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Mathematical Model of Thermal Energy Storage for Solar Water Heating System

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Abstract: The objective of this research is to develop thermal energy storage for domestic solar water heater with simple and flexible design, easy installation and low maintenance requirements. The prototypes of thermal energy storage are constructed using stainless steel and tested at Mandalay Technological University. The storage unit stores the heat in sodium chloride (NaCl) solution the day and supplies the energy during the night and cloudy days. A mathematical model is developed to do the experiment and simulate the temperature distribution of thermal storage tank. The model design month is chosen as May. The storage has 0.2159 m height and diameter 0.3048 m. Its volume is 0.0105 m^3. Ethylene glycol is used heat transfer fluid. It absorbs energy from the sum and transfers the heat to the sodium chloride solution. Sodium chloride solution carries as heat storage media to store the energy. The two tubes are used to exchange heat. It has 0.254 m of diameter. It consists of hot tube (filling with ethylene glycol) and cold (water) tube which pass through a NaCl solution inside a storage tank. The hot tube is carried out as solar collector to absorb the solar energy from the sun. The cold tube is used to pass water. There are three operation modes in this system such as charging, discharging and simultaneously both charging and discharging. In this study present simultaneously charging and discharging process. The maximum temperature of NaCl solution is 46˚C and outlet temperature of water is 43˚C at 3:00 pm.

Keywords: Thermal Energy Storage, Phase Change Material, Solar Energy, Temperature Distribution, Performance Analysis.

I. INTRODUCTION

Energy is an important factor for every country all over the world. The growth of world population couple with the rate of energy is increasing. Scientists all over the world are in search of new and renewable energy sources to reduce the CO_2 emissions from the combustion of fossils fuels. So, renewable energy has been considered instead of conventional energy. Types of renewable energy are geothermal energy, solar energy, tidal energy, hydraulic energy, biological energy, wind energy and wave energy etc. Among the energy, solar energy is one of the most popular energy. Solar energy is the energy that is coming from the sun. Solar energy can be used as thermal energy and electrical energy. Solar energy has an enormous potential for producing hot water for domestic and industrial purposes, cooking, warming greenhouses for agricultural crops, etc .Solar energy can be used during sunshine hours. It is not available all the time. This problem can be solved by energy storage. Therefore, heat storage has been considered for using at night and cloudy day. Heat storage save energy during sunshine hour and then it can be used off-shine hour. Conservation of solar energy into thermal energy is the easiest and the most widely method. Due to this nature, thermal energy storage system can play an important role in the solar energy systems. Energy storage not only plays an important role in conservation of the energy but also improves the performance in wide range of energy systems.

II. BAKGROUNG OF THERMAL STORAGE SYSTEM

The main types of energy storage system are sensible heat storage and latent heat storage. Latent heat storage (LHS) system is more effective than sensible heat storage (SHS) system. SHS stores heat as its temperature rises and releases this heat later. It has high storage density and storage process is isothermal at melting temperature. There are many main parts in the storage system. They are solar collector, storage system and heat exchanger etc. During the charging time, solar collector concentrates the sunlight to heat a heat transfer fluid to a high temperature. This temperature is absorbed by phase change material into the storage tank. During the discharging time, storage energy is extracted to the cold heat transfer fluid by means of heat exchanger. In thermal energy storage system as shown in

Fig1, phase change material (PCM) and heat exchanger are important part. Therefore, design of heat exchanger is an important part for rising heat transfer on LHS system. And then the volume of PCMs expands in melting so, design of container is also necessary. In this paper, there will be focus temperature distribution on the thermal storage system as shown in Fig.2.

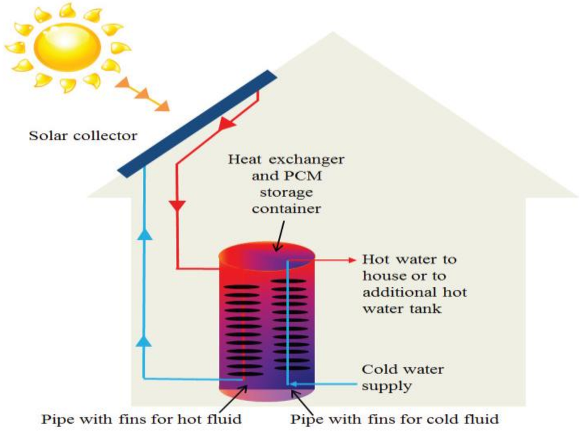

Fig.1. Schematic of solar hot water system with latent heat energy storage system [7].

Fig.2. photo of constructed thermal storage system.

A. Types of Energy Storage System

Energy storage is storing energy during the time when excess is available in order to be used later. Solar energy is available in day time in solar system. So, the storage systems are used to store the energy for night time use. Therefore the storage system is the critical point of solar energy system. The energy can be stored in different forms such as mechanical, electrical and thermal energy storage.

1. Mechanical Energy Storage: Mechanical energy storage systems include gravitational energy storage or pumped hydropower storage (PHPS), compressed air energy storage (CAES) and flywheels. The PHPS and CAES technologies can be used for large-scale utility energy storage while flywheels are more suitable for intermediate storage. PHPS is the oldest and largest among all commercially available energy storage methods. It uses two water reservoirs that are separated vertically at different elevations. When water moves from the lower reservoir to the higher one, energy is stored. Energy is extracted when water flows back from the higher reservoir to the lower reservoir. Energy is stored according to the theory of the potential energy. CASE is new energy storage. CASE facilities are considered as a hybrid storage technology because they must be integrated with a combustion turbine. The power is generated by the turbine as a result of the burning of the compressed air with the fuel in the combustion chamber. The advantage of this simplified turbine is that it produces much more energy than the conventional turbine by using the same fuel, because of the potential energy that is stored in the compressed air. Flywheels energy storage systems include a heavy rotating cylinder supported on a stator by magnetically bearings that eliminate the bearing wear and increase the system life.

2. Electrical Energy Storage: Batteries can be used for storing the electrical energy. A battery is charged by connecting it to a source of direct electric current. When it is discharged, the stored chemical energy is converted into electrical energy. Potential applications of batteries are utilization of off-peak power, load leveling and storage of electrical energy generated by wind turbine or photovoltaic plants.

3. Thermal Energy Storage: Thermal energy storage can be stored as a change in internal energy of a material as sensible heat, latent heat and thermo-chemical heat or combination of these. In sensible heat storage (SHS), thermal energy is stored by raising the temperature of a solid or liquid. A material is not considered good for SHS if it discharges quickly. Thus, it is desirable for the storage medium to have high specific heat capacity, long term stability under thermal cycling, and low cost. SHS system utilizes the heat capacity and the change in temperature of the material during the process of charging and discharging. The amount of heat stored depends on the specific heat of medium, the temperature change and the amount of storage material.

Latent heat storage (LHS) is based on the heat absorption or release when the storage material undergoes a phase change from solid to liquid or liquid to gas or vice versa. Two types of latent heat are known, latent heat of fusion and latent heat of vaporization. Latent heat of fusion is the amount of heat absorbed or released when the material changes from the solid phase to the liquid phase or vice versa, while latent heat of vaporization is the amount of thermal energy absorbed or released when the material changes from the liquid phase to the vapor phase or vice versa. LHS systems have certain benefits in comparison with SHS systems. The most important is the higher energy density per unit mass and unit volume.

4. Thermochemical Energy Storage: Thermo-chemical systems rely on the energy absorbed and released in breaking and reforming molecular bonds in a completely reversible chemical reaction. In this case, the heat stored depends on the amount of storage material. This storage technique, latent heat thermal energy storage is particularly attractive due to its ability to provide high-energy storage density and its characteristics to store heat at constant temperature corresponding to the phase transition temperature of phase change material (PCM). Phase change can be in the following from: solid-solid, solid-liquid, and liquid-gas and vice versa.

B. Phase Change Material

All materials are phase change materials. The most important different between these materials is the phase change temperature as shown in Fig3. Each material makes its phase change at different temperature. In addition, each material has different value of latent heat and thermal conductivity. The main drawback of most phase change materials is low their thermal conductivity that decreases the heat transfer. The PCM to be used in the design of thermal-storage systems should possess desirable thermo-physical, kinetics and chemical properties which are as follow:

1. Thermo-physical Properties:

- Phase change temperature fitted to the application
- High latent heat of fusion per unit mass
- High thermal conductivity in both solid and liquid phase
- Low volume change during the phase change
- No sub cooling during freezing
- High density
- Low density variation during phase change
- High value of specific heat to give additional benefits of sensible heat storage

2. Chemical Properties:

- Long term chemical stability
- No chemical decomposition
- Non-corrosive to construction material
- Non-poisonous, non-toxic
- Non-explosive, non-dangerous
- Non- flammable

3. Economics:

- Available in large qualities
- Cheap in order to make the system

C. Classification of Phase Change Material

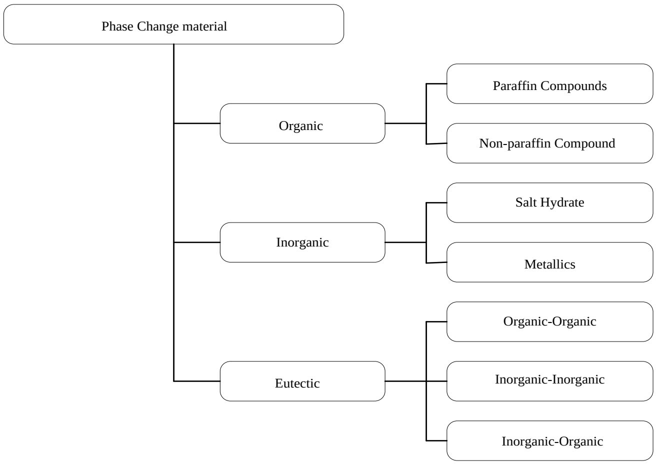

Fig.3. Classification of PCMs [4].

Inorganic phase change materials, which include salt hydrates, have a volumetric thermal storage density higher than most organic compounds due to higher latent heat and density. As well, salt hydrates have relatively small volume changes during melting. Salt hydrates consist of a salt and water that in a crystalline matrix when the material solidifies. There are many different salt hydrates that have melting temperature ranges between 15˚C – 117˚C. Salt hydrates are considered as the most important group of PCMs that have been studied for application in latent thermal energy storage systems. So, sodium chloride (NaCl) include in salt hydrates. NaCl has the same attractive properties.

- It has temperature gradient.
- It has voltage so it can produce electricity.
- It has non-conductive zone so it does not mixed with fresh water.
- It has high thermal conductivity
- It is not flammable.
- It is lower in cost than other organic compound.
- It is inexpensive and readily available.

NaCl is chosen for the research because of the above properties.

III. MATHEMATICAL FOR STORAGE SYSTEM

The temperature distribution in the solar thermal storage system is studied by mathematically. The solar system consists of mainly of a solar collector and a storage unit. The storage unit is a cylindrical tank with sodium chloride solution. A theoretical analysis is made for temperature distribution during the charging and discharging process.

A. Physical Model

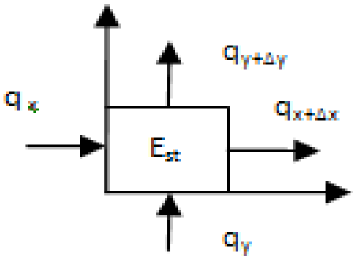

Fig.4. Schematic of two dimensional transient heat conduction.

$E_{in} = q_x$ [W] –heat input
$E_{in} = q_y$ [W] –heat input
$E_{out=}\ q_{x+dx}$ [W]-heat output
$E_{out=}\ q_{y+dy}$ [W]-heat output

$$E_{st} = \rho\, c_p \frac{\partial T}{\partial t}\, dxdydz \text{ [W] - heat storage}$$

A physical model which consists of a cylindrical tank has length H and diameter D. Helical coil of heat exchanger is fixed inside the storage tank. Ethylene glycol is used heat transfer fluid (HTF) and sodium chloride solution and water are used as heat storage medium. During the charging process, the HTF is heated inside a solar collector and pumped through the heat exchanger from top of the tank to the bottom. At this time, heat storage medium gets heat from the HTF as shown in Fig.4. The temperature of heat transfer fluid increases gradually until it attains the required storage temperature and it remains constant until the equilibrium state between the HTF and solution temperature, then the charging process terminates. But heat exchanger is not considered in this paper.

B. Mathematical Models Governing Equation

In the continuous liquid model, the liquid is assumed as a continuous medium. In addition, it is assumed that the heat transfer in the tank is by conduction along the axial and radial directions. The energy equations that used to analyse the temperature in this system are subjected to the following assumptions:

- The tank is cylindrical.
- The fluid inside the storage tank is vertical from the top during charging process and from the bottom during discharging process.
- The fluids properties are temperature independents.
- There is no heat generation inside the tank.
- There are no chemical reactions in the tank.
- The radiation of heat transfer inner mechanism is neglected.
- The tank is well insulated and there is no heat loss from the tank.
- The tank is in thermal equilibrium with the ambient when the charging process starts.

C. Mathematical Model by Partial Differential Equation

A major objective in a conduction analysis is to determine the temperature field in medium resulting from conditions that are imposed on its boundaries. To know the temperature distribution, this represents how temperature varies with position in the medium.

$$q_{x+\Delta x} = q_x + \frac{\partial q}{\partial x} dx \qquad \textbf{(1)}$$

$$q_{y+\Delta y} = q_y + \frac{\partial q}{\partial y} dy \qquad \textbf{(2)}$$

$$E_{st}^{\circ} = \rho c_p \frac{\partial T}{\partial t} dxdydz \qquad \textbf{(3)}$$

Energy Conservation on the system

$$E_{in} + E_g - E_{out} = E_{st} \qquad \textbf{(4)}$$

The energy generation term E_g is not considered because no need external heat source.

So the equation (5) becomes

$$E_{in} - E_{out} = E_{st} \qquad \textbf{(5)}$$

Hence, recognizing that the conduction rates constitute the energy inflow, E_{in}, and outflow, E_{out}, and substituting Equation (5),

$$q_x + q_y - q_{x+\Delta x} - q_{y+\Delta y} = \rho c_p \frac{\partial T}{\partial t} dxdydz \qquad \textbf{(6)}$$

$$q_x + q_y - (q_x + \frac{\partial q_x}{\partial x} dx) - (q_y + \frac{\partial q_y}{\partial y} dy) = \rho c_p \frac{\partial T}{\partial t} dxdydz \qquad \textbf{(7)}$$

By Fourier's law

$$q_x = -kdydz \frac{\partial T}{\partial x} \qquad \textbf{(8-a)}$$

$$q_y = -kdxdz \frac{\partial T}{\partial y} \qquad \textbf{(8-b)}$$

Substituting Equations (8) into Equation (7) and dividing out the dimensions of the control volume (dx dy dz)

$$k \frac{\partial^2 T}{\partial x^2} + k \frac{\partial^2 T}{\partial y^2} = \rho c_p \frac{\partial T}{\partial t} \qquad \textbf{(9)}$$

Equation (9) is the general form, in Cartesian coordinates, of the heat diffusion equation.

The above equation reduces to the following form:

$$\frac{\partial T}{\partial t} = \frac{k}{\rho c_p} \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \qquad \textbf{(10)}$$

PDE of two-dimensional transient heat conduction From equation (10)

Suppose

$$c^2 = \frac{k}{\rho c_p} \Rightarrow \frac{\partial T}{\partial t} = c^2 \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \qquad \textbf{(11)}$$

Where $c^2 = k/\rho c_p$ (which is defined as the thermal diffusivity of the fluid), k is the thermal conductivity, ρ is the density, c_p is the specific heat capacity, t is the time, T is the temperature and d/dt is the substantial derivative.

To solve this equation we will describe by step as follow:

D. Boundary and Initial Condition

To solve this equation, some important type of boundary and initial condition will be assumed as the end of the tank (x=0→D & y=0→H) are kept at temperature zero, therefore T(0,y,t)=0, T(D, y, t)=0, T(x,0,t)=0, T(x, H, t)=0.

The initial temperature f(x) is

$$T_t(x, y, 0) = f(x, y) \qquad \textbf{(12)}$$

Step 1:

$T(x,y,t)=X(x)Y(y)\Gamma(t)$ be the solution of eq (11) (12)

$$T_t(x,y,t)=X(x)Y(y)\Gamma'(t) \qquad \textbf{(13a)}$$

$$T_{yy}(x,y,t)=X(x)Y''(y)\Gamma(t) \qquad \textbf{(13b)}$$

$$T_{xx}(x,y,t)=X''(x)Y(y)\Gamma(t) \qquad \textbf{(13c)}$$

If the equations (13) are substituted in eq(11), eq(14) becomes

$$X(x)Y(y)\Gamma'(t)=c^2\left[X''(x)Y(y)\Gamma(t)+X(x)Y''(y)\Gamma(t)\right] \qquad \textbf{(14)}$$

Both sides must be equalled to constant (-λ) because if they are variable, then the changing x, y or t would affect only one side

$$\frac{\Gamma'(t)}{c^2\Gamma(t)}=\frac{X''(x)}{X(x)}+\frac{Y''(y)}{Y(y)}$$

$$\text{Let } \frac{X''(x)}{X(x)}=-\lambda \qquad \textbf{(15)}$$

$$\frac{Y''(y)}{Y(y)}=\frac{\Gamma'(t)}{c^2\Gamma(t)}+\lambda=-\mu$$

$$X''(x)+\lambda X(x)=0 \qquad \textbf{(16a)}$$

$$Y''(y)+\mu Y(y)=0 \qquad \textbf{(16b)}$$

$$\Gamma'(t)+(\lambda+\mu)c^2\Gamma(t)=0 \qquad \textbf{(16c)}$$

To solve the equation (13), the above the initial conditions are used

$$T(0,y,t)=X(0)Y(y)\Gamma(t)=0 \qquad \textbf{(17a)}$$

$$T(x,0,t)=X(x)Y(0)\Gamma(t)=0 \qquad \textbf{(17b)}$$

$$T(D,y,t)=X(D)Y(y)\Gamma(t)=0 \qquad \textbf{(17c)}$$

$$T(0,H,t)=X(x)Y(H)\Gamma(t)=0 \qquad \textbf{(17d)}$$

$$T_t(x,y,0)=X(0)Y(y)\Gamma'(0)=f(x,y) \qquad \textbf{(18)}$$

$$X(0)=0,X(D)=0,\ Y(0)=0,Y(H)=0$$

If a negative value are selected or a value of λ=0 chosen, it can be readily shown that it would be impossible to obtain a solution that satisfies the prescribed boundary conditions.

Case (1) $\lambda=0$

$\Rightarrow X''(x)=0 \Rightarrow X'(x)=0 \Rightarrow X(x)=0$

So, we prefer case λ is positive

Case (2) $\Rightarrow \lambda>0$, Let $\lambda=\rho^2$

$$\text{Let } \lambda=\rho^2 \Rightarrow X''(x)+\rho^2X(x)=0 \qquad \textbf{(19)}$$

Characteristic equation is

$\Rightarrow m^2+\rho^2=0 \Rightarrow m=\pm i\rho$

The general solution to equation (20) is,

$$X(x)=A\cos(\rho x)+B\sin(\rho x) \qquad \textbf{(20)}$$

Applying the condition that X(0)=0, it is evident that A=0.

$X(0)=A\cos 0+B\sin 0$

In addition from the requirement that X (D)=0, we obtain

$X(D)=0 \Rightarrow A\cos\rho D+B\sin\rho D=0 \Rightarrow B\sin\rho D=0$

Setting $B=1 \rightarrow \rho D=\sin^{-1}0=n\pi \Rightarrow \rho=\frac{n\pi}{D}$

$$X_n(x)=\sin(\frac{n\pi}{D})x=\sin\rho x,\rho=1,2,3,... \qquad \textbf{(21)}$$

Case(3) $\lambda<0 \rightarrow \lambda=-\rho^2$

$X(x)-\rho^2X(x)=0 \Rightarrow m^2+\rho^2=0$

$X(x)=Ce^{\rho x}+De^{-\rho x}$

$X(0)=0 \Rightarrow Ce^0+De^0=0$, $C=-D$

$X(D)=0 \Rightarrow Ce^{\rho L}+De^{-\rho L}=0$

$C=0,D=0 \Rightarrow \therefore X(x)=0$

So, there is no solution in λ is negative and zero.

In this case, there is no general solution.

Case(1) $\Rightarrow \mu=0$

$\Rightarrow Y''(y)=0 \Rightarrow Y'(y)=0 \Rightarrow Y(y)=0$

So, we prefer case μ is positive.

Case (2) $\mu>0,\ \mu=q^2$

The characteristic equation is

$m^2+q^2=0,\ m=\pm iq$

The general solution is

$$\Rightarrow Y(y)=A\cos(qy)+B\sin(qy) \tag{22}$$

Applying the condition that Y(0)=0, it is evident that A=0,

$$Y(0)=A\cos 0+B\sin 0=0 \Rightarrow A=0,\ B\neq 0$$

In addition from the condition Y(H)=0

$$Y(H)=0 \Rightarrow A\cos(qH)+B\sin(qH)=0$$

$$B\sin(qH)=0 \Rightarrow q=\frac{n\pi}{H}$$

$$Y_n(y)=\sin(\frac{n\pi}{H})y=\sin qy, q=1,2,3,... \tag{23}$$

$$\text{Case(3)} \Rightarrow \mu<0,\ \mu=-q^2$$

$$Y''(y)-q^2Y(y)=0 \Rightarrow m=\pm q$$

$$Y(y)=Ce^{qy}+De^{-qy}$$

$$Y(0)=0 \Rightarrow Ce^0+De^0=0 \Rightarrow C=-D$$

$$Y(H)=0 \Rightarrow Ce^{Hy}+De^{-Hy}=0$$

$$C=0,\ D=0 \Rightarrow Y(y)=0$$

Integrating both sides of Equation (16c) with respect to t,

$$\mathrm{Ln}\left|\Gamma(t)\right|=-c^2(\lambda+\mu)t+C_1$$

$$\Gamma_n(t)=b_n e^{-c^2(\lambda+\mu)t},\ (e^{C1}=b_n) \tag{24}$$

b_n is constant and n=1,2,3…

Substituting Equation (22),(23) and (24) into Eq.(12)

$$T_n(x,y,t)=X_n(x)Y_n(y)\Gamma_n(t)$$

$$T_n(x,y,t)=\sin\rho x\times\sin qy\times b_n\times e^{-c^2(\lambda+\mu)t} \tag{25}$$

$$\rho=m,\ q=n,\ A_{mn}=b_n$$

To satisfy A_{mn} must be the coefficient of Fourier Sine Series

$$A_{mn}=\frac{2}{H}\int_0^H\frac{2}{D}\int_0^D f(x)\sin(\frac{mx}{D})g(y)\sin(\frac{ny}{H})dxdy \tag{26}$$

By Fundamental Theorem

$$T(x,y,t)=\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\sin mx\sin nyA_{mn}e^{-c^2(m^2+n^2)t} \tag{27}$$

The initial conditions are used to solve the Fourier Sine Series

$$T(x,0)=f(x)\left|\begin{array}{l}26x,0\le x\le D/2\\ 26(D-x),D/2\le x\le D\end{array}\right.$$

$$T(y,0)=g(y)\left|\begin{array}{l}26y,0\le y\le H/2\\ 26(H-y),H/2\le y\le H\end{array}\right.$$

From equation (30);

$$A_{mn}=\frac{2}{H}\int_0^H\frac{2}{D}\int_0^D f(x)\sin(\frac{mx}{D})g(y)\sin(\frac{ny}{H})dxdy$$

$$\int_0^D f(x)\sin(\frac{mx}{D})dx=\int_0^{D/2}26x\sin(\frac{mx}{D})dx...$$

$$+\int_{D/2}^{D}26(D-x)\sin(\frac{mx}{D})dx=52\frac{D^2}{m^2}\sin(\frac{m}{2})$$

$$A_{mn}=\frac{4}{H}\int_0^H 52(\frac{D}{m})^2\sin(\frac{m}{2})g(y)\sin(\frac{ny}{H})dy \tag{28}$$

$$A_{mn}=10816\frac{DH}{(mn)^2}\sin(\frac{m}{2})\sin(\frac{n}{2}) \tag{29}$$

Substituting Equation (29) into equation (27)

$$T(x,y,t)=\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\frac{10816DH}{(mn)^2}\sin(\frac{m}{2})\sin(\frac{n}{2})...$$
$$\times\sin mx\sin nye^{-c^2(\sqrt{m^2+n^2})t} \tag{30}$$

$$m=\rho=\frac{m\pi}{D},\ n=q=\frac{n\pi}{H}$$

$$T(x,y,t)=\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\frac{10816D^3H^3}{(m\pi)^2(n\pi)^2}\sin(\frac{m\pi}{2D})...$$
$$\sin(\frac{n\pi}{2H})\sin(\frac{m\pi x}{D})\sin(\frac{n\pi y}{H})...$$
$$\times e^{-c^2(\sqrt{(\frac{m\pi}{D})^2+(\frac{n\pi}{H})^2})t} \tag{31}$$

IV. RESULTS AND DISCUSSION

Temperature Distribution for NaCl Solution:

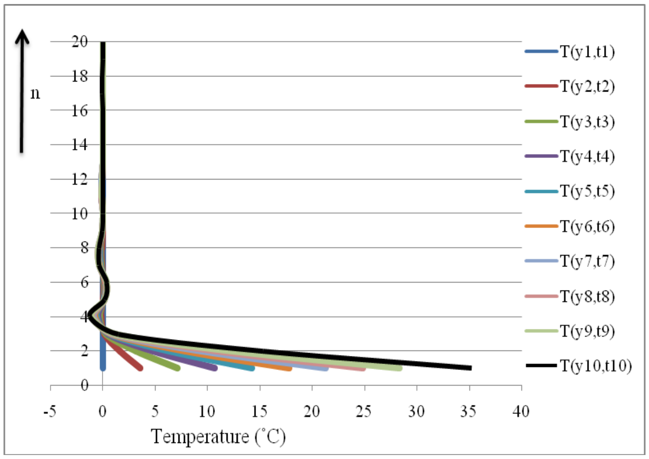

Fig.5. Temperature distribution along the storage tank for NaCl.

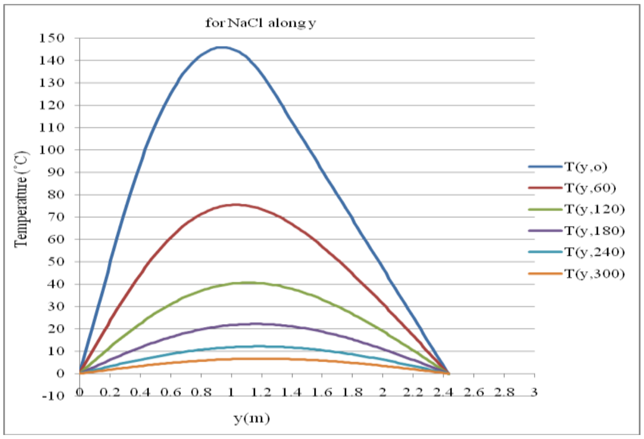

Fig.6. Temperature distribution in the storage tank for NaCl.

Figs.5 and 6 present temperature distribution of thermal storage tank.

V. RESULTS FROM EXPERIMENT

The system shown in fig.7 consists of hot heat transfer fluid (HTF) tube and cold heat transfer fluid pipe which pass through a NaCl solution tank. The hot HTF tube carries the energy collected from the sum, and the cold HTF carries the water which is to be heated for use in the building and results shown in Figs.7, 8 and 9. In this system, there are three possible operating modes;

- Heat exchange from the hot HTF to NaCl solution, heating the NaCl solution and charging the system.
- Heat exchange from the NaCl solution to the water, cooling the NaCl solution and discharging the system.
- Both 1)and 2) at the same time; heat exchange from the hot HTF to the NaCl solution, and heat exchange from the PCM to the water at the same time, resulting in simultaneous charging and discharging.

The third operating mode occurs when there is a demand for hot water at the same time that solar energy is available. In this paper, simultaneous operating modes are presented.

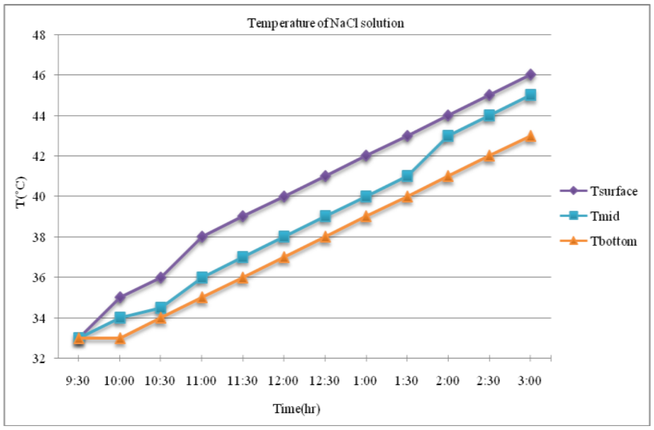

Fig.7. Temperature of NaCl solution in storage tank.

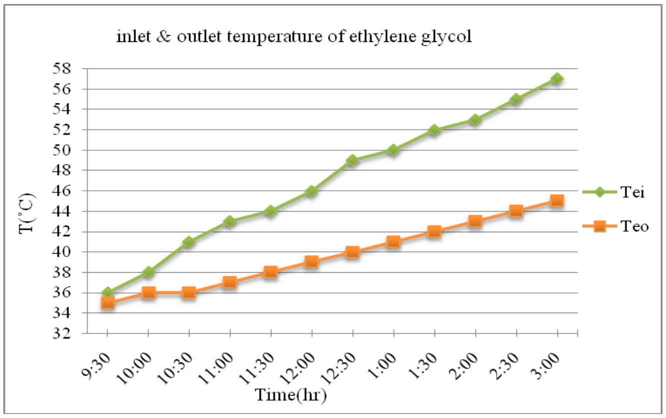

Fig.8. Inlet and outlet temperature of ethylene glycol.

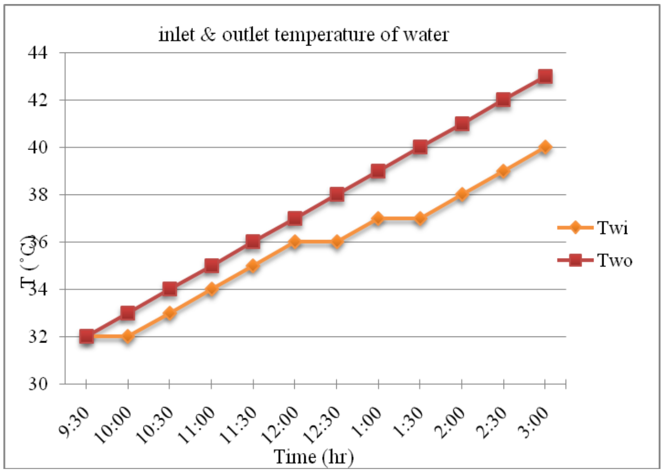

Fig.9. Inlet and outlet temperature of water.

VI. CONCLUSION

In this paper, has been presented a mathematical model for thermal storage tank. A heat storage system containing sodium chloride in cylindrical tank is designed with an effective water storage capacity. A two dimensional model was developed to investigated the temperature distribution. From the experiment, shown in figure 8, the temperature gradient in the storage tank is that the temperature at the top of tank is higher than that of bottom. The simultaneously operation mode is performed. This system provides a simple technique for storing solar energy for hot water supply. It is desirable for long term stability under thermal cycling and low cost. If new generations research the solar heat storage system, it should be studied with high thermal conductivity and high density phase change material for industrial water heating.

VII. ACKNOWLEDGMENTS

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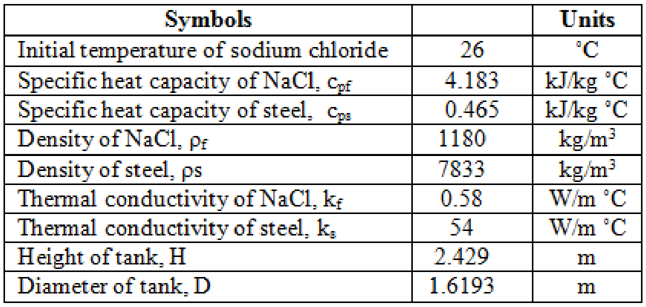
VIII. APPENDIX

TABLE I: Fixed Parameter for Calculation



Symbols		Units
Initial temperature of sodium chloride	26	°C
Specific heat capacity of NaCl, c_{pf}	4.183	kJ/kg °C
Specific heat capacity of steel, c_{ps}	0.465	kJ/kg °C
Density of NaCl, ρ_f	1180	kg/m^3
Density of steel, ρs	7833	kg/m^3
Thermal conductivity of NaCl, k_f	0.58	W/m °C
Thermal conductivity of steel, k_s	54	W/m °C
Height of tank, H	2.429	m
Diameter of tank, D	1.6193	m

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