Numerical and Experimental Study on Heat Transfer Enhancement of Paraffin in Heat Storage Unit

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Abstract

In this research, the phase change process and properties of paraffin (CnH2n+2) were studied by means of experimental and numerical analysis. Creating a mathematic model by Matlab for analyzing the heat transfer process and parameter of paraffin in melting process. Comparison of result was made between the experiment, mathematic model and computational fluid dynamics (CFD) simulations software. By figuring out the factor affecting the performance of the phase change process, the enhancement of paraffin-composites were tested by mixing the paraffin with metal foams. Phase change material as a thermal storage allows the heat energy to be stored and released in different purposes. For latent heat storage, phase change material is the option containing a high heat of fusion which is an ideal medium for heat storage and paraffin wax was selected in this research study. The enhanced thermal conductivity of paraffin composites had successfully speeded up the melting process.

Keywords

Paraffin wax, Phase change material, Enhancement larboratory, Matlab, Ansys fluent

1. Introduction

Nowadays, the energy storage is one of the trends in worldwide. From the reports made by the companies of energy storage in the world, the expected annual growth rate of adopting the paraffin as phase change material is around 16% from 2017-2024 [1]. By adopting the efficient thermal storage, energy costs less at night and reduce the peak usage charge at the daytime. Also, building structure made of phase change material can greatly reduce the heat gain to save up the energy cost of building by adsorbing the heat. Energy efficiency of using phase change material in thermal storage can be up to 75% to 95%[2]. Phase change material is an effective energy storage material. Compare to water, the amount of heat can be absorbed/released is 5 to 14 times more with using paraffin. Thermal storage can store up the energy through the phase change and avoid the problem of energy mismatching. During the phase transition, heat will be released/absorbed in case of melting/solidification. The performance depends on the properties of phase change material. Although paraffin has a high heat of fusion and density, it has a low thermal conductivity around 0.2 W/mK which is not ideal for heat exchange process.

2. Literature Review

Researchers have done a lot of studies on the comparison of those kinds of material. They have compared the thermal properties of the material and matched them into different application such as paraffin in low temperature application. They have reported numerical model is required for further research in order to obtain reliable result.

Numerical models are needed for verifying the performance of phase change material as the commercial software was a simplified calculation and the result may not reliable as the numerical method. Nagaraja Shamsundar [3] verified the enthalpy equation with the use of finite difference method in test of solidifying the flat plate. The method was proven which is suitable for further calculation. Fomin and Saitoh [4] described that the accuracy of the data output using the simple commercial model will be lowered by 10%-15% compare to the complicated and comprehensive solution. D. MacPhee and I. Dincer [5] pointed out the difference of energy efficiency result between the ANSYS FLUENT and numerical model. The result of ANSYS FLUENT was over 99%. But according to the numerical result, the range of result should be within 72% to 92% which included the factor such as heat loss that exist in reality application. Yvan Dutil, Daniel R. Rousse, Nizar Ben Salah and Stéphane Lassue [6] mentioned that they have cited over 250 references in his research paper and most of them were proven that the numerical model development was essential for the further research instead of relying on coding.

Samer Kahwajia [7] examined the accuracy of the properties of paraffin. The melting/freezing temperature, heat of fusion, thermal conductivities, density and specific heat capacity of solid/liquid phase of paraffin were found as the main factors of performance of phase change material. Heat of fusion determine the amount heat can be absorbed and released during the phase transition. Vikas and Ankit Yadav [8] tested the heat transfer process were mainly done by conduction in first 30 minutes. The rate of melting remained unchanged between 30 minutes and 240 minutes. J.M.POWERS [9] have investigated that different composition of paraffin with different thermal properties will directly affect the amount of heat as the heat of fusion was a variable for several paraffin. U. R. FISCHER [10] found that the thermal conductivity of paraffin composite (0.286W/mK) increased about 76% with using the mixture of paraffin (0.162W/mK) and zeolite (0.07W/mK). Ali Lateef Tarish [11] studied that the amount of thermal energy change vary in 10-15% as the heat transfer coefficient vary in melting and solidification process. On the other hand, Jaume Gasia [12] tried to use paraffin as a phase change material in heat storage. The transition temperature of paraffin is low (around 50-60ºC) and no subcooling/overheating occured in laboratory test. The heat exchange time were reasonable to store and release large amount of energy. Francesco Goiaa [13] verified the performance of the paraffin by differential scanning calorimetry DSC analyses. There was a 5% reduction of latent heat after the aging effect. The melting temperature of paraffin has decreased by about 1.5°C.

3. Research Gap

In recent years, most of the researches are focusing on comparing the performance of different kinds of phase change material such as paraffin, salt hydrates and metallics. Few studies were made between the comparison on different properties of the same phase change material and enhancement of heat storage. Also, the commercial software simulation may not suitable for scientific studies and research. Validated and verified mathematic model is more reliable with higher flexibility and accuracy. Enhancement will be made by testing different composites.

4. Objectives

The objective of this study is to examine the effectiveness and properties of phase change material in **one** dimension by means of experiment and numerical calculation. Comparison will be made between the result of experiment, simulation and mathematic model. Validating the mathematic model by Matlab and verifying the accuracy of the commercial software and mathematic model. By checking the factors of the performance of phase change material and process to investigate the **enhancement** of paraffin wax by mixing it with metal foams.

5. Methodology

Comparison and Enhancement of phase change process		
Mathematic Model (Matlab)	Laboratory result	CFD Simulation

For analyzing the heat transfer and parameter of paraffin in phase change process. There were four steps in order to make a meaningful comparison between the result of different approach. Recording the laboratory result by the data logger. Then computing the mathematic model by **Matlab** for analyzing the phase change material in one dimension and simulating the result in **Ansys Fluent** software. Comparison of accuracy were made from those results. Testing the enhancement and performance of different paraffin composite with several metal foams.

5.1 Software simulation (ANSYS FLUENT)

ANSYS FLUENT software was used for the transient simulation of the melting process of paraffin wax in **one** dimension. The mesh size setting is 50x50, 2500 nodes were formed on the mesh. With total 2700 iterations, time step size 120 seconds, 90 numbers of time step and 30 iteration per timestep. The input data and setup followed the configuration of laboratory test 1 in order to obtain a more accurate result and comparison.

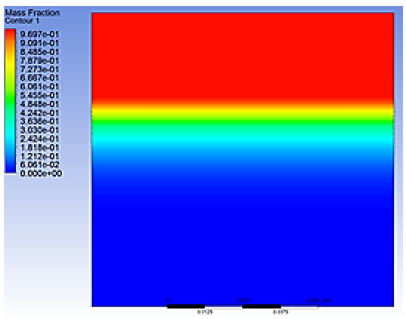

Fig. 1 Ansys Fluent contour result

5.2 Mathematic model (Matlab)

In this research, the mathematic model was created by combining the energy, heat and enthalpy equation to form a framework of calculation. The energy balanced equation will be transformed into the heat equation. Due to the moving boundary condition, the enthalpy method was applied for simplifying the calculation. Finite difference method was then employed for analyzing the paraffin at multiple nodes in **one** dimension.

Assumptions of mathematic model:

1.The fluid is incompressible.

2. Thermal conductivity remains constant.

3. The specific heat capacity is constant.

4. There is no any internal heat generation.

5. The model is studied in one dimension.

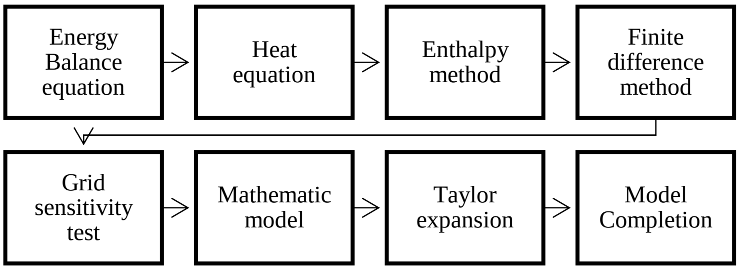

Fig. 2 Flow chart of model

The numerical model was created step by step. For an infinitesimal material element **v** and Energy balance equation :

$$\frac{d}{dt}\int_{v} p(h+\frac{1}{2}\mathbf{v}\cdot\mathbf{v})\,dv = \int_{\partial v}[\mathbf{v}\cdot(\boldsymbol{T}\cdot n)-\boldsymbol{q}\cdot\boldsymbol{n}]\,da + \int_{v}[\mathbf{v}\cdot(\rho\boldsymbol{b})+s]\,dv \tag{1}$$

By considering the external and internal energy of the paraffin wax and use of identity :

$$\mathbf{v}\cdot(\boldsymbol{T}\cdot\boldsymbol{n}) = [(\boldsymbol{T})^{\boldsymbol{T}}\cdot\boldsymbol{V}]\cdot\boldsymbol{n} \tag{2}$$

The Eq. (1) becomes

$$\int_{v}(h+\frac{1}{2}\mathbf{v}\cdot\mathbf{v})(\frac{\partial\rho}{\partial t}+\rho\nabla\cdot\mathbf{v}+\mathbf{v}\cdot\nabla\rho)+\mathbf{v}\cdot(p\frac{\partial v}{\partial t}+\rho\nabla\mathbf{v}\cdot\mathbf{v}-\nabla\cdot\boldsymbol{T}-\rho b)+\rho(\frac{\partial h}{\partial t}+\mathbf{v}\frac{\partial h}{\partial t}\nabla h)-\boldsymbol{T}:\nabla\mathbf{v}+\nabla\frac{\partial h}{\partial t}\boldsymbol{q}-s]\,dv=0 \tag{3}$$

According to the conservation of mass and momentum

$$p\left(\frac{\partial h}{\partial t}+\mathbf{v}\cdot\nabla h\right)-\boldsymbol{T}:\nabla\mathbf{v}+\nabla\cdot q-s=0 \tag{4}$$

For incompressible fluid (Paraffin wax in study), the divergence of velocity is 0, therefore

$$p\left(\frac{\partial h}{\partial t}+\mathbf{v}\cdot\nabla h\right)=\boldsymbol{\nabla}\cdot(k\nabla T)+\mu(\nabla\mathbf{v}+\nabla\mathbf{v}^{T}):\ \nabla\mathbf{v}+\mathrm{s} \tag{5}$$

The paraffin at rest with constant thermal conductivity and without internal heat source, the Eq.(6) is reduced to

$$p\frac{\partial h}{\partial t}=k\nabla^{2}T \tag{6}$$

Phase change of paraffin involves the moving boundary condition (Stefan problem), therefore enthalpy method is employed for making the problem of two regions more easier to solve. For the Enthalpy method :

$$h = C_P T + \Delta H \tag{13}$$

$$T < Tm\,, h = C_P s(T-Tm) \tag{7}$$

$$T = Tm\,, h = f_{PL}L \tag{8}$$

$$T > Tm\,, h = C_P l(T-Tm)+h_{sl} \tag{9}$$

Using the Finite difference method, the one dimensional problem can be studied at different nodes :

$$h_i^{n+1}=\frac{\Delta t\cdot\frac{T_{i+1}-2T_1+T_{i-1}}{\partial x^2}}{q}+h_i^n+O(\Delta t,\Delta x\text{^}2) \quad (11)$$

$$T_j^{n+1}=\begin{cases} T_m+\ h_j^{n+1}/\,c_{ps} & h_j^{n+1}\le 0 \quad (12)\\ T_m & 0<h_j^{n+1}<h_{sl} \quad (13)\\ T_m+(\ h_j^{n+1}-\ h_{sl})/c_{pl} & h_j^{n+1}\ge h_{sl} \quad (14)\end{cases}$$

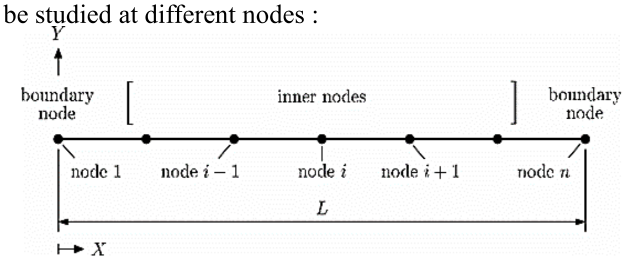

Fig. 3 Nodes in finite difference method

The above mathematic method was applied by using **Matlab** software to obtain the result at different literation. The grid sensitivity test and Taylor expansion were performed to verify the accuracy and feasibility of the model.

5.3 Laboratory studies

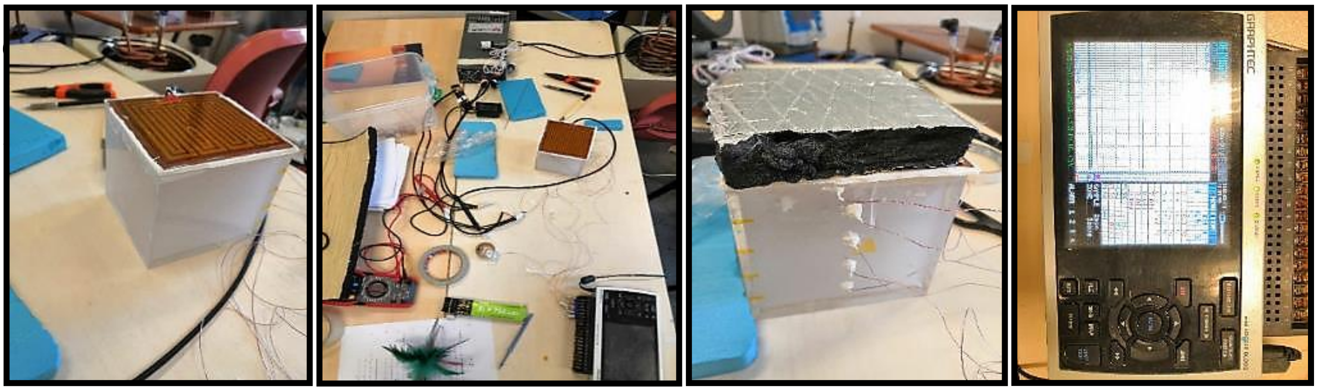

Fig. 4,5,6,7 Laboratory 1 setup

For **laboratory test 1**, the phase change process of paraffin was analyzed. The solid paraffin was tested in a 10cm x 10cm x10cm container which made of glass. The thermal properties were tested by experiment. 12V heating coil was employed for giving steady heat flux into the paraffin. The container was well sealed to prevent the leakage of paraffin and heat. The figure below shows the Robin boundary conditions of paraffin. The 12V heating coil transfered the heat into the phase change material with steady temperature 100ºC in 3 hours duration.

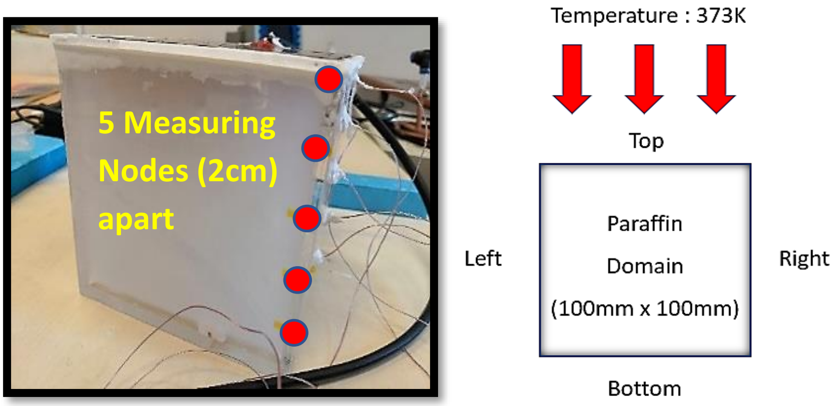

Fig. 8&9 Laboratory 1 principle

Properties	Paraffin Wax
Melting point (˚C)	42
Latent heat (j/kg)	102100
Thermal Conductivity (W/mK)	k_f= 0.1 k_s= 0.3
Density (kg/cm^3)	785.02
Specific heat (J/gK)	2850

Table 1 Paraffin properties

Five nodes of paraffin inside the container were monitored for several parameters by the data logger and energy meter. The temperature changes at different time were recorded. Constant heat fluxes are supplied from the top of container. Thermal insulation with 5cm sealed container for reducing the heat loss to obtain more accurate result.

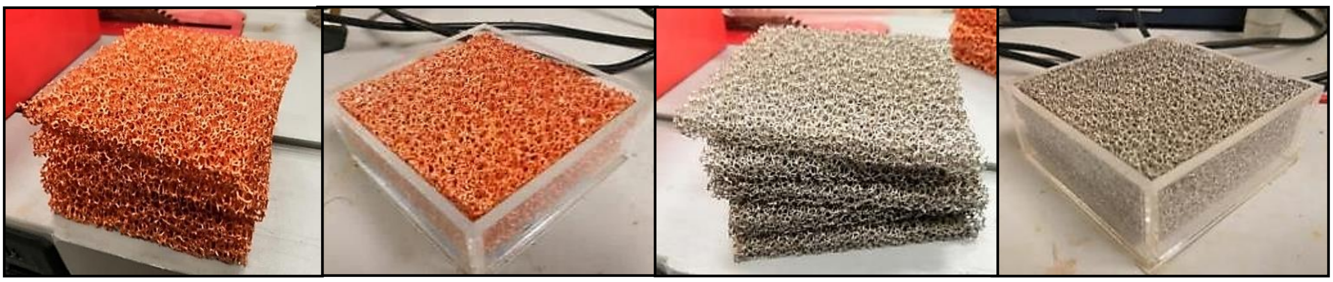

Fig. 10,11,12,13 Laboratory 2 setup

For **laboratory test 2**, the enhancement test was carried out with mixing the paraffin in laboratory 1 with different metal foams. Copper foam and nickel foam are the metal foam which have a very high thermal conductivity compared to the paraffin. These metal foams in skeleton structure can fill up 95% volume of paraffin with their porosity. The changes of thermal properties of paraffin composites were examined after the enhancement test.

6. Result and discussion

6.1 Laboratory 1– Comparison of software simulation, mathematic model and experimental result

6.1.1 Mathematic model result (Matlab)

In the first 90 minutes, the temperature results at node 1 (reference node) were higher than the laboratory result. Due to consideration of natural convection in model, the final temperature at 10800 seconds was 60.6°C which is lower than the laboratory result having 63.9°C. The accuracy of model was 91.7% and average temperature were +5.3% higher compare to laboratory in 3 hours.

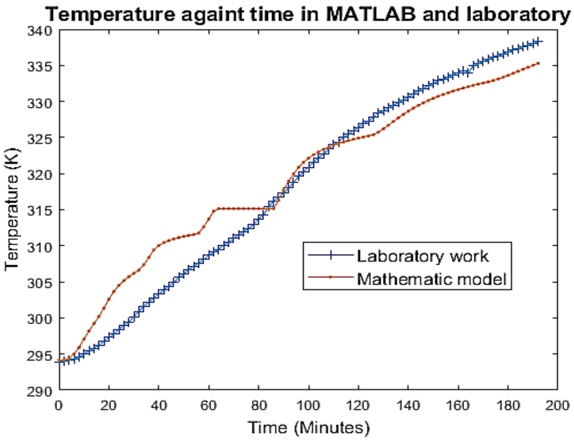

Fig. 14 Matlab result

6.1.2 Experimental result

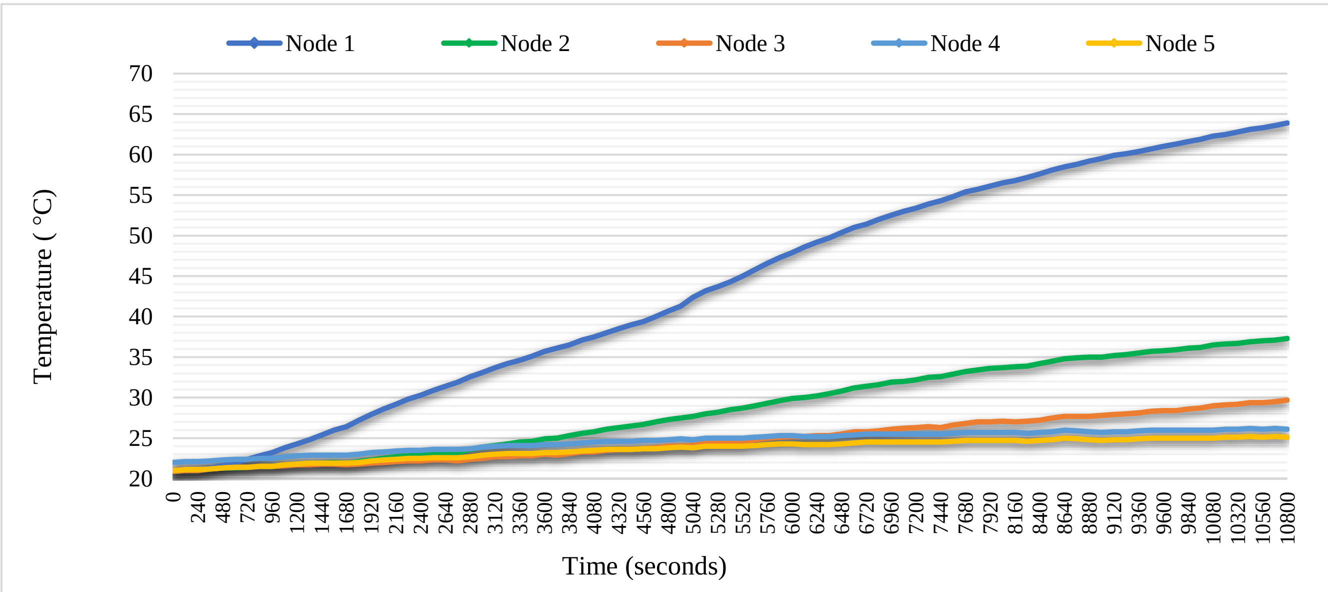

Fig. 15 Temperature against time at different nodes

From the chart above, the temperature variation at different nodes and phase change process were observed. Node 1 was the point having the largest temperature change than other nodes. The temperature has increased by 43°C from 20.9°C to 63.9°C in 3 hours duration. The temperature of node 1 was almost 300% of that in node 5 at 10800 seconds which proved the low thermal conductivity and slow heat transfer rate properties of paraffin. The melting fraction was around 32% after heating up in 3 hours duration. Enhancement test was carried out in laboratory 2.

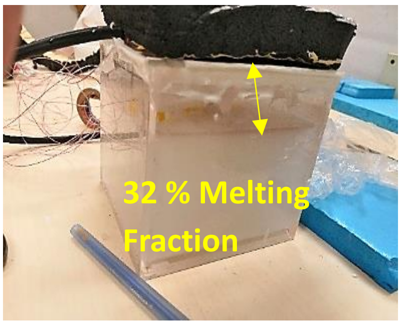

Fig. 16 Melting fraction of paraffin

6.1.3 Software simulation result (ANSYS Fluent)

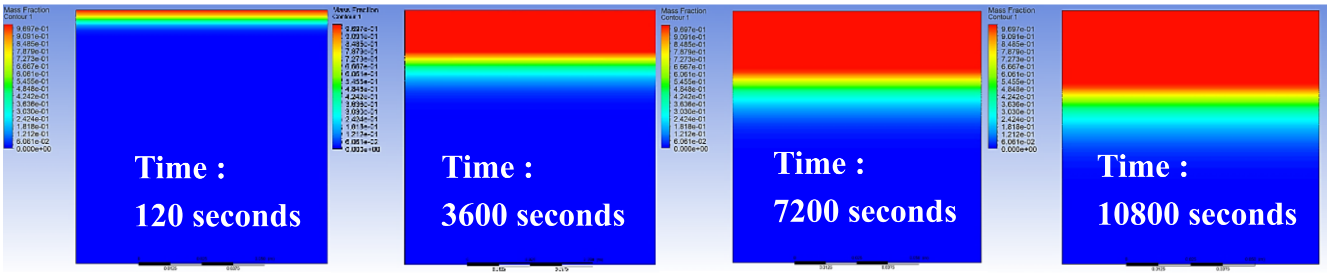

Fig. 17,18,19,20 Contour of temperature and melting fraction in Ansys fluent result

The Contour of temperature changes and melting fraction at 2500 nodes in 3 hours were shown above. The visualization of phase change process shows the melting fraction of the paraffin which was around 28% near to the laboratory result. This figure showed the residual value of the transient simulation calculation with 2700 literation are near to 1e-03 and 1e-06. With lower residual value, the continuity and energy equation were proven to be converging result of fluid. The oscillating curve with 30 iteration per time step was very steady and error were minimized to a very low level. The simulation result was compared with experimental and mathematic model result in 7.1.4 section.

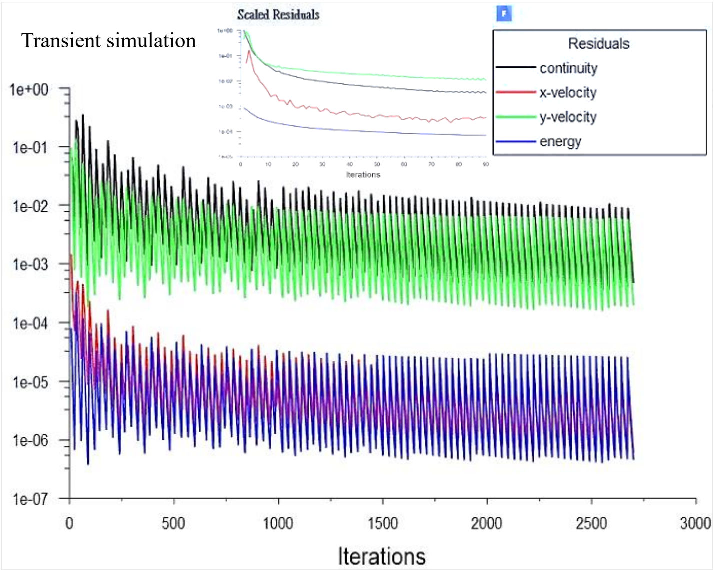

Fig. 21 Residual value of simulation result

6.1.4 Comparison of accuracy of result

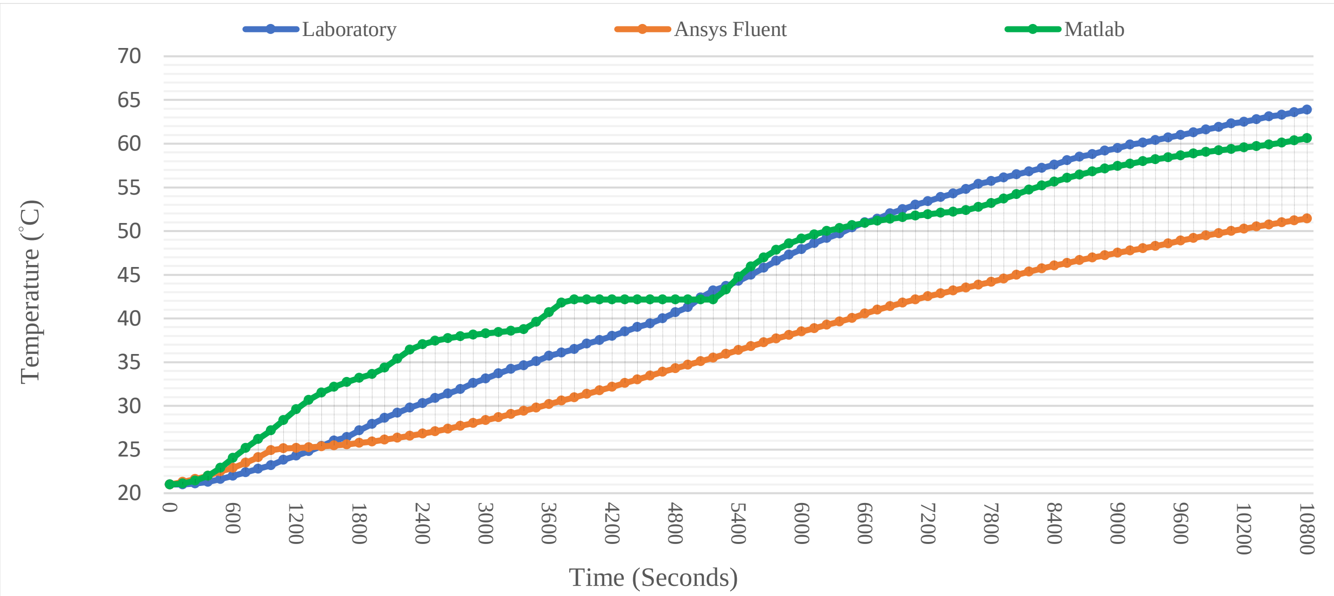

Fig. 22 Comparison of temperature in Matlab, Ansys fluent and laboratory

By combing all the curves of node 1, the mathematic model result was more close to the laboratory data. The accuracy of mathematic model was 91.7% with average temperature +5.3% higher than laboratory data. For the software simulation, the temperature and rate of heat transfer are much lower than the actual case in 3 hours period. The accuracy of ANSYS fluent was 84.6% with average temperature -14.4% lower than laboratory data. The mathematic results after 5400 seconds were slightly lower than the laboratory result due to the consideration of natural convection so it is still very accurate.

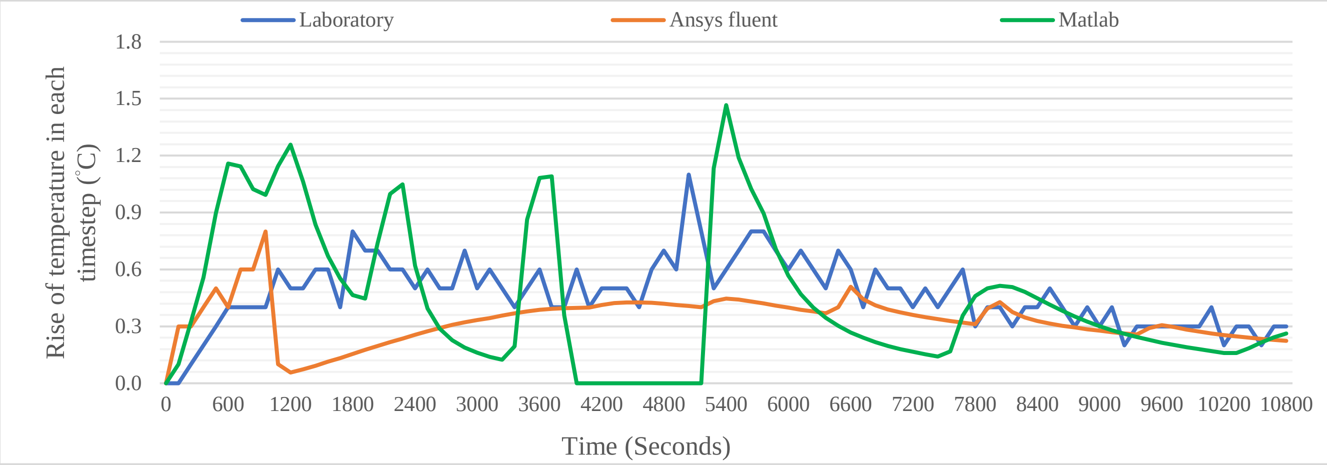

Fig. 23 Comparison of rise of temperature in Matlab, Ansys fluent and laboratory

ANSYS fluent as a commercial software has a more stable trend but the accuracy was 7.2% lower than the mathematic. The unknown formula in software may consider the heat loss and included the safety factors which make the simulation result lower than the expected value. The mathematic model can be further improved and offer greater flexibility for the research experiment as the heat loss problem can be considered in the known set up. Therefore, mathematic model will be a more suitable choice for the future research studies which may require a result with very high accuracy. On the other hand, the software offered a more quick and simple approach saving resources to generate result by inputting the data for commercial purpose.

6.2 Laboratory 2– Enhancement test of paraffin composites (Copper, nickel metal foam)

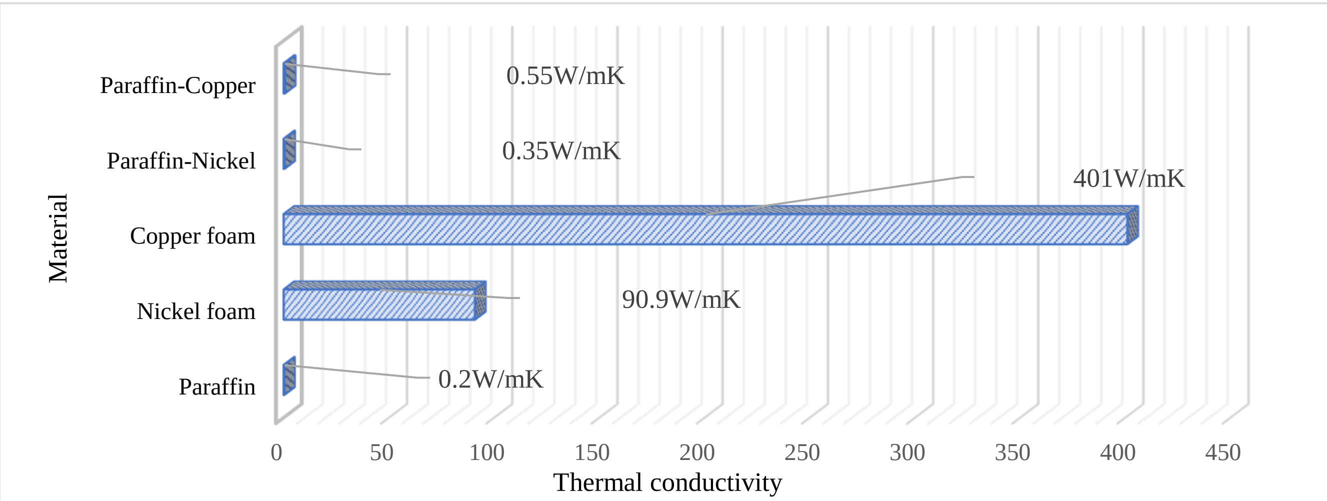

Fig. 24 Thermal conductivity enhancement

The porosity of copper foam and nickel foam was 95%. The overall thermal conductivity of paraffin composites have increased to 0.55W/mK and 0.35W/mK from 0.2W/mK with 95% volume of paraffin. With the enhancement, the paraffin (node 1) required shorter and almost 1/2 time for reaching 35°C. The results above proved the heat conduction rate was increased and less time is required for phase change material absorbing the heat energy with higher thermal conductivity.

The detail performance comparison of different paraffin composite was shown below.

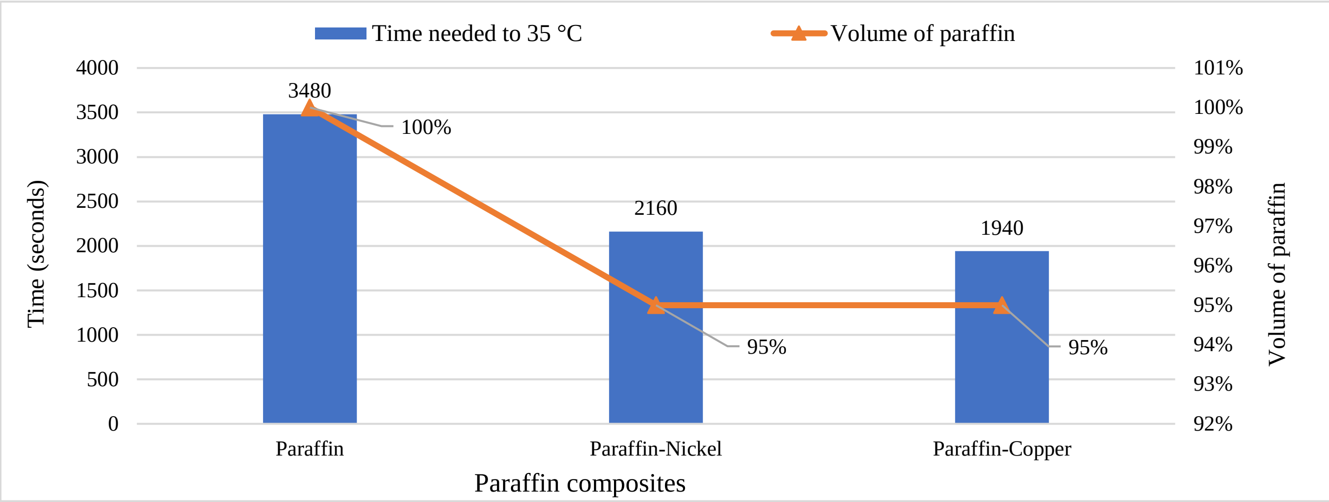

Fig. 25 Performance of paraffin composites

From the chart below, it was obvious that the rate of heat conduction has increased by mixing the paraffin with nickel and copper metal foam. The rate of heat transfer has increased by 21.8% with using copper foam and 17.3% with using nickel foam. After 1 hour, the final temperature at node 1 with using metal foam were around 43.5 °C and 41.9°C respectively. Comparing to original paraffin, the final temperature has increased by 7.8°C and 6.2°C respectively. The result proved that the paraffin-metal foam composite is an effective mean to improve the poor thermal conductivity of paraffin and phase change process without the change of volume. Copper foam with 401W/mK has the best performance in this paraffin composites enhancement test. It proved the higher thermal conductivity will lead to shorter time required for completing the melting process of the phase change material.

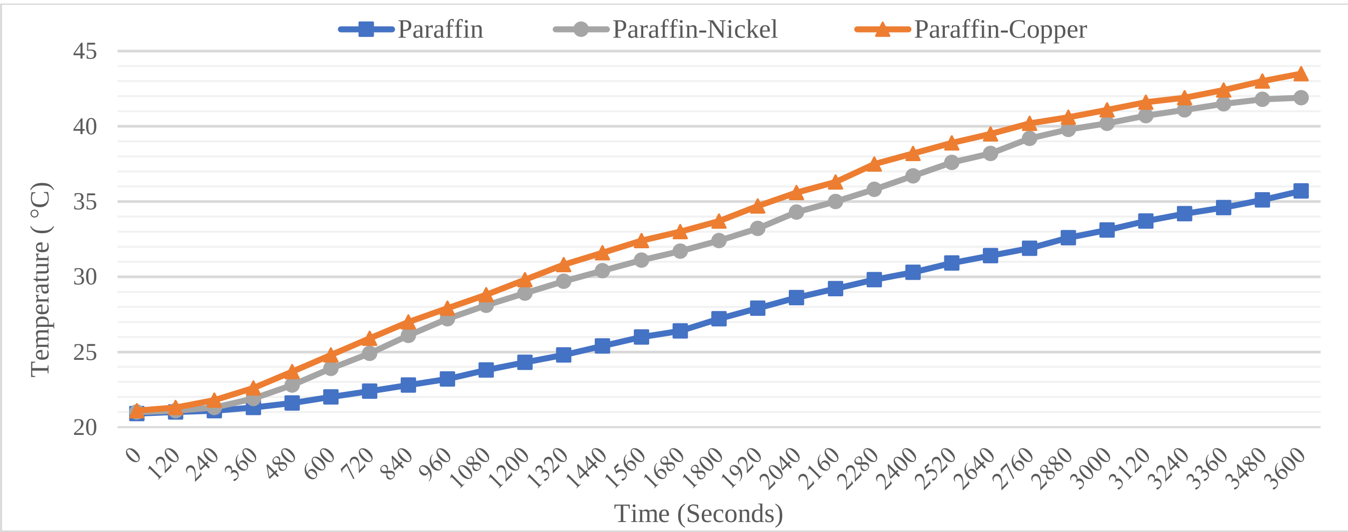

Fig. 26 Enhancement test comparison of different paraffin composites

7. Conclusion

In conclusion, the accuracy of software simulation and mathematic model are quite high as the result from both means are close to the laboratory work. Software simulation is better for the simulation of reality energy storage application and mathematic model is more suitable for further research studies because of resource effectiveness of software. The mixture of paraffin and metal foam has successfully enhanced the phase change process by improving the poor thermal conductivity of paraffin. The paraffin composites have speeded up the melting process with increased rate of heat conduction. The higher conductivity of paraffin composite lead to better performance.

8. Acknowledgement

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