observation in the data set. If the model fit to the data were correct, the residuals would approximate the random errors that make the relationship between the explanatory variables and the response variable a statistical relationship. Therefore, if the residuals appear to behave randomly, it suggests that the model fits the data well. On the other hand, if non-random structure is evident in the residuals, it is a clear sign that the model fits the data poorly. The comparison graph shows that ANN fit values are appreciably close to the experimental values. The deviation from the fitted line to the observed values gives the residuals for the charging and discharging processes of paraffin and honey wax. Plotting the residuals on the y-axis against the explanatory variable on the x-axis reveals the possible non-linear relationship among the variables, the ANN models are evolved by calculating residual from model value and observed values are shown in Fig. 9.

ANN is widely used for prediction and forecasting, where it is use has substantial overlap with the field of experimental analysis. ANN analysis is also used to understand, which, among the independent variables are relate to the dependent variable, and to explore the forms of these relationships. The performance of this method in practice depends on the form of the data generating process, and how it relates to the networking approach being used. Neural networks do play an important role as confirmatory methods for graphical techniques. The comparison graphs (Fig. 10) show the experimental and ANN fit. Neural values are appreciably close to the experimental values during charging and discharging processes of paraffin and honey waxes.

Through experimentation, the heat absorption and heat rejection have been calculated (but not demonstrated in great detail in this paper) for paraffin and honey waxes during charging and discharging processes at all levels with different flow rates. The charging process of paraffin wax absorbed 5840 kJ of heat at the flow rate of 6 kg/min, and then the paraffin wax absorbed 5760 kJ and 5720 kJ of heat at the flow rate of 4 kg/min and 2 kg/min respectively. Then the charging process of honey wax 6408 kJ of heat can be absorbed at the flow rate of 6 kg/min, then 6344 kJ and 6280 kJ of heat has been observed in the flow rate of 4 kg/min and 2 kg/min respectively. The honey wax is the energy storage materials that have considerably higher thermal energy storage densities compared to paraffin materials and are able to absorb or release large quantities of energy at a constant temperature by undergoing a change of phase. The energy storage can be increased by changing the honey wax in place of paraffin wax which gives 6408 kJ of heat at 70 °C. Hence, honey wax is found to best suitable thermal energy storage system for the domestic applications. From the modelling results the ANN fit values are appreciably close to the experimental values during charging and discharging process of paraffin and honey wax. Hence, it can be implied that there is a good agreement with ANN modelling and experimental results.

6. Conclusions

Combination of SHS and LHS approach using honey and paraffin waxes could be a potential method of storing heat energy in a fabricated TES system. It has the benefit of higher energy storage density and also for the non-iso and iso-thermal processes of storage. The model was designed and fabricated, and several experiments were successfully executed. After gathering the experimental results, the design of experiment modelling was performed on this non-isothermal energy storage system. We have performed the model with 95% confidence level and 5% error significance, and found that the results are very close with experimental results. From the ANN modelling results, all models are found to be well fitted to the experimental data and better accuracy were achieved when using this method. Chi-Square, MAPE, tests are preformed to evaluate the models. The models are validated with both physical and DOE experimental data. The χ^2 values are much lower than the table value, so the null hypothesis is accepted and proved that the models developed are significant. It is noted from the MAPE in the range of 10–20% and ANN model is lesser than 5% reveals that both the models are found to be beneficial. It was observed that, the residuals were closed to the fitted line and showed least deviation. Therefore, in this modelling the factor time has the dominating impact on the entire thermal energy storage system, as this was confirmed by the percentage of parameter contribution through the design expert statistical software tool.

Acknowledgement

We would like to thank the Sathyabama University management for providing necessary financial and technological support. Also, we thank the welding and statistical modelling team for their help on fabrication, experimentation, and modelling. Importantly, authors thank the anonymous reviewers for their constructive comments, which consequently improved this paper quality.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.applthermaleng.2017.05.122.

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