Heat Transfer of Charging and Discharging Experiment of High Thermal Energy Storage System by Thermal Oil as Heat Transfer Fluid

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ABSTRACT

The thermal energy storage (TES) of solar power plant was presented by small scale experiment for testing the mathematical model. Charging performance of heat transfer fluid (HTF) was investigated at various flow rates. The heat transfer rate was rapidly risen HTF temperature that obtained by low flow rate. The discharging experiment was set by HTF from room temperature to discharge temperature. It shows the starting discharge temperature at turning point. HTF and storage temperature are parallel decreased in the experiment. The calculation was validated with the measurement in charging experiment from room temperature to maximum HTF temperature.

Keywords: *High thermal energy storage, Heat transfer fluid, Charge, discharge.*

1. INTRODUCTION

Solar energy is the most abundant energy source compared with other energy, and unlimited supply clean energy. Solar energy can be transferred to thermal energy by a collector and send to the equipment by heat transfer fluid (HTF). The most important application of solar energy is to transfer its thermal energy and to electricity. Solar thermal power plant is one of the available applications of solar energy that its energy source depends on time, weather condition, and electricity demand. Solar energy source of solar power plants is needed to be stored for smooth electric generation. The thermal storage system of the solar thermal power plant is necessary for the power plant stability and reducing rate of mismatch between energy demand and supply. The HTF is used in solar storage system to charge and discharge thermal energy to a storage medium in the storage tank. The storage medium is the material which is used to keep the heat from HTF. Thermal energy is usually collected by a concentrating collector and transferred to a thermal storage by HTF, and then transferred to steam and an electric generator by the storage medium. For the active thermal energy storage in a direct system, HTF collects the solar heat and serves also as a storage medium with high temperature performance.

Parabolic trough power plant is one of the lowest cost of solar electric power options available today and has significant potential for further cost reduction. A parabolic trough system consists of trough shaped mirrors that can focus the sun's ray onto a pipe lying along the focus line. The circulating fluid within the pipe is the selected HTF. Solar energy heats HTF, and then it circulates through the trough collecting field to heat exchangers and storage media.[1] Parabolic trough power plants have long runs of exposed receiver tubes that cannot be easily drained. There are two key challenges to meet the generation of HTF and storage fluid for trough plants. The first is raising the operating temperature above 250^{o}C. The second is developing fluid that will function as both HTF and thermal storage medium. The thermal energy storage system for parabolic trough power plant can be classified to sensible heat and latent heat storage system. In this paper, the sensible heat storage with heat exchanger is presented, and includes the mechanism of charging and discharging heat for keeping high thermal energy.[2]

2. MATHEMATICAL MODEL OF CHARGING AND DISCHARGING

The total amount of heat transferred, $\dot{Q}$, was calculated based on the mass flow rate, $\dot{m}$ the specific heat processing fluid, C_p, and the different in inlet and outlet temperatures (T_{mi}-T_{mo}) in a pipe is given by [3]

$$\dot{Q}_c = \left(\dot{m} C_p\right)_c \left(T_{mi} - T_{mo}\right) \quad (1)$$

The heat transfer by the HTF flow in a pipe must be characterized by turbulent or laminar flow conditions. Accordingly, the simulation evaluates the Reynolds Number of the fluid, *Re* for turbulent flow to calculate the Nusselt Number of the fluid, *Nu*. The Heat Transfer Coefficient to the fluid, *h* is then evaluated by equation.

$$Nu = hD/k \quad (2)$$

where *D* is represented the diameter length of the pipe and *k* is the thermal conductivity of HTF. For a circular tube, length *L,* is subjected to constant surface temperature. The average Nusselt number for the thermal entrance region can be determined from Nusselt recommend, for 10<(*L/D*)<400

$$Nu = 0.036Re^{0.8}Pr^{1/3}(D/L)^{0.055} \quad (3)$$

When the HTF flows inside tubes as fully developed turbulent, the Petukhov equation was suggested to be used follow with the accuracy of turbulent flow in the tubes at lower Reynold number (2300 < *Re* <5x10^6)[4]

$$Nu = \frac{(f/8)(Re)Pr}{1.07 + 12.7\sqrt{f/8}\left(Pr^{2/3} - 1\right)}\left(\frac{\mu}{\mu_w}\right)^n \quad (4)$$

where n = 0.11 for heating and 0.25 for cooling, μ and μ_w are oil viscosity at bulk temperature, and tube wall temperature respectively and the Darcy friction factor, f for smooth pipes is given by

$$f = (0.790 \ln Re - 1.64)^{-2} \quad \text{and} \quad h = \frac{Nuk}{D} \quad (5)$$

The HTF temperature outlet shows the amount of the thermal energy transfer to storage medium which is calculated by the energy balance

$$\left(\dot{m} C_p\right)_c \left(T_{mi} - T_{mo}\right) = UA\,(T_b - T_s) \quad (6)$$

where T_b is the bulk temperature (average value of T_{mi} and T_{mo}). This equation leads to determine the outlet temperature as shown in equation (7)

$$T_{mo} = \frac{T_s + \left[\frac{\dot{m}C_p}{A}\left(\frac{1}{h_x} + \frac{1}{h_\infty}\right) - \frac{1}{2}\right]T_{m,i}}{\left[\frac{\dot{m}C_p}{A}\left(\frac{1}{h_x} + \frac{1}{h_\infty}\right) + \frac{1}{2}\right]} \tag{7}$$

It has been found that an average free convection heat transfer coefficients can be represented in the following functional form for a variety of circumstances

$$Nu = C(Gr_L Pr)^n \tag{8}$$

A comparison by Warner and Arpaci of the relation with experimental data indicates both sets of constants fit available data. There are some indications from the analytical work of Bayley [5] that the relation may be preferable.

$$Nu = 0.10(Gr_L\ Pr)^{1/3} = \frac{h_\infty D}{k} \tag{9}$$

The storage temperature is assumed as a well mixed storage and its temperature increases may calculate from the energy balance equation. The overall heat transfer coefficient of the circular tube is given from [6]

$$T_s = \frac{T_{mo} - T_{mi}\, e^{-\frac{UA}{\dot{m}C_p}}}{1 - e^{-\frac{UA}{\dot{m}C_p}}} \tag{10}$$

The thermal energy loss by the ambient air of which it has the average temperature (about 29^{o}C), is calculated from the equation (11)

for charging $$T_s = T_a + \left[\left(T_s^{old} + \frac{q_s A}{Mc_p}\right) - T_a\right] e^{-\left(\frac{UA}{M c_p}\right)}$$

for discharging $$T_s = T_a + \left[\left(T_s^{old} - \frac{q_s A}{Mc_p}\right) - T_a\right] e^{-\left(\frac{UA}{M c_p}\right)} \tag{11}$$

3. EXPERIMENTAL SETUP

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 0.22 m and 0.88 m, respectively. The micro fiber insulator of the tank was filled between two tanks in order to decrease heat loss from the inner tank, a tank of storage fluid. The insulation layer thickness is 20.32 cm wrapped the inner tank. The outer tank with diameter and height of 0.63 m and 128.60 cm respectively is used to keep the inside insulator. The tank stands vertically at ambient temperature.

The vertical charging straight pipe was made of stainless steel of 0.8 m 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 0.20, 0.30, and 0.4 l/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 (29^{o}C) was used as the inlet fluid and came from the inner tank reservoir that was being constantly recharged at 3 kW by an electric heater.

The 30 l of thermal oil was filled in the tank for storing heat. This oil was assumed to be well mixed storage medium. For testing calculation, the oil use as HTF and storage medium are the same fluids. The 2 K-type thermocouples are used to measure the inlet and outlet HTF temperatures. The storage temperature was measured by type K thermocouple and extension wire was attached to the inner tank through the outer tank surface which was mounted with a thermocouple recorder.

4. RESULTS AND PREDICTON

Storage and outlet HTF temperatures are presented for comparing the temperatures between bulk HTF temperature and mixed storage temperature of charging experiment in Fig. 1. The charging characteristic of Shell Thermia oil, as HTF, which thermal energy rate 3 kW at flow rate 0.1 kg/s is shown in Fig. 1. The storage medium is also used thermal oil, as the same as HTF. The results of HTF temperature and storage temperature measurement show that HTF temperature increases rapidly in the first two hours while the storage temperature is slightly increases. The HTF oil has the maximum operating temperature at 340^{o}C. However, in this experiment, the control switch is used to cut off the heater at 340^{o}C before the maximum after two hours, the HTF temperature was set to constant at high temperature as its maximum, decomposition point. The storage temperature still increases continually to the maximum storage temperature, 300˚C for 73 hours. For this result, a small scale characteristic of a high temperature storage tank can be applied for enlarging the storage tank to the large scale, real thermal power plants. However, the mathematical calculation method can be applied to those of real high thermal energy storage.

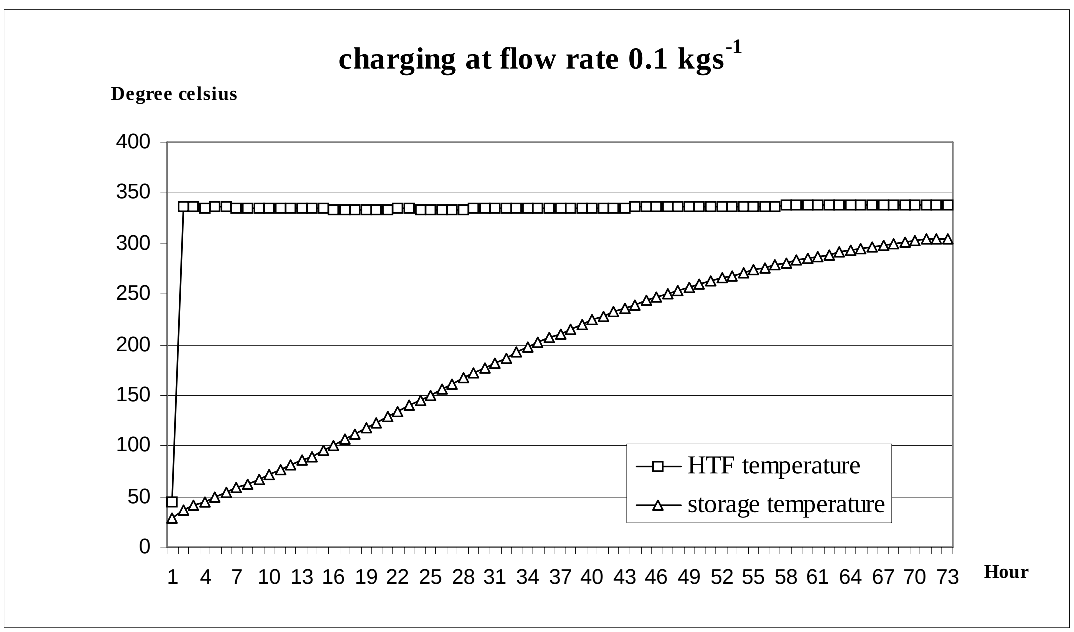
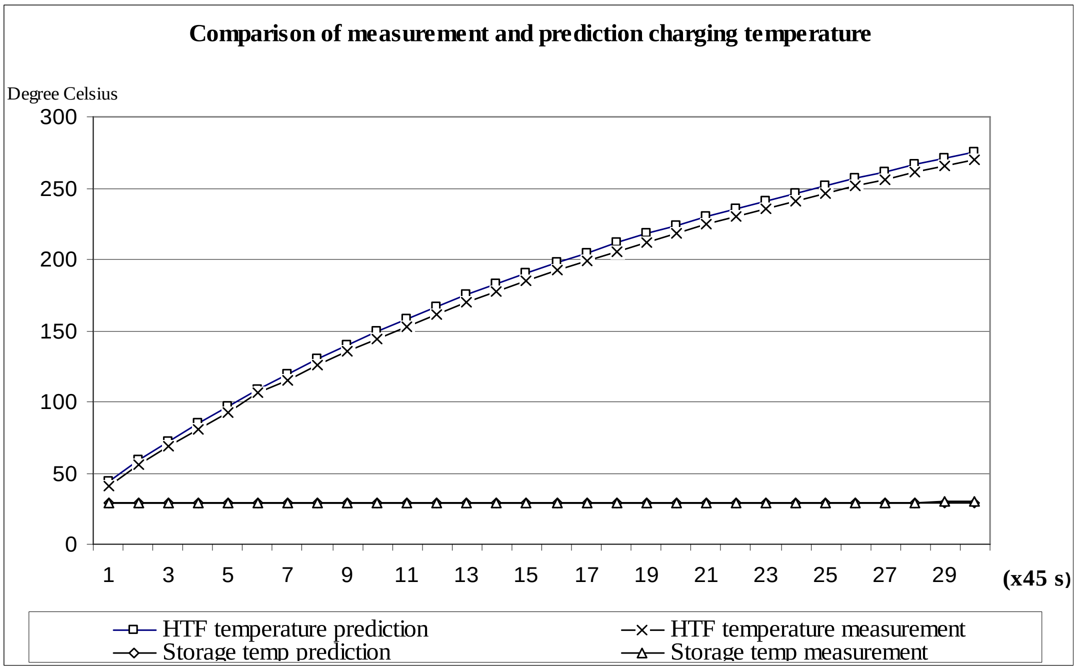


Fig. 1 Temperature of HTF and storage medium in charging experiment

The prediction of mathematical model of storage tank was shown compared with the experiment, about 22 minutes (45 s for each round). Fig. 2 shows an agreement of measurement and calculation especially in storage temperatures. Both results are quite no difference in term of charging temperature.



The increasing storage temperature is influenced by HTF flow rate as shown in Fig. 3. Three HTF flow rates, 0.2, 0.3 and 0.4 kg/s, are used to compare the results of HTF increasing temperature with charging rate of 3 kW. The HTF temperature reaches to 340°C for 1.3 hour with a low flow rate of 0.2 kg/s. This result shows that the heat transfer from the HTF is influenced by its flow rate. The flow rate decreased as the heat transfer increased.

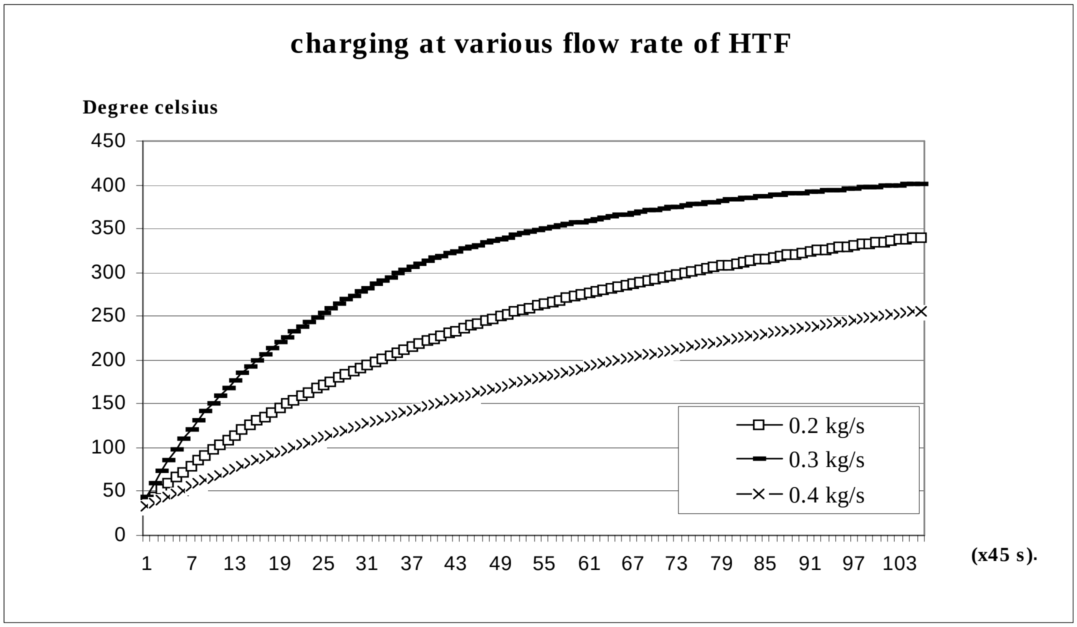


Fig. 3 Temperature profile at various HTF flow rate during charging mode

For discharging experiment, thermal oil was used as HTF for drawing the heat from the storage tank to the load of 1 kW. This load power was adjusted for a long period of discharge. The storage temperature start at 300°C with thermal loss to ambient as HTF flows through the pipe submersed in the storage tank. The extracted heat from the storage tank is affected on its increasing the temperature. The HTF and storage temperatures are parallel decreased after the HTF temperatures reach the turning point, the beginning HTF temperature for discharging from storage medium to the load. The period of discharge is 19.7 hours. The initial temperature of HTF (average room temperature at 29°C), as shown in Fig. 4, is increased to 270°C, a turning point, and then decreased to 100°C, the final point of discharge.

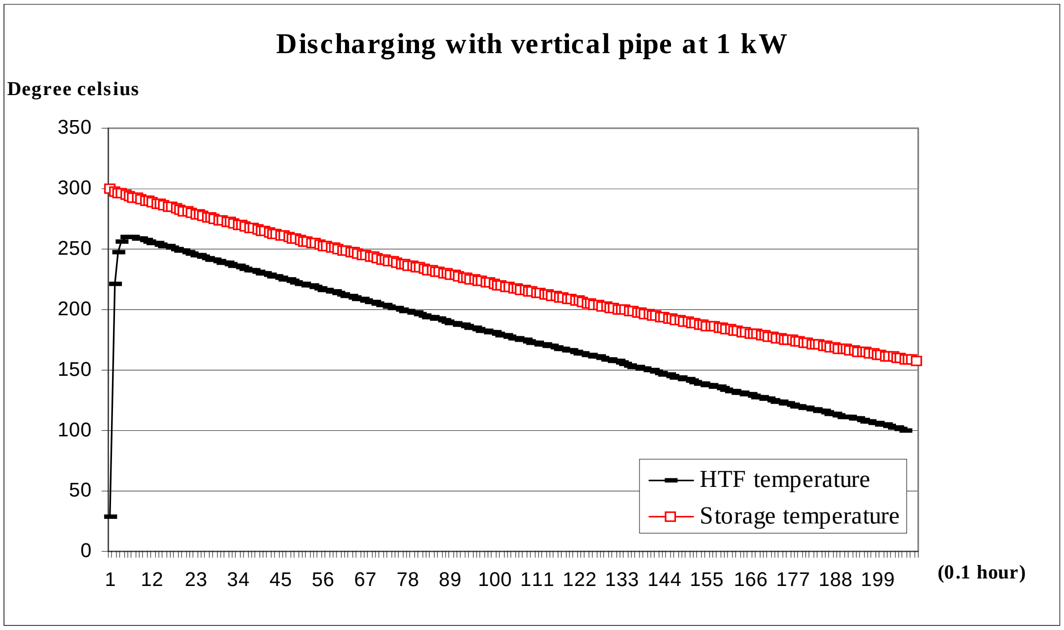


Fig. 4 Storage discharging and both fluid temperatures decreasing with the flow rate of 0.1 kg/s

5. CONCLUSIONS

The solar high thermal energy storage was presented in charging and discharging experiments. In charging experiment, the increasing storage temperature depends on HTF temperature, flow rate, and initial temperature. The high heat transfer rate to storage medium caused by a small flow rate, but the storage temperature was closely increasing with the same temperature of other flow rates. The design of thermal storage from this conclusion that the thermal storage with heat exchanger, appropriate HTF, motor pump for a slow charge, and the preheating for HTF discharge is used before discharge to heat HTF to turning point for rapid discharge process.

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