CHAPTER III

RESEARCH METHODOLOGY

Material properties

Based on thermodynamic data, corrosiveness and handling characteristics, three non-phase change materials (NPCM) were selected for experimental investigations: sodium nitrate ($NaNO_3$), potassium nitrate (KNO_3) and sodium chloride (NaCl). The most important properties of these Three NPCMs and lubricant oil (LO) are given in Table 8.

Table 8 Properties of three NPCMs and lubricant oil [34, 35]

Properties	$NaNO_3$	KNO_3	NaCl	LO [35]
melting temperature (°C)	306	335	800	340
heat of fusion (melting) (kJ/kg)	172	74	492	-
Density (kg/m^3)	2261	2100	2160	863
heat capacity of heat transfer solid (kJ/kg-K)	1.10	1.21	0.85	1.882
Thermal conductivity (W/mK)	0.5	0.5	7	0.133

Experiment 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 25.8 cm. and 26.8 cm, 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 as shown in Figure 17.

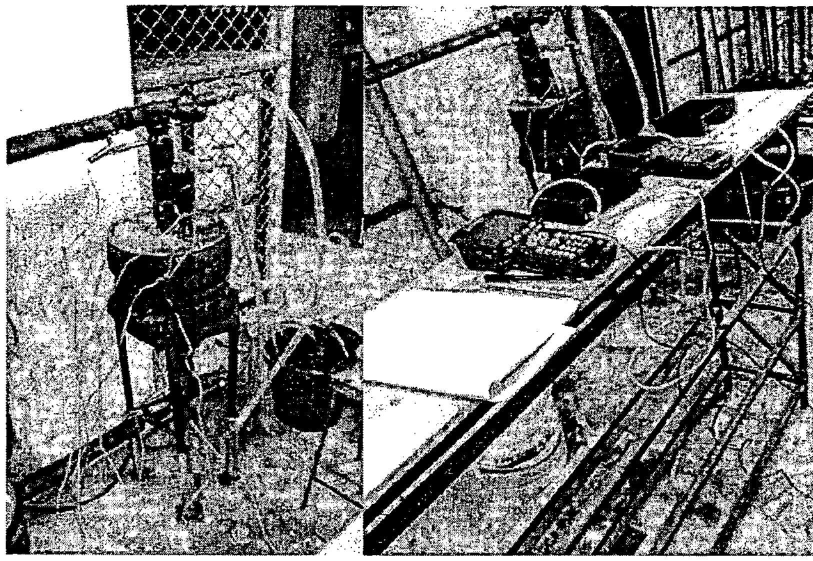

Figure 17 The model of experimental set up

The temperature distribution in the storage tank was carefully investigated using about K-type thermocouples (TC) whose positions are schematically illustrated in Figure 18. The temperature measurements are made both in the NPCM and in the heat transfer fluid. The different TC positions allow to accurately follow the thermocline through the tank and to investigate the perturbation in the axial temperature distributions.

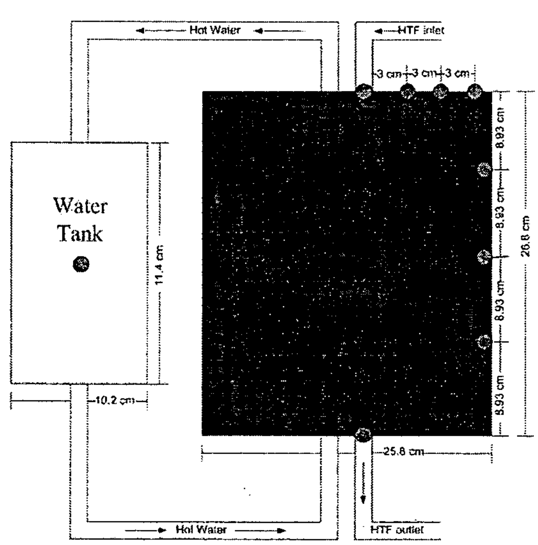

Figure 18 The positions of thermocouple distribution in storage tank

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 0.58, 0.87, 1.16 and 1.45 kg/s, respectively. Three non-phase change materials (NPCM) were selected for experimental investigations: sodium nitrate ($NaNO_3$), potassium nitrate (KNO_3) and sodium chloride (NaCl). These correspond to laminar and turbulent flow regimes that depend on the HTF viscosity from the Reynolds numbers.

Temperature profile charging and discharging set up

For charging process, HTF brings heat from heater 3 kW to the storage tank. The purpose of using different flow rates was to observe the rate of heat transfer from HTF to storage medium. Lubricant oil (LO) (from Shell Company) at an average room temperature (25°C) was used as the inlet HTF and flowed from the inner 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. The load was made by a boiler vessel that was filled with water of 10 kg for absorbing heat. The water tank has a diameter and height of 11.4 cm. and 10.2 cm, respectively. 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.

Temperature distribution in radius set up

The HTF pump brings heat from heater 3 kW to the storage tank. The speed of motor was adjusted to obtain the flow rates of 0.58, 0.87, 1.16 and 1.45 kg/s, respectively. The Temperature distribution in the radius was carefully investigated using about K-type thermocouples (TC) at three different levels as shown in Figure 18. It is observed from the figures that the temperature variation between each levels (x = 3 cm, x=6 cm, x=9 cm) having differences among them due to the flow direction, time consumption and surface contact of HTF around the stainless steel tubes.

Calculation of thermal distribution performance

The performance parameters are charging time, discharging time, energy stored, energy recovered and energy efficiency respectively. Details about the different components of the performance:

1. Storage Equation

The storage system is the sensible heat in solid storage. Assuming that the storage tank has a uniform temperature so the energy balance on the storage tank gives if the cumulative heat energy in the storage tank is not constant so we can re-write into the new equation as;

$$T_{s+1} = T_s + \frac{\Delta t}{(MC_p)_s}\left[\dot{Q}_c - \dot{Q}_L - (UA)_s(T_s - T_a)\right] \qquad \text{[Eq.42]}$$

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

2. 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

$$\dot{m}C_p(T_{mi} - T_{mo}) = \bar{h}A(T_b - T_s) = q_s A \qquad \text{[Eq.43]}$$

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

$$\dot{m}C_{pl}(T_{mi} - T_{mo}) = \frac{A(T_b - T_s)}{\frac{1}{\bar{h}} + \frac{r_1 \ln(r_2 / r_1)}{k}} \qquad \text{[Eq.44]}$$

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 45

$$T_{mi} = T_{mo}^{old} + \frac{\dot{Q}_c}{\dot{m}C_p} \qquad \text{[Eq.45]}$$

Where $\dot{Q}_c$ is the charging thermal energy rate by heater, (kW) and 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 46.

$$T_{mo}^{1} = \frac{T_s + \frac{\dot{m}C_{pl}}{A}\left[\left(\frac{1}{\bar{h}} + \frac{r_1 \ln(r_2/r_1)}{k}\right) - \frac{1}{2}\right]T_{mi}}{\left[\frac{\dot{m}C_{pl}}{A}\left(\frac{1}{\bar{h}} + \frac{r_1 \ln(r_2/r_1)}{k}\right) + \frac{1}{2}\right]} \qquad \text{[Eq.46]}$$

3. Energy Storage

The amount of thermal energy stored in the different storage materials at their respective charging times is calculated using Eq. 47.

$$Q = \rho_s V C_{ps}(T(t) - T_{inl}) \qquad \text{[Eq.47]}$$

where, Q, ρ_s, C_{ps}, V and ΔT are storage capacity (J), density (kg/m^3), specific heat (J/kg K) Storage volume required (m^3) and charging temperature range, respectively.

4. Energy Recovered

The amount of thermal energy recovered from storage bed of different materials at their respective discharging time is calculated using Eq. 48.

$$Q = \rho_s V C_{ps} (T_{ch} - T(t)) \qquad [Eq.48]$$

where, T_{ch} is the volume average temperature of the storage bed at the end of charging cycle.

5. Energy Efficiency

Energy efficiency is the ratio of energy recovered from the storage bed during discharging cycle to the total energy input to storage bed which is given by the Eq. (47). The total energy input is the sum of energy supplied to heat the storage bed from atmospheric temperature (T_{atm}) 298 K to 523 K and energy stored in the bed during charging.

$$\eta_{Energy} = \frac{T_{ch} - T(t)}{T_{ch} - T_{atm}} \qquad [Eq.49]$$