Indian Institute Of Technology, Kanpur

Departement:-Sustainable Energy Engineering

Lab Manual For Experiment

“Thermal Energy Storage System”

OBJECTIVE:

To determine the thermal energy storage capacity and efficiency of the paraffin wax.

WHAT WILL YOU LEARN FROM EXPERIMENT:

1. To learn about thermal energy storage .
2. To estimate Overall efficiency of thermal energy storage system.
3. To estimate Charging , Storing and Discharging period efficiency of PCM material.
4. Effect of variable mass flow rate on discharging period of thermal energy storage system

SAFETY PROCEDURES FOR THIS EXPERIMENT:

DO's:

1. Switch on the heaters only after ensuring that the tank is completely filledd
2. Check level of water in the bottom tanks before draining in or out from them
3. Valve position are critical so ensure their position before and after every experiments
4. Very high current flows into the system so make sure that all connections are properly
5. Before performing any experiments ensure that the surface temperature probe is with right pcm cylinder

DON'Ts

1. Don't switch on the heater(s) during the observation period
2. Don't hold any pipe with bare hands
3. Don't run the pump in dry condition
4. Don't open any valves without taking utmost care
5. Don't pour water over the control unit

EXPERIMENTAL OVERVIEW:

Thermal energy storage experiment consist of 3 process

1. Charging Period: Here PCM's material is charged with the thermal energy of the heat transfer fluid.
2. Storing Period: in this process energy which was supplied to PCM's material during charging period is stored for later use.
3. Discharging Period: stored thermal energy is abstracted from PCM's material for required purpose

Fig: Hot water tank of thermal energy storage system

Fig: Paraffin wax cylinder of thermal energy storage

Fig: Values of thermal energy storage system

Fig: Temperature sensor of thermal energy storage system

Fig: Chiller of thermal energy storage

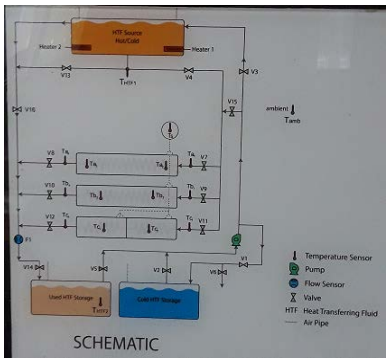

Fig: Schematic of thermal energy storage

EXPERIMENTAL PROCEDURE:

A) CHARGING PERIOD

A.1) Methodology :

1. Open valves 6 and fill the cold HTF storage tank fully.
2. Open valves 2 and 3 and fill the HTF hot / cold source tank by switching On the pump.
3. When water overflows the HTF hot/cold source tank and water start come back to the used HTF storage tank switch off the pump and closed all valves.
4. Switch on the electric heaters
5. Observed the water temperature continuously on temperature meter
6. When water in the HTF hot/cold source tank reached the required temperature switch off the heaters
7. Note all reading corresponding to temperature sensors Ts, Tb1, Tb2, Tb3, Tb4 and Ta.
8. Open valves 4,9 and 10 to flow the hot water through the heat exchanger
9. Adjust the flow rate by adjusting the valve number 10. Keep adjusting at regular interval.
10. Note the temperature reading corresponding to temperature sensors T1, Tb1, Tb4, Tb2, Tb3, Ta in a step of minutes.
11. Continue the above process till the average temperature of PCM reached melting temperature of PCM.
12. Once the above condition is achieved stop the charging stage by closing valve number's 4, 9 and 10.
13. On completing the charging process open valve number 13, 14 and empty the HTF hot/ cold source tank completely.

14. To bring the HTF hot/cold source tank to normal temperature wash it internally by cold water with the help of the pump.

Table 1: Observed values during charging period:

s.no.	Time (min)	Water temp. of HTF source tank (Thtf1) (°C)	Ambient Temp. (Ta) (°C)	Cylinder Surface Temp. (Ts) (°C)	Inlet Temp. Of HTF during inlet(Tb1) (°C)	Outlet Temp. Of HTF During Outlet (Tb4) (°C)	PCM Front End Temp. (Tb2) (°C)	PCM Rear End Temp. (Tb3) (°C)	Flow Rate Of HTF (kg/sec)
1									
2									
3									

A.2) CALCULATION OF CHARGING PERIOD:

On completing the charging stage we can calculate the following aspects

1. Calculate rate of heat transfer from the cylinder by using equation (1) through (11)
2. Calculate energy input to the TES system during charging period by using equation (12)
3. Calculate energy accumulated in the TES system during charging period by using equation (13)
4. Evaluate the system thermal efficiency during charging period by using equation (16)

Table 2: Calculated values during charging period of Paraffin wax:

s.no	Time (min)	Average temp. of PCM During charging ((Tb2+Tb3)/2) (°C)	Energy Loss from System (J)	Energy input To the System (J)	Energy accumulated In the System (J)	System Thermal Efficiency During Charging (Ƞ)
1						
2						
3						
4						

A.3) RESULT OF CHARGING PERIOD:

1. Draw graph of PCM temperature Vs TIME during the charging period

2. Draw graph of inlet and outlet temperature Vs TIME during charging period

B) STORING PERIOD:

Table 3: Observed values during energy storing period

S.No	Time (min)	Ambient temp. (°C)	PCM front end temp (°C)	PCM rear end temp (°C)
1				
2				
3				
4				

B.1) CALCULATIONS DURING STORING PERIOD:

1. Calculate TES during storing by using equation (17)
2. Calculate storing period efficiency by using equation (19)

Table 4: Calculated values for paraffin wax during energy storing period

S.no	TIME (min)	Energy loss from the system during storing period(J)	Energy stored in the system during storing period(J)	System thermal efficiency during storing period(J)
1				
2				
3				
4				

B.2) RESULT OF STORING PERIOD:

1. Draw graph of PCM temperature Vs TIME during the storing period
2. Draw graph of ENERGY LOSS Vs TIME during storing period
3. Draw graph of EFFICIENCY Vs TIME during storing period

C) DISCHARGING PERIOD:

C.1)Methodology :

1. Preset the duration between charging and discharging
2. To start the discharging process, open valve numbers 2 and 3 and fill the HTF hot/cold source tank fully with the help of the pump
3. When water overflows the HTF hot/cold source tank switch off the pump and close all valves
4. Open valve numbers 5, 1 and 6; empty the used HTF storage tank by switching the pump on.
5. In choosing one of the above two options the user will have to decide the frequency experiments
6. Note all readings corresponding to temperature sensors Ts, Tb1, Tb2, Tb3, Tb4 and Ta.
7. Open valve numbers 4, 9 & 10 to flow through cylinder containing PCM-2
8. Adjust the flow rate by adjusting valve number 12
9. Note the temperature reading continuously corresponding to temperature sensors
10. Continue the above process till the PCM's temperature become equal to the inlet water temperature (almost)
11. To finish the discharging stage close valve numbers 4, 9 and 10
12. On completing the discharging process open valve number 13,14 and empty the HTF hot/cold source tank completely

OBSERVATION DURING DISCHARGING PERIOD OF PCM-2:

Table 5: Observed values during discharging period of Paraffin wax

s.no.	Time (min)	Water temp. of HTF source tank (Thtf1) (°C)	Ambient Temp. (Ta)(°C)	Cylinder Surface Temp. (Ts)(°C)	Inlet Temp. Of HTF during inlet (Tb1) (°C)	Outlet Temp. Of HTF During Outlet (Tb4) (°C)	PCM Front End Temp. (Tb2) (°C)	PCM Rear End Temp. (Tb3) (°C)	Flow Rate Of HTF (kg/sec)
1									
2									
3									

C.2) CALCULATIONS :

On completing the discharging stage the user can calculate/ observe the following aspects :

1. Calculate the Energy recovered from TES during discharging period by using equation (20)

2. Calculate amount of energy available to discharge by using equation (21)
3. Evaluate the system thermal efficiency during
4. discharging of the system by using equation (23)
5. Calculate the overall system efficiency (24)
6. Calculate the value of FOM by using equation (25)

Table 6: Calculated values during discharging of Paraffin wax:

S.No	Time (min)	Energy loss from the system (J)	Energy available to recover from the system(J)	Energy recovered from the TES during discharging(J)	System thermal efficiency during discharging period(J)
1					
2					
3					
4					
5					

C.3) RESULT OF DISCHARGING PERIOD:

1. Draw graph of PCM temperature Vs TIME during the discharging period
2. Draw graph of inlet and outlet temperature of HTF Vs TIME during discharging period
3. Draw graph of EFFICIENCY Vs TIME during discharging period

QUESTIONS TO CONSIDER:

1. How flow rate will effect charging and discharging heat transfer rate?
2. What will be effect on system overall efficiency if cold flow rate of heat transfer fluid is altered?
3. Why efficiency of thermal energy storage is low?

APPENDIX:

A). CHARGING, STORING AND DISCHARGING EFFICIENCY OF PCMS:-

The basic understanding involve in analysing the system are as follows:

During charging period,

Energy Stored = Energy Input - Energy Loss

Charging Efficiency = $\frac{\text{Energy Stored}}{\text{Energy Input}}$

During storing period,

Energy Retained = (Energy Stored -Energy Loss)

Storing Efficiency = $\frac{\text{Energy Retained}}{\text{Energy Stored}}$

During discharging period

Energy Recovered = (Available Energy – Remaining Energy -Energy Loss)

Discharging Efficiency = $\frac{\text{Energy Recovered}}{\text{Available Energy}}$

B). EQUATIONS REQUIRED TO ANALYZE THE SYSTEM:

B.1) CHARGING PERIOD

Analysis of Heat Exchanger

The rate of heat transfer for the HTF per unit length of the cylinder can be expressed as

$$\dot{q}_{1,j} = \frac{T_{av,HTF,ch,j} - T_a}{R_1} \quad (1)$$

Where,

$T_{av,HTF,ch,j}$: Average HTF temperature during charging (°C)

T_a: Ambient air temperature (°C)

R1: Total thermal resistance of the PCM cylinder through which The HTF flows

$$R_1 = \frac{1}{h_i A_i} + \frac{\ln\left(\frac{r_2}{r_1}\right)}{2\pi k_1 L_1} + \frac{\ln\left(\frac{r_3}{r_2}\right)}{2\pi k_2 L_2} + \frac{\ln\left(\frac{r_4}{r_3}\right)}{2\pi k_3 L_3} + \frac{\ln\left(\frac{r_5}{r_4}\right)}{2\pi k_4 L_4} + \frac{\ln\left(\frac{r_6}{r_5}\right)}{2\pi k_5 L_5} + \frac{1}{h_0 A_0} \quad (2)$$

Here,

r, k and l : represents radius, conductivity and length of different layers used in the PCM cylinders .

A_i and A_o: surface area of the copper tube (inner) and cylinder (outer) respectively

h_i and h_o : inner and outer convective heat transfer coefficients and can be calculated as follows

Inner Radius of Copper Tube (r1) =0.00545 m

Outer radius of copper tube (r2) = 0.00635 m

Inner radius of PCM cylinder (r2) = 0.00635 m

Outer radius of PCM cylinder (r3) = 0.085 m

Inner radius of SS pipe (r3) = 0.085 m

Outer radius of SS pipe (r4) = 0.087 m
inner radius of insulation (r4) = 0.087 m
outer radius of insulation (r5) = 0.12 m
inner radius of GI cover (r5) =0.12 m
outer radius of GI cover (r6) = 0.1229 m
L1 = Length of copper tube = 2.1 m
L2 = Length of PCM cylinder = 0.34 m
L3 = Length of SS pipe = 0.34 m
L4 = Length of insulation = 0.34 m
L5 = Length of GI cover = 0.34 m
k1 = conductivity of copper tube = 390 W/mK
k2 = conductivity of PCM = 0.22 W/mK
k3 = conductivity of SS pipe= 16 W/mK
k4 = conductivity of insulation = 0.033W/mK
k5 = conductivity of GI cover = 16 W/mK

Calculation of h_i

Following is the basic equation to calculate h_i

$$h_i = \frac{N_U \times K}{D_i} \tag{3}$$

(D_i =internal diameter of copper tube)

Where, the Nusselt number N_U can be calculated by using the following empirical formulae

a) For smooth Circular Tube with constant heat supply and laminar flow

$$N_U = \frac{h_i \times D_i}{K} = 4.36 \tag{4}$$

b)For smooth Circular Tube with constant surface temperature and laminar flow

$$N_U = \frac{h_i \times D_i}{K} = 3.66 \tag{5}$$

c) For fully developed turbulent flow

$$N_U = 0.023 * R_e^{0.8} * P_r^n \tag{6}$$

Where n is equal to 0.4 for heating and 0.3 for cooling of the fluid flowing through the tube. For more accurate values of Nusselt number there are several equations which include the friction factor.

To use the above equation (s), we will need to know the values of certain properties of HTF (water) at the given temperature. The required properties are Reynolds number (Re), Conductivity of water (kw), Kinematic viscosity (v); Specific heat capacity (Cp),Prandtl number (P) and velocity (V) of water through the cooper pipe. Out of the above parameters the Reynolds number and Velocity of water through the copper pipe (V) will have to be calculated during each experiment by using the following formula:

$$R_e = \frac{D_i \times V}{v} \tag{7}$$

$$V = \frac{\dot{m}_w}{\rho_w A_i} \tag{8}$$

Where,

$\dot{m}_w$ = mass flow rate (kg/s)

D_i =Internal diameter of the copper tube (m) 0.0109 m
A_i = Copper tube inner cross sectional area (m^2)

N_u = Nusselt No.
ρ_w=density of water = 964.45 kg/m3
P_r = Prandtl No.= 1.85 (at 90 deg.)
K = conductivity of water = 0.676 W/mK (90°C)
R_e = Reynolds No.
V = velocity of water through copper tube
ν = kinematic viscosity of water = 0.000000318 (m^2/s)

Calculation of h_o

For a horizontal cylinder there may be two cases:

If, $10^4<(p_rG_r)<10^9$

Then,

$$h_0 = 1.3((T_{s,cy}-T_a)/D_o) \quad (9)$$

If, $10^9<(p_rG_r)<10^{12}$

Then,

$$h_0 = 1.8((T_{s,cy}-T_a)^{0.33} \quad (10)$$

Here G_r is known as Grashof number and can be calculated as,

$$G_r = \frac{D_o^3 \rho_{air}^2 g(T_{s,cy}-T_a)\beta}{\mu^2} \quad (11)$$

Where,

D_0 :Characteristic length parameter(e.g. diameter for natural convection from a circular cylinder) (m) =0.0127m
ρ_{air} : Density of air= 1.225 kg/m^3
T_a : Ambient air temperatures(°C)
μ_{air} : Dynamic viscosity of air (0.00000001983 N-sec /m^2)
β : Coefficient of volume expansion of the air = 0.025 (1/K)
T_{scy} : Cylinder's surface temperature
g : Acceleration due to gravity 9.81(m/sec^2)
J : represents the number of observation

Analysis of sub-system process Charging Period:

In this stage the hot HTF flows through the heat exchanger and gives energy to PCM. The Charging Period Efficiency can be expressed as follows:

$$\eta_{ch} = \frac{\text{Energy accumulated during charging}}{\text{Energy input during charging}}$$

Here energy input during charging :-

$$E_{in,j-1} = \dot{m}_{HTF,ch,j} * C_{p,HTF}(T_{i,HTF,ch,j} - T_a)*t \text{ (KJ)} \quad (12)$$

Energy accumulated during charging,

$$E_{1,j}=E_{in,j-1}-E_{loss,1,j}-E_{loss,wa,j} \text{ (KJ)} \quad (13)$$

Where,

$\dot{m}_{HTF,ch}$: Hot HTF flow rate during charging
C_{HTF} : Specific heat capacity of HTF (water)
$T_{i,HTF,ch}$: Inlet temperature of hot HTF during charging(°C)

$T_{o,HTF,ch}$: outlet temperature of hot HTF during charging (°C)
$E_{loss,1}$: Amount of Energy loss during the charging period through the cylinder (J)
$E_{loss,wa,j}$: Amount of energy loss without absorption (J)
L4 : Length of PCM cylinder = 0.34 m

$$E_{loss,1,j}=q_{1,j} * L_4 * t \quad (J) \tag{14}$$

$$E_{in,j-1}= \dot{m}_{HTF,ch,j} * C_{p,HTF}(T_{o,HTF,ch,j}- T_a)*t \quad (kJ) \tag{14a}$$

Therefore,

$$\eta_{ch,j} = \frac{E_{1,j}}{E_{in,j-1}} \tag{15}$$

B.2) STORING PERIOD:

In this period, the energy stays ideally inside the PCM. Due to losses to the environment the amount of available energy reduces with time. The storing period efficiency can be expressed as follows:

$$\eta_{st}= \frac{\text{Energy stored in TES at the end of storing}}{\text{Energy stored in TES at the beginning of storing}}$$

Energy Stored in TES at the beginning of storing:

$$E_{1,total,j-1}=E_{in,total}-E_{loss,1,total}-E_{loss,wa,total}-E_{loss,2,j} \tag{16}$$

$$E_{2,j}=E_{1,total,j-1}-E_{loss,2,j} \tag{17}$$

$$E_{loss,2,j}= q_{2,j} * L_4 * t \quad (J) \tag{18}$$

$$\dot{q}_{2,j} = \frac{T_{pcm,j} - T_a}{R_2}$$

$$R_2 = \frac{\ln\left(\frac{r_4}{r_3}\right)}{2\pi k_3 L_3} + \frac{\ln\left(\frac{r_5}{r_4}\right)}{2\pi k_4 L_4} + \frac{\ln\left(\frac{r_6}{r_5}\right)}{2\pi k_5 L_5}$$

Here,
$E_{loss,2,j}$: Loss of energy during storing period
$T_{pcm,st,j}$: Temperature of stored PCM (°C)
j-1 : represent an observation step ahead of the j^{th}step. For j=0 the above logic is not valid.

Therefore,

$$\eta_{st,j} = \frac{E_{2,j}}{E_{1,\,total,\,j-1}} \tag{19}$$

B.3) DISCHARGING PERIOD:

In this stage the energy stored in the PCM is extracted to use in the load. The efficiency for the discharging period can be expressed as follows:

$$\eta_{dis}= \frac{\text{Energy stored from TES during discharging}}{\text{amount of energy available to discharge}}$$

The energy recovered from TES during discharging:

$$E_{dis,j} = \dot{m}_{HTF,dis,j} * C_{p,HTF}(T_{HTF,o,dis,j} - T_{HTF,i,dis,j}) * t \quad (kJ) \tag{20}$$

Amount of energy available to discharge,

$$E_{3,J} = (\text{Energy available at the end of the storing period} - (E_{dis,j-1} + E_{loss,3,j-1})) \quad (kJ) \tag{21}$$

Where,

$$E_{loss,3j} = \dot{q}_{3,j} * L_4 * t \quad (J) \tag{22}$$

$$\dot{q}_{3,j} = \frac{T_{pcm,j} - T_a}{R_3}$$

$$R_3 = \frac{\ln\left(\frac{r_4}{r_3}\right)}{2\pi k_3 L_3} + \frac{\ln\left(\frac{r_5}{r_4}\right)}{2\pi k_4 L_4} + \frac{\ln\left(\frac{r_6}{r_5}\right)}{2\pi k_5 L_5}$$

$T_{pcm,st,j}$: Temperature of stored PCM (°C)

$\dot{m}_{HTF,dis}$: Cold HTF flow rate during discharging ($\frac{kg}{sec}$)

$T_{HTF,o,dis}$: Outlet temperature of the HTF during discharging (°C)

$T_{HTF,o,dis}$:Inlet temperature of the HTF during discharging (°C)

$$\eta_{dis} = \frac{E_{dis,j}}{E_{3,j-1}} \tag{23}$$

C). OVERALL SYSTEM EFFICIENCY:-

Overall system efficiency of thermal energy storage systems can be defined as the ratio of the energy extracted from the TES to energy input. The overall system efficiency is also the first law efficiency of the TES system.

The overall system efficiency can be expressed as follows:

$$\eta_{overall} = \frac{\text{Energy recovered from TES during discharging}}{\text{energy input during charging}}$$

Therefore,

$$\eta_{overall} = \frac{E_{dis,total}}{E_{in,total}}$$