MATHEMATICAL MODEL OF CHARGING AND DISCHARGING IN SODIUM CHLORIDE STORAGE MEDIA SOLAR THERMAL PARABOLIC TROUGH POWER PLANT

P. Tooklang[a,b]*, and S. Vaivudh[b]

[a] *Physics and General Science Department, Faculty of Science and Technology, Nakhonratchasima Rajabath University, Nakhonratchasima 30000, Thailand*
[b] *School of Renewable Energy Technology (SERT), Naresuan University, Phitsanulok 65000, Thailand*

Received 20 October 2012; Revised 10 January 2012; accepted 15 February 2013

ABSTRACT

The thermal energy storage used salt media for a storage system of a parabolic trough concentrator was tested and determined. The cylindrical storage system made of stainless steel with 32 cm diameter and 120 cm height that contains of 125 kg NaCl. There were five pipes for HTF with 1.27 cm diameter each manipulate in the storage tank and submerge to NaCl. The inner were connected to the 2.27 cm diameter outer HTF tube. The tube was further connected to the thermal pump, heater and load. The pump circulates the synthetic oil (thermia oil) within the pipe for heat transferring purposes (charging and discharging). The 3 kW_{th} heater was transferred thermal energy by the HTF and then transferred to NaCl. A discharging process, to was started by NaCl in the tank that transfer heat to HTF and then to the load. The data of HTF temperature were measured in various points: the inlet, the inner and the outer of the tank. The temperature of NaCl in the storage tank was also measured. These measurements were analyzed heat transfer between HTF and NaCl, storage by NaCl, and then discharge to the load. The result of HTF the flow rates of 0.1, 0.2 and 0.3 kg/s and were shown from 30 ^{o}C to 250 ^{o}C in 120 ,130 ,and 140 minute, with the error of 7.6%. The thermal energy storage was 2.46 kW.h. Discharge process, HTF from the NaCl in the storage tank at the flow rate of 0.3 kg/s were lied from 250 ^{o}C to 100 ^{o}C in 110 , 120, and 130 minute, with the error of 9.3% that valid with mathematical model.

KEYWORDS: thermal energy storage, parabolic trough, charging, discharging, storage tank

INTRODUCTION

The sun is the powerful source of energy that releases a large amount of clean and renewable energy to the earth [1]. Specifically, the most advantage region that located near by the equatorial line like as Thailand. This region is employed a solar irradiance of 5 kW/m^2 per day. The solar energy from the sun can be converted to electricity, for instance, via solar thermal power plants. These power plants need the heat from a high concentrate collector. There are many types of solar thermal power plants such as solar power towers, solar dish/ sterling system and parabolic trough power plants.

For the parabolic trough power plants, they need to use trough with a parabolic shape to collect and reflect the sun beam onto the tube with a line focus pattern. The tube contains the work fluid inside for a heat collecting and transferring to push a turbine at the temperature between 200 ^{o}C and 400 ^{o}C. However, the serious problem of using solar thermal power plants is due to the fluctuation of the sun intensity which caused by the moving of the sun , the changing of the season, the changing of weather etc [2-5]. These reasons affect to the continuous running of solar thermal power plants. To solve the problem, we do need to use the back up energy such as the energy from natural gas. Otherwise, we have to use the thermal energy storage system [6].

---

* Corresponding authors; e-mail: tpisate@hotmail.com, Tel.: +660868738604

The parabolic trough power plants using synthetic oil as the heat transfer medium, the application of solid media sensible heat storage is an attractive option regarding investment and maintenance costs. Cost effective systems demand the utilization of inexpensive storage materials, which usually exhibit a low thermal conductivity. Essential for the successful development of a storage system is the sufficient heat transfer between the synthetic oil and the storage material [7-8].

In some concepts using the sensible heat of solid media for thermal storage, the storage material contains a tube register heat exchanger to transfer the thermal energy to or from the heat transfer fluid. The feasibility of such systems has already been proven in laboratory scale [9]. Since the storage of thermal energy is not identical with the storage of energy, the design of such a system demands the analysis of the complete power plant [10].

The thermal energy storage system will substitute the use of energy from fossil fuels. The conventional storage system is used liquid for a heat transferring purpose. However, the liquid is changed a phase at a high temperature which follow by a pressure change [11]. So my research is focused on a simple system by using solid: NaCl as a medium for a transferring. NaCl has a high specific heat capacity, cheap price and unchanged the phase. NaCl is used to be a sensible storage in terms of solid at temperature between 100-200 °C and 300-200 °C for the 10 kW solar thermal power plants.

MATERIALS AND METHODS

1. Heat Transfer in the Storage System

1.1 Storage Equation

The storage system is the sensible heat in solid storage. Assuming that the storage tank has a uniform temperature and the energy balance on the storage tank gives

$$(MC_{ps})\frac{dT_s}{dt} = Q_c - Q_L - (UA)_s(T_s - T_a) \quad (1)$$

From equation (1); if the cumulative heat energy in the storage tank is not constant so we can re-write into the new equation as;

$$T_{s+1} = T_s + \frac{\Delta t}{(MC_p)_s}\left[\dot{Q}_c - \dot{Q}_L - (UA)_s(T_s - T_a)\right] \quad (2)$$

Where M : the medium mass in storage tank, $\dot{Q}_c$: heat rate the tube from collector, $\dot{Q}_L$: heat rate to the load, U : total heat exchange coefficient (W/m^2K), T_s : temperature of storage tank, T_a : temperature of surrounding, A : surface area of storage tank, T_{s+1} : the final temperature of storage tank , the initial temperature of storage tank, C_p : specific heat capacity of medium $(J/kg \cdot K)$ and Δt time of heat accumulation (s), respectively.

1.2 Heat Transfer fluid

After the heat collecting of the fluid in the pipe, the heat of fluid can be determined from

$$\dot{Q} = (\dot{m}C_{ps})_c(T_{c,o} - T_{c,i}) \quad (3)$$

Where : $\dot{m}$ mass rate of fluid (kg/s), C_p : specific heat capacity of fluid $(J/kg \cdot K)$ and $(T_{c,o} - T_{c,i})$: temperature difference between the inner and outer fluid (K). The transferring heat from the heater HTF to NaCl can be calculated from this formula as;

$$q_s = \frac{A(T_b - T_s)}{\frac{1}{\bar{h}} + \frac{r_1 \ln(r_2/r_1)}{k}} \quad (4)$$

Where q_s : heat energy (J), T_b : tube temperature (K), T_s is medium temperature (K), $\bar{h}$: convective coefficient, k : thermal conductivity, r_1 : tube radius (m) and r_2 : storage tank radius (m) respectively.

1.3 Mathematical model charging and discharging

The total amount of heat transfer between the HTF to storage medium was calculated based on the mass flow rate $\dot{m}$, the specific heat of the processing fluid, C_p and the difference in inlet and outlet temperature of non steady state heat exchanger as given by

$$\dot{m}C_p(T_{mi} - T_{mo}) = \bar{h}A(T_b - T_s) = q_sA \quad (5)$$

The heat balance from the convection of the HTF to the storage medium is used to calculate the outlet HTF temperature from the pipe by

$$\dot{m}C_{pl}(T_{mi}-T_{mo}) = \frac{A(T_b-T_s)}{\frac{1}{h}+\frac{r_1\ln(r_2/r_1)}{k}} \qquad (6)$$

The inlet temperature of HTF is changed when it flows out of the pipe and is heated by a heater for the next round of charging experiment, HTF temperature is increased and flowed back to the pipe again after heated by the heater, the inlet HTF temperature is given by equation (7)

$$T_{mi} = T_{mo}^{old} + \frac{\dot{Q}_c}{\dot{m}C_p} \qquad (7)$$

Where $\dot{Q}_c$ is the charging thermal energy rate by heater, (kW). T_{mi} is the inlet temperature of heated HTF,(K).

The outlet HTF temperature after HTF transfer heat to the pipe and the storage medium is decreased from the calculation that depends on the storage temperature, flow rate of HTF, heat capacity, and the mathematical model will be explained as in the equation (8).

$$T_{mo}^{1} = \frac{T_s + \frac{\dot{m}C_{pl}}{A}\left[\left(\frac{1}{h}+\frac{r_1\ln(r_2/r_1)}{k}\right)-\frac{1}{2}\right]T_{mi}}{\left[\frac{\dot{m}C_{pl}}{A}\left(\frac{1}{h}+\frac{r_1\ln(r_2/r_1)}{k}+\frac{1}{2}\right)\right]} \qquad (8)$$

However, the outlet HTF temperature can also be calculated by equation (8) in the case of storage system, $T_{co} = T_{mi}$ and $T_{ci} = T_{mo}$. The outlet temperature is given as

$$T_{mo} = T_{mi}e^{\frac{UA}{\dot{m}C_{pl}}} + \left(1-e^{\frac{UA}{\dot{m}C_{pl}}}\right)T_s \qquad (9)$$

In the charging, the thermal energy which transferred from HTF***3.1***was added to the storage medium and lost to the ambient. In contrast, the discharge storage equation would change to subtract thermal energy from the storage temperature and again loss to the ambient as written in Eq. (10)

$$T_s = T_a + \left[\left(T_s^{old} \pm \frac{q_sA}{MC_{ps}}\right)-T_a\right]\exp\left[-\frac{(UA)}{(MC_{ps})}t\right] \qquad (10)$$

2. Experiment Setup

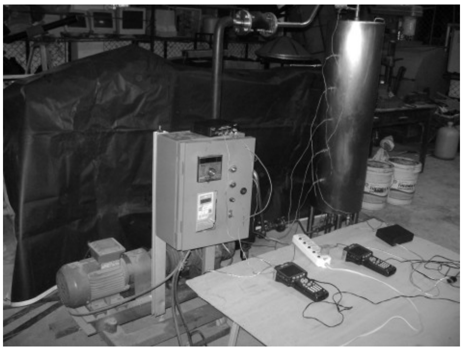


Fig. 1. The model of experimental set up

A two co-axial cylindrical storage tank was used to house the charging and discharging pipe. The inner tank has a diameter and height of 32 cm and 110.5 m, respectively. The storage tank stranded vertically in ambient air during the experiment and the storage temperature was reduced from heat loss to the air through the insulator.

The vertical charging straight pipe was made of stainless steel of 95 cm length, 1.27 cm diameter and 0.1 cm thickness. The fluid was pumped through the pipe using a positive displacement pump connected to a variable speed motor. The speed of motor was adjusted to obtain the flow rates of 0.1, 0.2 and 0.3 kg/s . These correspond to laminar and turbulent flow regimes that depend on the HTF viscosity from the Reynolds numbers. The purpose of using different flow rates was to observe the rate of heat transfer from HTF to storage medium. Thermal oil (from Shell Company) at an average room temperature (30 °C) was used as the inlet HTF and flowed from the inner tank that was being constantly recharged at 3 kW by an electric heater outside the tank.

3. Material property

The NaCl storage medium has 2160 kg/m^3 density, 0.85×10^3 $J/kg\cdot K$-specific heat capacity and 7 $W/m\cdot K$-thermal conductivity of NaCl.

The HTF for the charging-discharging study for this research is the synthetic oil of 714.11 kg/m^3-density, 2715.425 $J/kg\cdot K$-specific heat capacity. 6.1×10^{-4} m^2/s-kinematics viscosity and 8.54×10^{-7} m^2/s-dynamic viscosity.

4. Experimental and Calculation

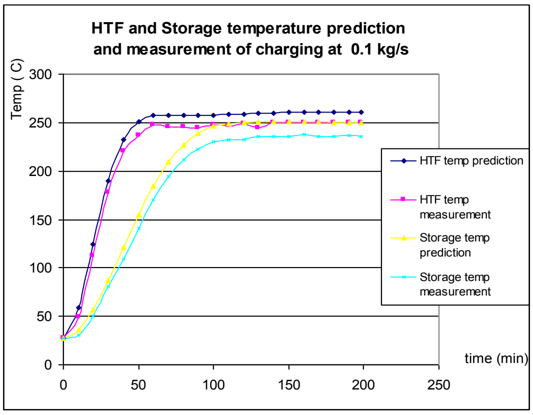
For charging process, HTF brings heat from heater 3 kW to the storage tank. The pump is used to circulate HTF in the system. For the discharging experiment, thermal oil was used as HTF for drawing the heat from the storage tank to the load of 1 kW . The load was made by a boiler vessel that was filled with water of 14.3 kg for absorbing heat from the discharging pipe to raise the average temperature of 1 °C in a minute. The storage temperature decreased from 250 °C with thermal loss to ambient during the time HTF flowed through the pipe that was submersed in the storage tank. The HTF temperature increased for around 50 min and went down to 100 °C a minimum temperature of load.

RESULTS AND DISCUSSION

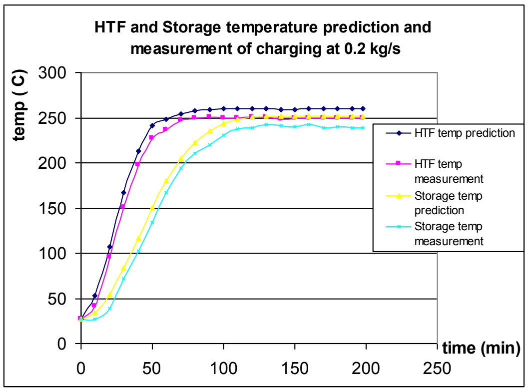
The experiments were classified in charging and discharging then the results were compared with for determine the validation of model and experiment.

1. Charging

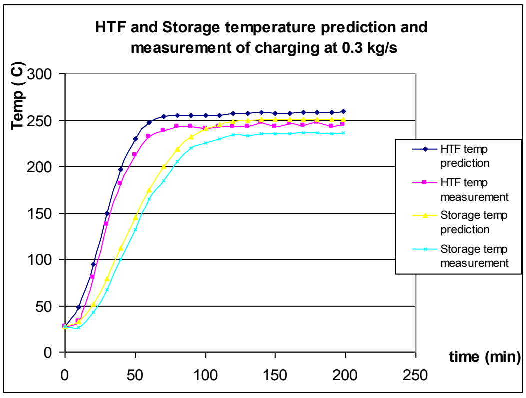
The HTF at 30 °C is flow pass the heater through the tube at the rates of 0.1, 0.2 and 0.3 kg/s , then the heat was transferred to NaCl media in the storage tank the temperature of all the temperate to 250 °C.



(a)



(b)



(c)

Fig. 2. Temperature predictions and experimental data of charging with power of 3 kW at; (a) the flow rate of 0.1 kg/s (b) the flow rate of 0.2 kg/s and (c) the flow rate of 0.3 kg/s

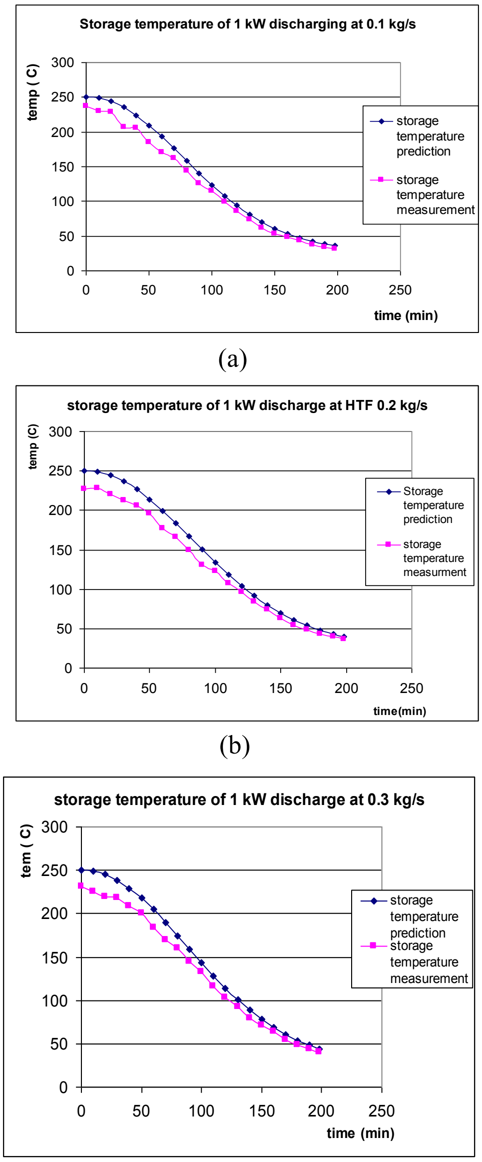
In the Fig. 2, HTF from 30°C were heated to 250 °C in 120, 130, and 140 minute respectively, with the error of 7.6% minute.

The increasing HTF temperature was influenced by its flow rate as shown in Fig. 2(a) (b) and (c). These results showed that heat transfer from the HTF was depend on the flow rate, since the HTF temperature was risen rapidly from the influence of low flow rate.

The storage temperature of charging experiment from the model prediction and measurement were validated within 10% of accuracy, as shown in Fig. 2(a), (b) and (c).

2. Discharging

The discharging experiment started from 250 °C to 100 °C by HTF flow rate of 0.1 0.2 and 0.3 kg/s . The discharge model of the HTF temperature was started with the initial temperature of 30 °C, the average room temperature, increased to 166 °C and down to 100 °C while the storage temperature decreased from 250 °C to 100 °C as shown in Fig. 3.



(a)

(b)

(c)

Fig. 3. Discharging predictions of storage temperature at 1 kW with HTF (a) the flow rate of 0.1 kg/s. (b) the flow rate of 0.2 kg/s. and (c) the flow rate of 0.3 kg/s

The HTF from NaCl media in the storage tank at the flow rate of 0.3 kg/s were lied from 250 °C to 100 °C in 110 , 120, and 130 minute, with the error of 9.3 % that valid with mathematical model, as shown in Fig. 3 (a), (b) and (c).

CONCLUSION

This paper was explained the determination of thermal storage system with NaCl media in the temperature performance compared by mathematical model of changing and discharging. The HTF of synthetic oil was used to transfer heat from 3 kW source to NaCl media in charging process and in opposite direction for discharging to load of 14.3 kg of water.

A mathematical model was developed to examine the result between prediction and experimental results. There were founded the both result valid with the error of for charging and for discharging.

Finally, this idea of research could be used for designing of thermal energy storage 10 kW parabolic trough power plants and enlarge the model to the various size of solar thermal power plant.

REFERENCES

[1] Neumann, A., Renewable Energy,Springer Berlin Heidelberg ,2006, pp 246 - 279 .

[2] Horst. M and Pitz-Paal, Robert. Cascaded latent heat storage for parabolic trough solar power plants

[3] Ibrahim, D and Sadik, D. A perspective on thermal energy storage systems for solar energy applications. International Journal of Energy Research, 20,1996,pp 547-557.

[4] Ismail, K.A.R and Goncalves ,M.M. Thermal performance of a pcm storage unit,_Energy Conversion & Management, 40,1999,pp. 115-138.

[5] Pilkington Solar ,InternationalStatusReport on Solar Thermal Power plants,:Report ISBN 3-9804901-0-6.1996.

[6] Vaivudh, S. System design of high thermal energy storage for solar thermal power plants,Naresuan University. 2006

[7] Herrmann,U., and David, W. K. Survey of Thermal Eergy Storage for Parabolic Trough Power Plants, Journal of Solar Energy Engineering,124, 2002.

[8] Tamme, R., Laing, D., Steinmann, W –D. Advance Thermal Energy Storage Technology For Parabolic Trough , (Proceeding of ISEC, 2003

[9] Soteris A. Kalogirou. Solar thermal collectors and applications Progress in Energy and Combustion: Science 30,2004,pp 231–295.

[10] Hamdan ,M.A. and Elwerr, F.A.Thermal energy storage unit using a phase change material, Solar Energy ,56(2), 1996, pp. 183 – 189.

[11] Herrmann, U., Kelly, B., and Price, H.Two-tank molten salt storage for parabolic trough solar power plants ,(DTD)4.3.1/Energy1121.