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Modelling Phase Change Material for Concentrating Energy Storage in Solar Thermal Cooking Stove

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ABSTRACT

Nowadays, cheaper and cleaner alternative energy source is a compulsory globally due to complex challenges with the conventional ones. Even though solar energy has huge potential to serve as an alternative, it can only be harvested during the day. Solar energy obtained during the day should be stored for cooking purposes during night time. Phase change material (PCM) absorbs heat energy at nearly constant temperature until it changes its state completely. The energy required for the material to completely change its state is called latent heat. The latent heat can be stored for later use such as cooking in the evening. The main objective of the current work is to model the thermal energy storage for solar cooking stove using PCM ($NaNO_3$ and KNO_3) for the evaluation of heat loading. Based on the result, the tank with 90 mm fins gap has the highest temperature of PCM at about 603 K. Also the higher the heat transfer fluid velocity, the higher the temperature of the PCM and fins. The current study is focused on the heat loading of the PCM at a steady state condition. Further investigation is recommended on the transient heat loading under laminar and turbulent heat transfer flow.

Keywords: Phase change; modelling; energy storage; solar thermal; cooking stove.

1. Introduction

A cheaper, clean and renewable energy is required recently due to the environmental concerns globally [1]. Among the numerous types of renewable energy, solar energy is one of the cleanest and cheapest in long term [2]. In many part of the world, solar energy is considered as the most preferable source of renewable energy. However, solar energy can only be obtained during the day and must be stored for use at night. [3]. An energy storage stores energy for later use. As this type of energy storage is still in development, absorbing energy from the sun as a form of heat energy for storage and then to be used for other purposes is one of the challenges for the researchers. This is because the energy storage involves complex engineering analysis such as selection of convenient material and the considerations of different types of heat transfer mechanisms such as conduction convection and radiation in the heat transfer and storage process. In order to use thermal energy for large-scale application, these problems need to be solved to make the thermal energy system more effective.

Thermal energy storage (TES) system absorbs heat from a higher energy sources and dissipates the heat to a lower energy load. Thermal energy storage mechanism is categorized into three types, which are sensible heat, latent heat and thermo-chemical energy storage. In the sensible heat storage (SHS), thermal energy is stored due to the temperature difference in the storage material [4]. The heat can be noticed during the charging (sensible) and discharging of the SHS system [5]. It uses the change in temperature according to its heat capacity of the storage material. The amount of the thermal energy stored depends on the specific heat capacity, difference of temperatures and amount of the material [3]. The latent heat storage (LHS) system occurs when the storage material changes its state from solid to liquid or liquid to gas absorbing heat energy at nearly constant temperature until it completely changes its state [6]. On the other hand, if the material change from gas back to liquid or liquid back to solid, thermal energy will be released to lower temperature body at about the same temperature. The phenomenon is also known as phase changing process and the material used in the process as phase change material (PCM). The heat energy required for the material to completely change its state is known as latent heat. Compared to the SHS, The LHS stores more heat to volume ration [1]. PCM as energy storage system stores heat based on the forming and breaking of the bonds between the particles during chemical reaction. Heat of reaction [3] will be absorbed during endothermic reaction as opposed to the exothermic reaction and that is why it is used as heat storage system. The PCM can be divided into three types namely organic, inorganic and eutectic PCMs [1, 7, 8]. Fig. 1 shows the category of thermal energy storage; and Table 1 shows the summary of the characteristics of a typical PCM to be selected as thermal energy storage.

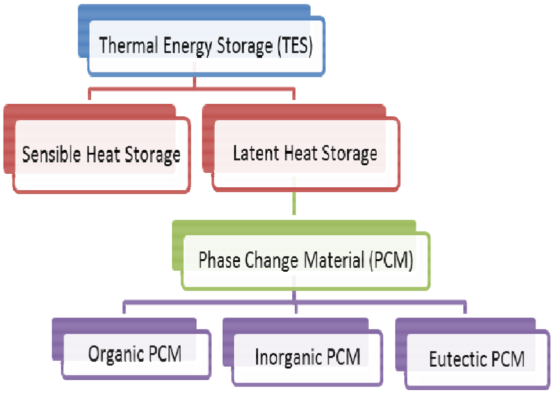


Fig.1 Categorization of thermal energy storage [1, 7, 8].

Table 1 Characteristics of typical PCM [9-11].

Properties	Advantages
Thermal properties	• Temperature range suitable for application • Desired specific heat • Thermal conductivity is high • Latent heat – mass ratio is high.
Physical properties	• Minimum density variation • High density • Minimum sub-cooling or under-cooling
Chemical properties	• Chemically stable • Inert to the container material • Non-poisonous, non-flammable, non-explosive • Not polluting
Economic properties	• Cheap • Available in large quantity

Paraffin waxes are the most common organic PCM in the market. They have medium range of storage capability [10, 12, 13]. Besides, paraffin waxes have low sub-cooling rate, chemically stable and reversible phase change process without segregation. Furthermore, they are non-toxic and corrosion free for the container [1, 5]. Fatty acid is another example of organic PCM. The drawback of the organic PCMs is that of their flammable nature [8]. Metals, salts and hydrates are example of inorganic PCMs. Salts like nitrate salts have high energy storage capability, better thermal conductivity and inflammable compared to organic PCM [8, 10, 12]. However, most inorganic PCM are chemically unstable and corrosive to the storage containers [14]. Eutectic salts are combination of organic and inorganic compounds. Organic-organic, organic-inorganic and inorganic-inorganic compounds are examples of Eutectic PCM, which have characteristics of reversible phase changing in the storage mechanism. Some reviews done on the available materials and they are potential materials that can be used for thermal energy storage [1, 10, 11]. Table 2 shows the selected materials that can be used as PCM and Table 3 shows the common material used in the storage tank.

Table 2 Selected materials potentially used as PCM [11].

Material	Melting point (°C)	Latent heat (kJ/kg)	Thermal conductivity (W/m K)	Density (kg/m^3)
$NaNO_3$	308	174	0.5	2260
KNO_3	336	116	0.5	2.110
KOH	380	149.7	0.5	2.044
$MgCl_2$	714	452	-	2140
NaCl	800	492	5	2160
Na_2CO_3	854	275.7	2	2.533
KF	857	452	-	2370
K_2CO_3	897	235.8	2	2.290

Table 3 Potential materials used as the thermal energy storage container [1].

Material	Thermal Conductivity (W/m°C)	Density (kg/m^3)	Specific heat (kJ/kg°C)
Glass	0.78	2700	0.840
Stainless steel	7.7	8010	0.500
Tin	64	7304	0.266
Aluminum mixed	137	2659	0.867
Aluminum	204	2707	0.896
Copper	386	8954	0.383

Previous works in the area of PCM was mostly experimental based where parameters could not be varied and comprehensive data could be not be obtained. The objective of the current investigation is to study the effect of fin spacing, heat transfer fluid velocity and the type of PCM on the heat loading characteristics of the PCM in a steady state, laminar heat transfer fluid flow.

2. Modelling and Simulation

The solar collector concentrates heat from the sun and is transferred in to the absorber. From the absorber, heat is transported in to the PCM in the thermal energy storage tank by using heat transfer fluid. Metals fins are added in the thermal energy storage to enhance the uniform heat transfer with in the storage. The thermal energy storage tank filled with PCM is insulated as show in the Fig.2. The $NaNO_3$ and KNO_3 representing the inorganic PCMs are used in the current study. Copper tube is used to circulate the heat transfer fluid from the receiver to the storage. The heat transfer fluid is selected to be XCELTHERM MK1 [15] with working temperature of 12-390°C, density of 695.3 kg/m^3 and specific heat of 0.00262 (kJ/kg°C).

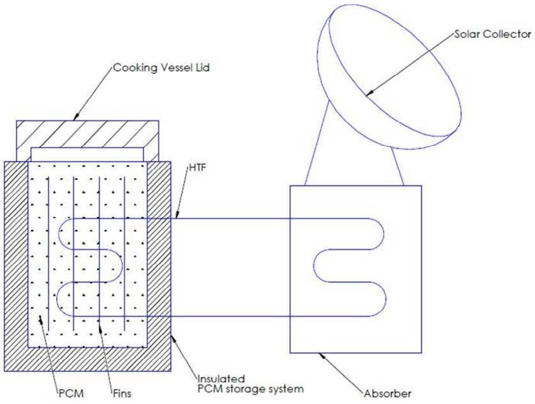


Fig.2 Concept model for the thermal energy storage system.

A scaled model was obtained by using the available dimensions from the market. The 3-dimensional model was developed by the use of solidwors Software. Fig.3 below shows the exploded view of the empty thermal energy storage tank.

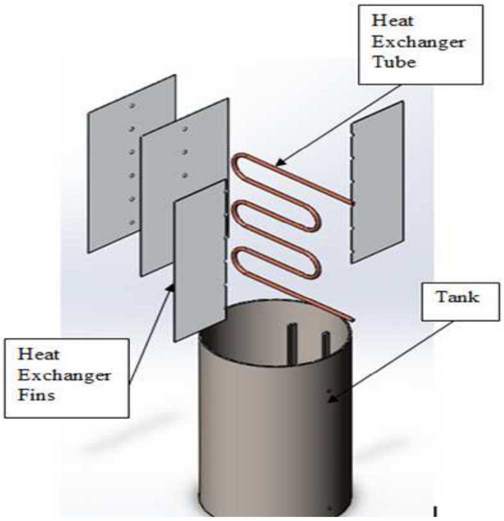


Fig.3 3 D model exploded view of the thermal energy storage with fins.

The 3D model was further imported into the ANSYS software to simulate the mechanism of heat exchange and to study the temperature distribution. Before setting the boundary conditions, the model was meshed using the ANSYS meshing as shown in Fig.4. Each of the surfaces was named for the ease of creating the interfaces during the simulation setting stage.

For the first step of the setting, the expression for density of both liquid and solid phase change material were created as in Eq. (1) and (2) :

$$\rho_{PCM,solid} = 1000 * [2.193 - 0.0006418 * (Temperature\ in\ °C)] \qquad (1)$$

$$\rho_{PCM,liquid} = 1000 * [2.112 - 0.0006891 * (Temperature\ in\ °C)] \qquad (2)$$

The materials used in this simulation are stainless steel as tank, copper tube, aluminum fins, solar fluid XCELTHERM MK1 and sodium nitrate as PCM material. Then the solar fluid or heat transfer fluid was created as the first fluid domain and the second fluid domain was the sodium nitrate, whereas the other materials were created as the solid domains. The boundary conditions were also included in these domain created. Other than that, the interfaces were defined the boundary conditions for the thin wall heat transfer model.

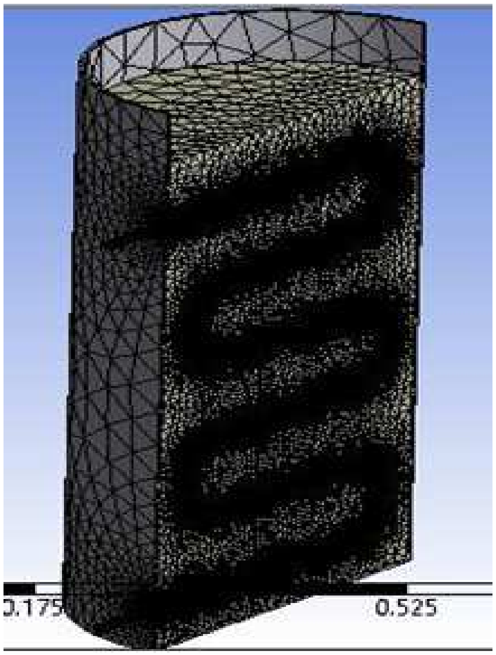
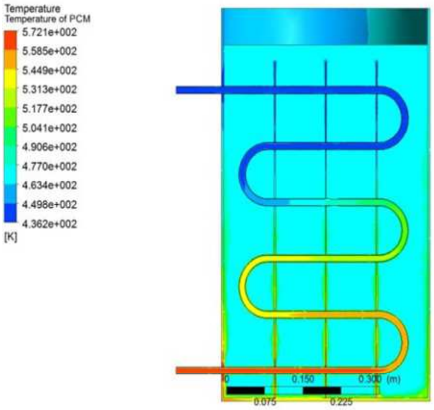


Fig.4 Meshed model.

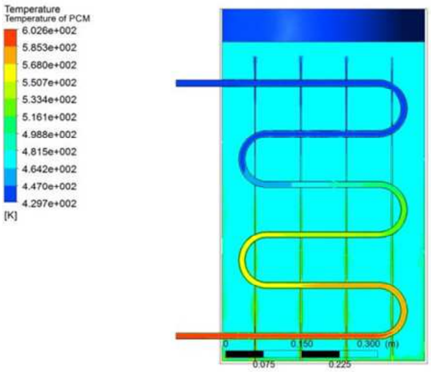
3. Results and Discussion

3.1 Effect of Heat Exchanger Fin Gaps

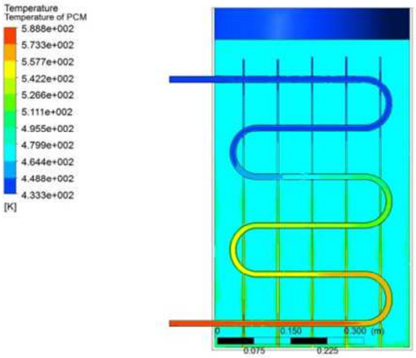
Fig.5 below shows the contour plots of the temperature distribution for different gap between the heat exchanger fins ranging from 50 mm to 100 mm. Fig.5 (a) shows the temperature distribution for fin gap of 100 mm, Fig.5 (b) for fin gap of 90 mm, Fig.5 (c) for fin gap of 70 mm, Fig.5 (d) for fin gap of 60 mm and Fig.5 (e) for fin gas of 50 mm. For most of the fin gaps, the higher temperature of PCM was located near the fins. This allows that if there are more fins in the tank, there will be higher temperature PCM available in the tank. Similar result from an experiment was reported for a square shaped TES design [16]. This is because the aluminum used as fin material has higher heat conductivity as compared to the PCM material. A point was also located in the middle of the PCM contours to measure the temperature of the PCM content. Fig.6 shows the effect of number of fins to the temperature of the central PCM temperature.



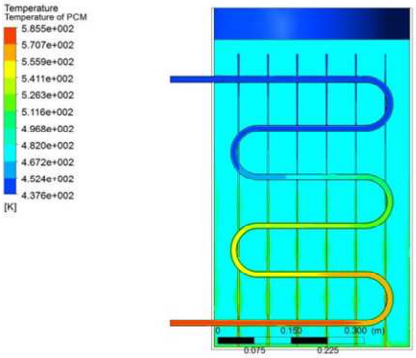
a) 100 mm



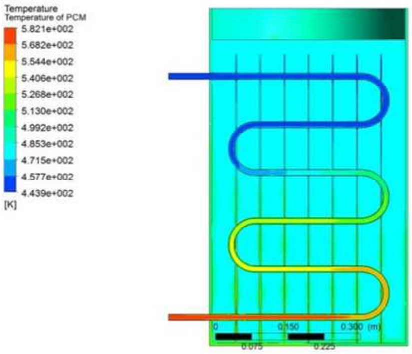
b) 90 mm



c) 70 mm



d) 60 mm



e) 50 mm

Fig.5 Temperature distribution for different distance between fins obtained from ANSYS CFX simulation.

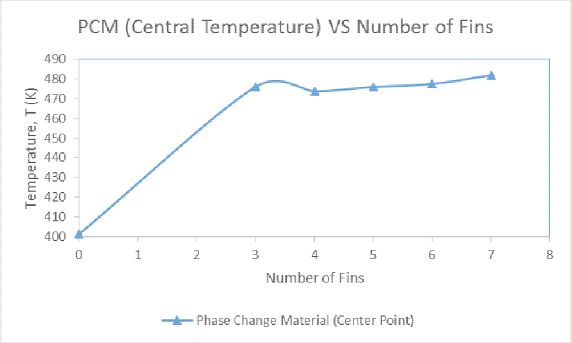


Fig.6 The effect of number of fins to the temperature at center of PCM.

The result showed that the more number of fins in the thermal energy storage tank, the higher the temperature of the PCM content. This happens due to the more fins in between the PCM, the higher the thermal conductivity of the content [12]. High thermal conductivity can help in improving the heat transfer between the heat transfer fluid and the PCM. A review done by Atul Sharma et al. stated that the higher the conductivity of the energy storage, the better the charging and discharging rate [1]. However, it has a drawback for the energy storage tank as the discharge heat energy is too fast. It will not store the energy for longer duration.

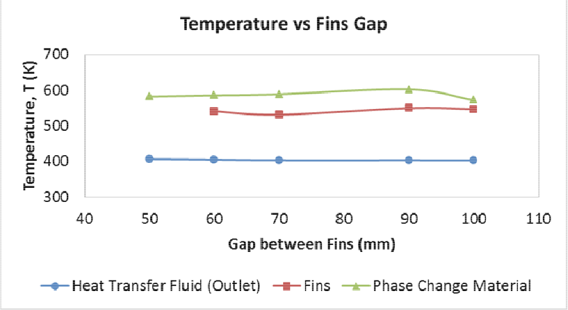


Fig.7 Effect of fin spacing on the temperature of the heat transfer outlet fluid, fins and maximum temperature of phase change material.

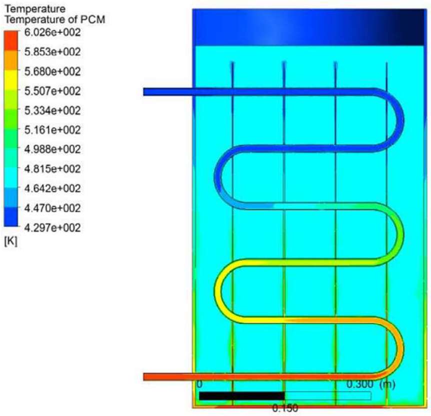
Fig.7 shows the effect of fin spacing on the temperature of the heat transfer fluid, the fin and the PCM. The result showed that the tank with 90 mm fin spacing (4 fins) recorded the highest temperature of PCM at about 603 K as compared to other fin configurations at about 580 K. This 23°C difference in temperature shows that the design with 4 aluminum fins or 90 mm fin gap was more efficient in heat transfer compared to 3, 5, 6, and 7 fin configurations. The energy storage tank with 4 fins has the optimum fin gap configurations and it will be used as a reference for other variable such as heat transfer fluid velocity, heat transfer medium and type of PCM as storage medium. Thus, the tank with 4 fins was achieved as the optimum design through this simulation. Also noted that a shortage of data in the fin temperature at 50 mm fin spacing. The data for fin temperature for 7 fins energy storage tank is unavailable due to the complexity of the simulation that requires too many domains.

3.2 Effect of Heat Transfer Fluid Velocity

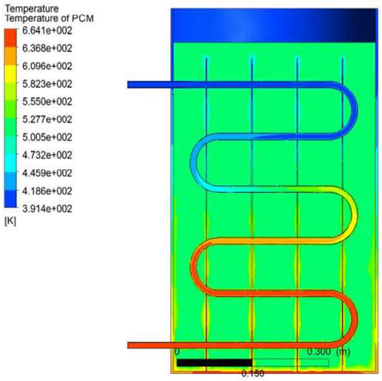
Assuming the simulation of the thermal energy storage system undergoes laminar fluid flow, variation of heat transfer fluid velocities were determined using Reynolds Number as in Eq. (3)

$$Re = \frac{\rho V D}{\mu} \tag{3}$$

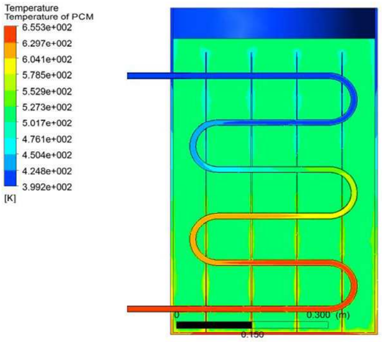
where *Re* is the Reynolds Number, ρ is the density of the heat transfer fluid (695.3 kg/m^3), V is the velocity of the heat transfer fluid, *D* is the diameter of the copper tube (13 mm), and μ is the dynamic viscosity of the heat transfer fluid (6.88347×10^{-7} kg/m·s). The highest velocity of the heat transfer fluid at laminar state is about 0.168 m/s as calculated from Eq. (3). To get a few more values of different fluid velocities, the velocity is varied as 0.168 m/s, 0.1305 m/s, 0.093 m/s, 0.0555 m/s, and 0.018 m/s. These values of velocities are later introduced into the simulation to investigate the relationships.



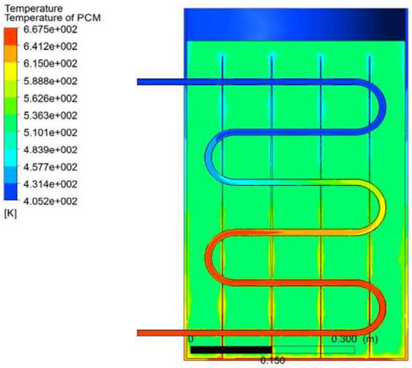
a) 0.018 m/s



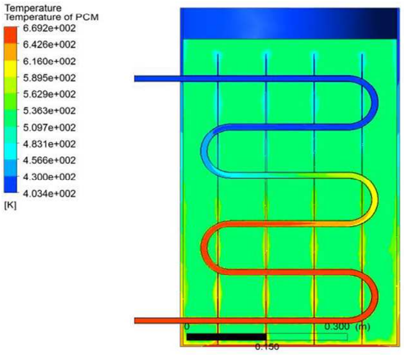
b) 0.0555 m/s



c) 0.093 m/s



d) 0.1305 m/s



e) 0.168 m/s

Fig.8 Temperature distribution for different heat transfer fluid velocities obtained from ANSYS CFX simulation

By referring to Fig.8 and Fig.9, the effect of heat transfer fluid velocity on the temperature distribution was investigated. The higher the velocity of the heat transfer fluid, the more amount of heat transfer fluid with higher temperature at a time in the tube of the TES. As a result, higher temperature of the heat exchanger fins and PCM is reported with higher heat transfer fluid velocity. Fig.9 shows the variation of heat transfer fluid, fins and the PCM temperature with the variation of heat transfer fluid velocity. The heat transfer fluid velocity has insignificant effect on the temperature of the heat transfer fluid. Based on the relation of rate of heat transfer [17], the rate of heat transfer is directly proportional to the mass flow rate, and mass flow rate is directly proportional to fluid velocity. Thus, the higher the heat transfer fluid velocity, the higher the rate of heat transfer. This happened because as the fluid in the tube circulates faster, more new and hot fluid from the solar collector flow into the tube that replaces cooler fluid in the tube. In the end, the temperature of the content will be higher as the heat transfer fluid transferred more heat to the PCM. Therefore, the fluid velocity at 0.168 m/s has shown to be the optimum for the thermal energy storage tank design. Similar result has been reported elsewhere [18].

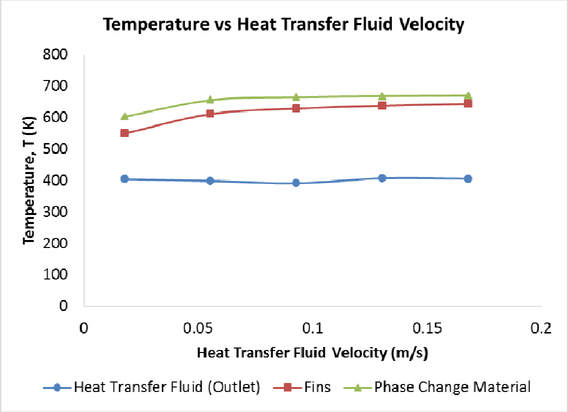


Fig.9 Effect of heat transfer fluid velocity on the temperatures

3.3 Effect of PCM Types

In the current study, the effect of PCM on the performance of the heat storage was also investigated. Fig.10 shows the variation of temperature for the two PCMs. In order to study the effect of the type of PCM toward temperature of the heat exchanger fins and PCM, potassium nitrate salt (KNO_3) and sodium nitrate ($NaNO_3$) are used. Different types of PCMs having different physical and thermal properties could be verified as a result.

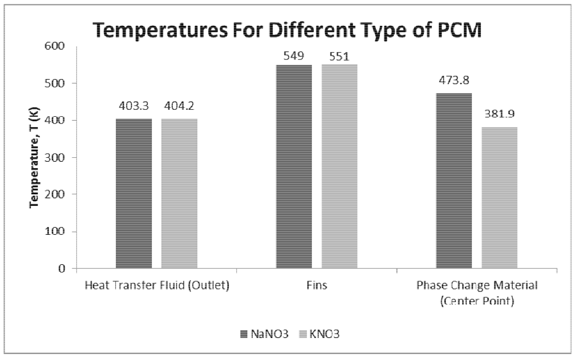


Fig.10 Temperature variation for different types of PCM.

As shown in Fig.10, the temperatures of heat transfer fluid and fins were about the same for both type of PCM. However, a local analysis at the middle of the PCM content, the temperature of the sodium nitrate salt was higher than potassium nitrate salt by 92°C. This is resulted from the higher latent heat of sodium nitrate as compared to potassium nitrate salt [11]. Thus, the sodium nitrate salt is better compared to potassium nitrate salt to be used as a phase change material in this thermal energy storage tank design.

3.4 Mesh Independency Test

In any computational analysis or simply called as simulation, meshing step can be considered as the most critical and important process. The quality of the mesh is strongly related to the result of the simulation. Too course meshing resulting for too small number of elements will increase inaccuracy in the computation, whereas too many elements (fine mesh) increases the time for computation in turn increasing the cost. Table 4 and Fig. 11 show the results of temperature using different quality of mesh sizing.

Table 4 Effect of mesh sizing on the temperatures.

	Sizing	Fine	Medium	Course
Mesh Characteristics	Smoothing	High	High	Medium
	Nodes	232199	213318	209616
	Elements	815931	737684	725097
Temperature (K)	Heat Transfer Fluid (Outlet)	402.783	403.321	403.311
	Fins	547.701	546.652	549.237
	PCM	601.572	601.009	602.562

Mesh dependence percentage (mesh error)

$$= \frac{602.572 - 601.009}{602.572} \times 100\% = 0.26\%$$

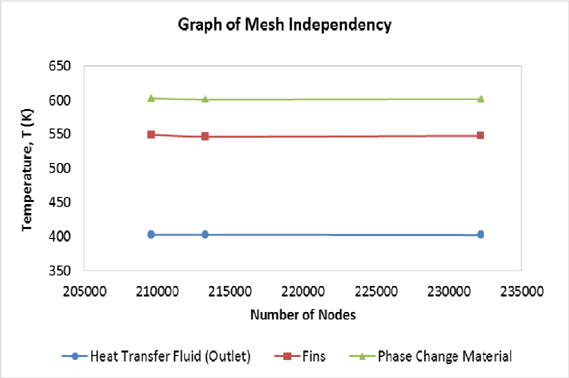


Fig.11 Mesh independence test.

Based on the Fig.11, the temperatures for all three objects to be remain at nearly a constant. With respect to the mesh number, the results obtained do not change much. The largest error from the results was about 0.26 percent which is very small. Therefore, these results showed that the simulation is not mesh dependent.

4. Conclusion

Design with 4 fins registered a PCM temperature of 23°C higher than other fin configurations. The higher speed of 0.168 m/s of the heat transfer fluid in the copper tube under laminar state was the optimum in the current simulation for both PCMs. Based on the reviews done on the PCM price and latent heat, sodium nitrate ($NaNO_3$) has lower price and higher latent heat than potassium nitrate salt (KNO_3). The simulation was computed by using different mesh quality, which showed a mesh dependency of 0.26% (in the range of mesh dependent). As a future work, modelling of the heat loading and unloading of the transient state of the system need to be investigated.

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NOMENCLATURE

$\rho_{PCM,solid}$: Density of solid PCM, kg/m^3
$\rho_{PCM,liquid}$: Density of liquid PCM, kg/m^3
ρ : desnity of heat transfer fluid, kg/m^3
D : transfer fluid pipe diameter, m
μ : dynamic viscosity, kg/m·s
V : Velocity of heat transfer fluid, m/s

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