CHAPTER IV

FINDINGS AND DISCUSSION

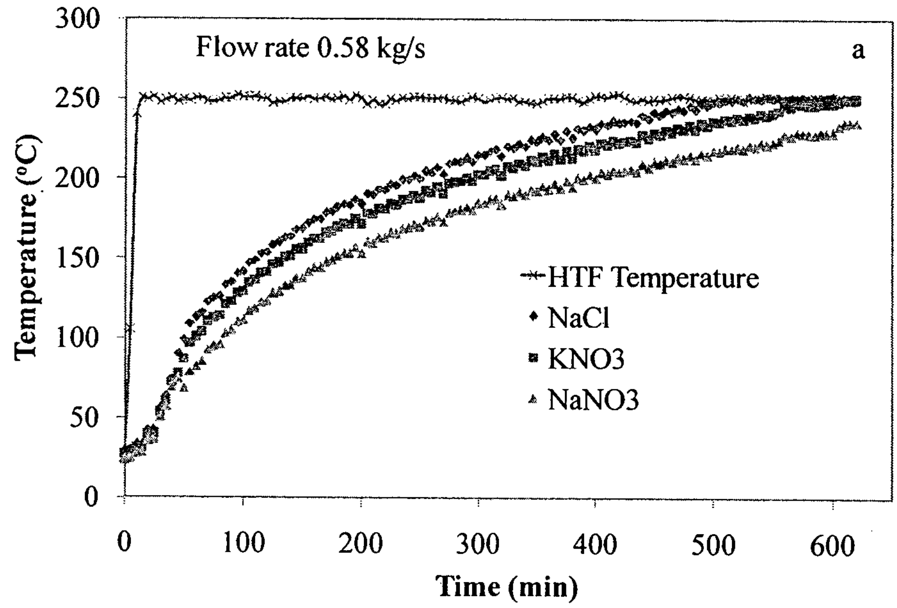
The result and analysis temperature distribution of the NPCM of this research were composed of the energy storage ,energy transfer, energy storage efficiency and calculation of multiplication for thermal storage

Temperature profile charging and discharging

1. Charging

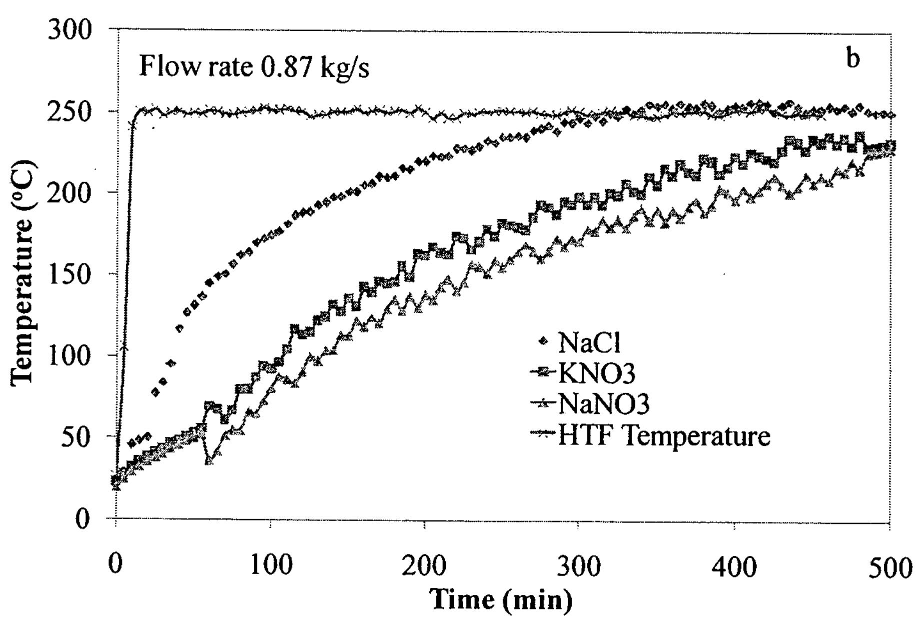
The temperature distribution of the NPCM, during charging was taken at four different mass flow rates at 0.58, 0.87, 1.16 and 1.45 kg/s, respectively. For each mass flow rates, curve was plotted for variation of temperature at each point in the wax against time elapsed, to get melting curve in case of charging. Storage and outlet HTF temperatures are presented for comparing the temperatures between bulk HTF temperature and mixed storage temperature of charging experiment in Figure 19. The storage medium is also used thermal oil, as the same as HTF. The results of HTF temperature and storage temperature measurement were shown 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 250°C. However, in this experiment, the control switch is used to cut off the heater at 250°C before the maximum after 1 hours, the HTF temperature was set to constant at high temperature as its maximum, decomposition point. Figure 19a comparison substance (NPCM) with a oil flow rates of 0.58 kg/s for NaCl are charging of heat faster than KNO_3 and $NaNO_3$. The temperature of storage bed is averaged over the entire bed volume thus it is the function of time only. Variation of average bed temperature with time is shown in Figure 19 for NPCNs [6]. It is seen from Figure 19a that initially, the rise in the volume average temperature of storage beds is rapid and decreases with time. This is because of higher driving potential available for conduction during initial period of charging cycle and this driving potential reduces with time as the storage bed gains the heat of HTF. The charging rates of KNO_3 and $NaNO_3$ are more than that

NaCl due to the high heat capacity and low thermal conductivity. The KNO_3 and $NaNO_3$ bed took 620 minutes for complete charging whereas NaCl gets completely charged within 500 minutes respectively. In Figures 19b, stored thermal energy as a function of time is depicted for oil flow rate of 0.87 kg/s. The KNO_3 and $NaNO_3$ bed took 500 minutes for complete charging whereas NaCl gets completely charged within 300 minutes respectively. For Figures 19c, stored thermal energy as a function of time is depicted for oil flow rate of 1.16 kg/s. The KNO_3 and $NaNO_3$ bed took 500 minutes for complete charging whereas NaCl gets completely charged within 270 minutes, respectively. The finally Figures 19d, stored thermal energy as a function of time is depicted for oil flow rate of 1.45 kg/s. The KNO_3 and $NaNO_3$ bed took 450 minutes for complete charging whereas NaCl gets completely charged within 300 minutes, respectively. The temperature distribution of the NPCM during charging was taken at four different mass flow rates at 0.58, 0.87, 1.16 and 1.45 kg/s, respectively. Comparing of NPCMs with oil flow rates for NaCl are more charging heat transfer than KNO_3 and $NaNO_3$ due to the high heat capacity and low thermal conductivity of NaCl compare with KNO_3 and $NaNO_3$, which is consistent with the research of Horst Michels and. Robert Pitz-Paal [6].



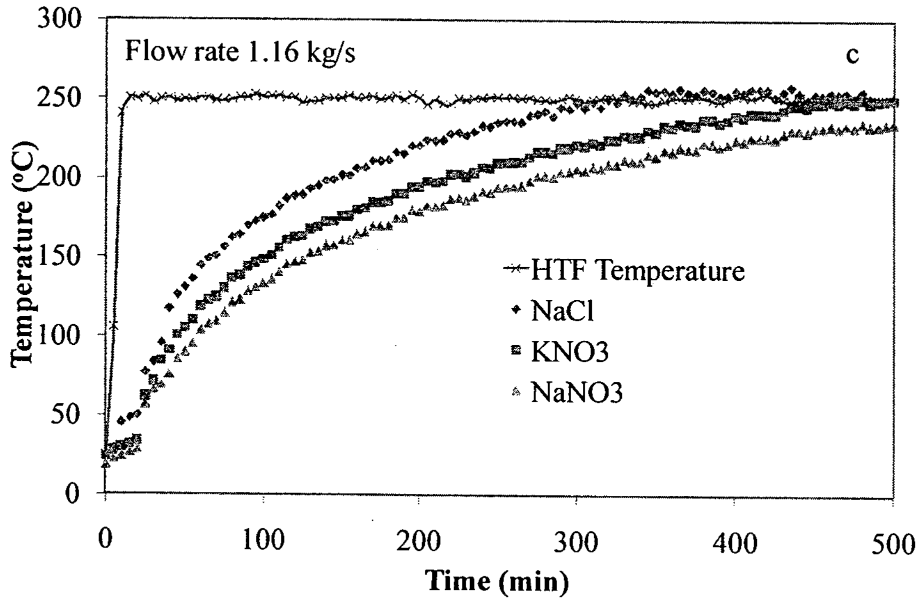
(a)

Figure 19 Heat transfer oil temperature over time for three different NPCM configurations and temperature of HTF and storage medium in charging experiment at Flow rate (a) 0.58 kg/s., (b) 0.87 kg/s, (c) 1.16 kg/s and (d) 1.45 kg/s.



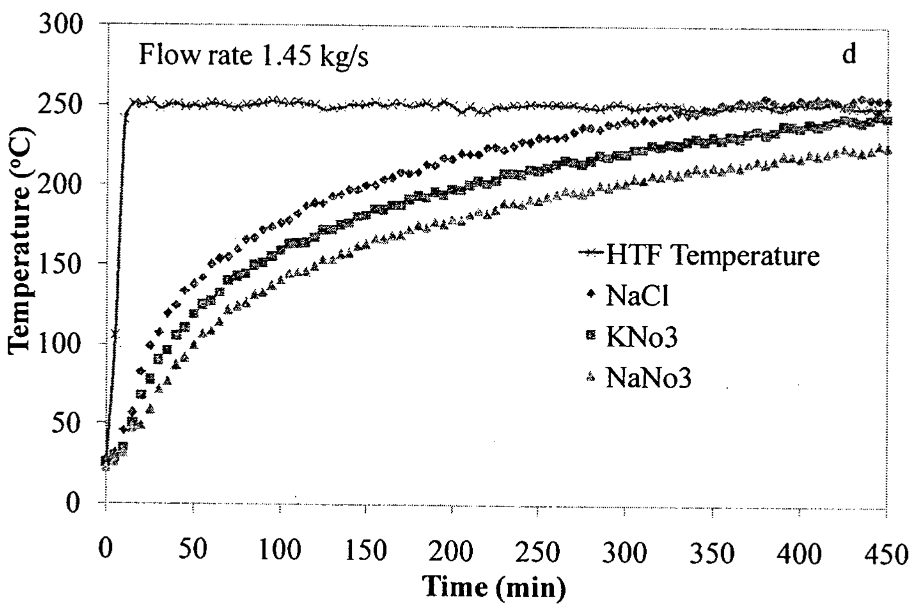
(b)

Figure 19 (cont.)



(c)

Figure 19 (cont.)

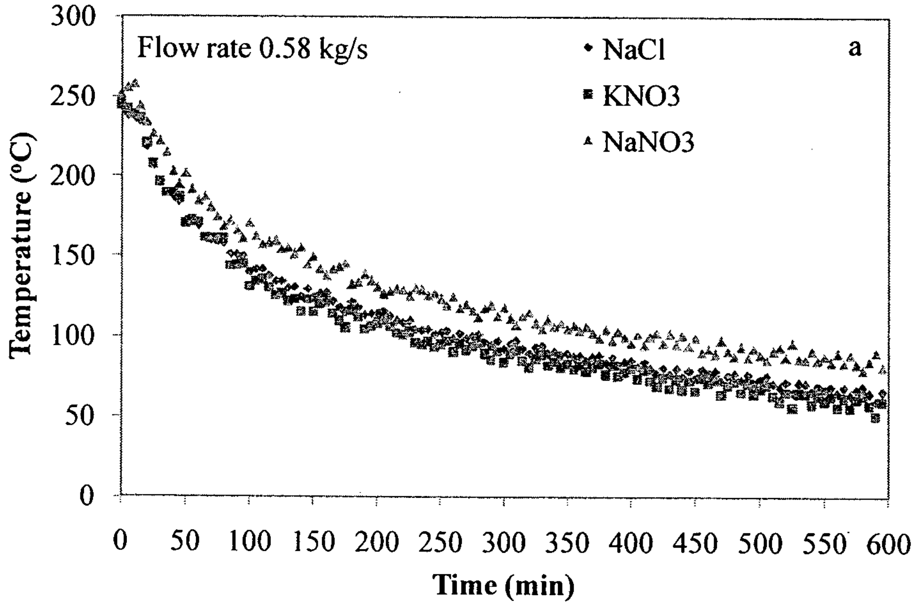


(d)

Figure 19 (cont.)

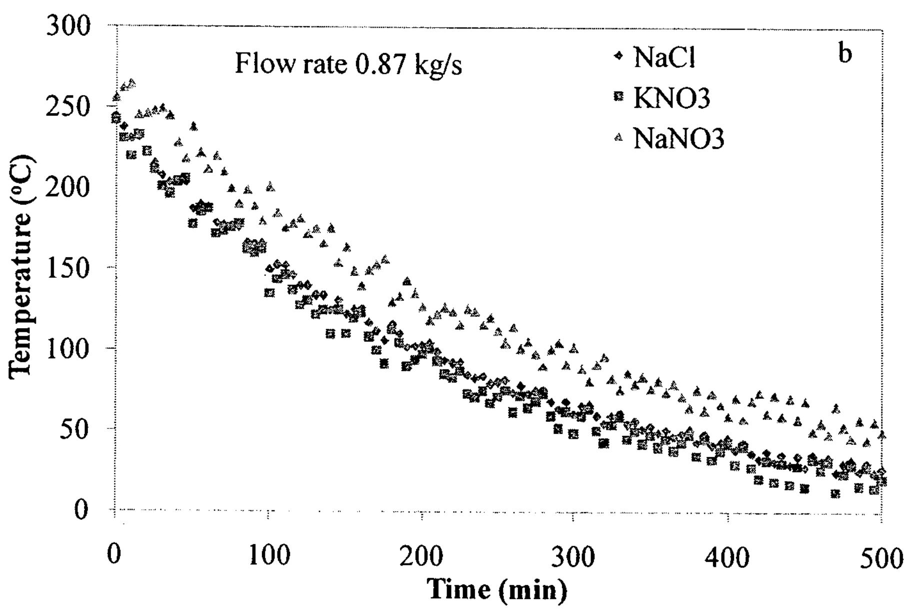
2. Discharging

For discharging experiment, thermal oil was used as HTF for drawing the heat from the storage tank. This load power was adjusted for a long period of discharge. The storage temperature started at 250°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 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 water heat exchange. The period of discharge was in the range of 450-600 minutes. The initial temperature of HTF average room temperature at 25 °C, as shown in Figure 20, was increased to 250-270°C, a turning point, and then decreased to 100 °C, the final point of discharge. Figure 20(a) comparison of NPCMs with oil flow rate of 0.58 kg/s, $NaNO_3$ discharging heat transfer was slower than KNO_3 and NaCl due to the low heat capacity and low thermal conductivity. The discharging time of NaCl was 260 minutes, $NaNO_3$ was 200 minutes and KNO_3 was 370 minutes respectively. For Figure 20(b) comparison of NPCMs with oil flow rate of 0.87 kg/s, $NaNO_3$ was discharging heat transfer slower than KNO_3 and NaCl due to the low heat capacity and low thermal conductivity. The discharging time of NaCl was 210 minutes, $NaNO_3$ was 275 minutes and KNO_3 was 170minutes respectively. In Figure 20(c) comparison of NPCMs with oil flow rate of 1.16 kg/s, for $NaNO_3$ was discharging heat transfer slower than KNO_3 and NaCl due to the low heat capacity and low thermal conductivity. The discharging time of NaCl was 140 minutes, $NaNO_3$ was 205 minutes and KNO_3 was 165 minutes, respectively. The finally Figure 20(d) comparison of NPCMs with oil flow rate of 1.45 kg/s for $NaNO_3$ was discharging heat transfer slower than KNO_3 and NaCl due to the low heat capacity and low thermal conductivity. The discharging time of NaCl was 165 minutes, $NaNO_3$ is 195 minutes and KNO_3 was 155 minutes, respectively. Comparing substances (NPCM) with oil flow rate. $NaNO_3$ discharging heat was more slower than KNO_3 and $NaNO_3$, so $NaNO_3$ is appropriate to store thermal energy that corresponding to the literature of Horst Michels and Robert Pitz-Paal [6].



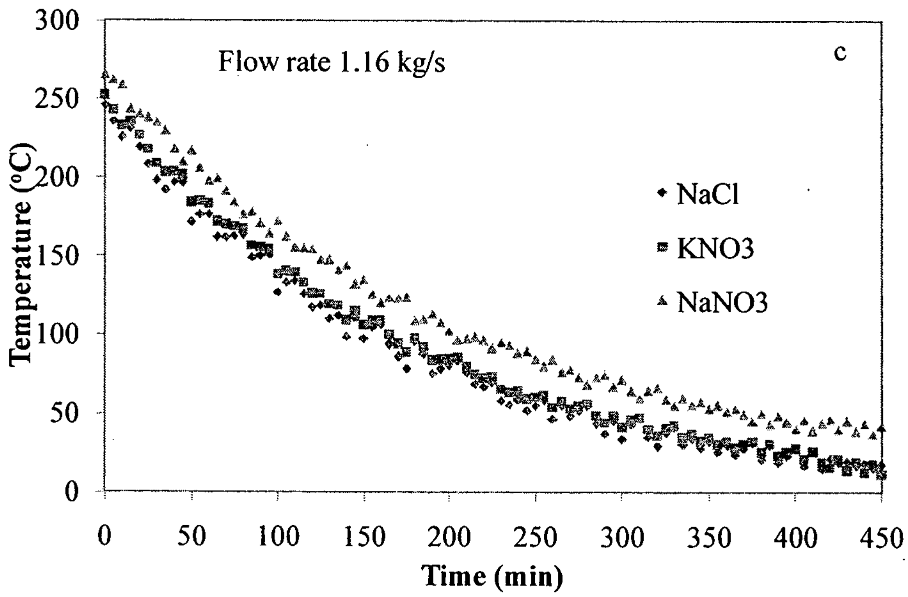
(a)

Figure 20 Storage discharging fluid temperatures decreasing at Flow rate (a) 0.58 kg/s , (b) 0.87 kg/s, (c) 1.16 kg/s and (d) 1.45 kg/s.



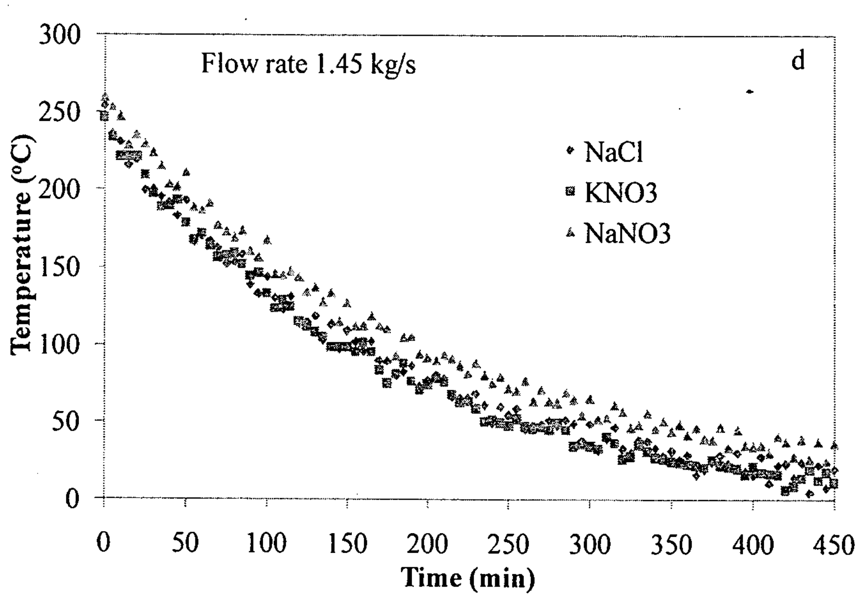
(b)

Figure 20 (cont.)



(c)

Figure 20 (cont.)

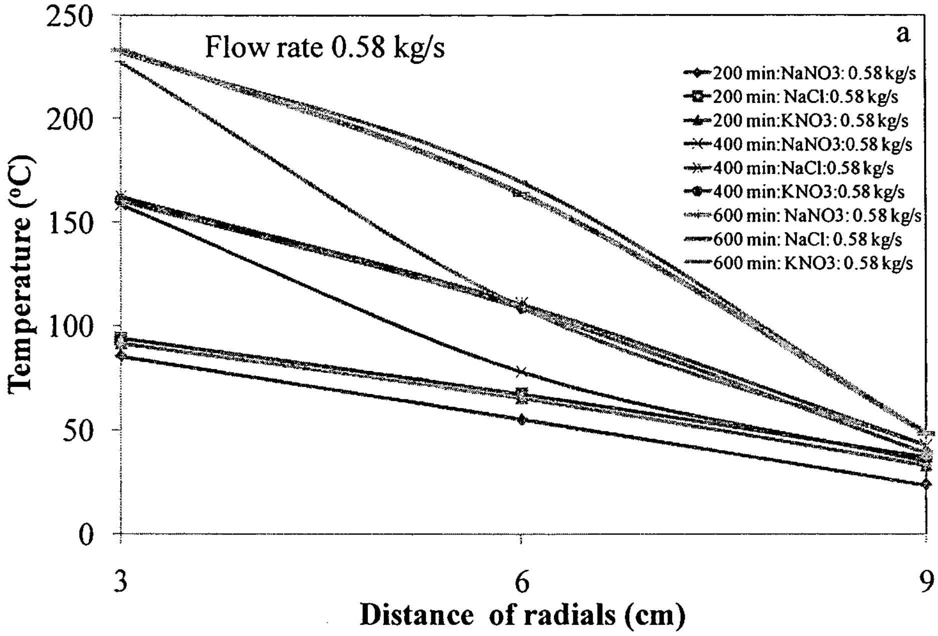


(d)

Figure 20 (cont.)

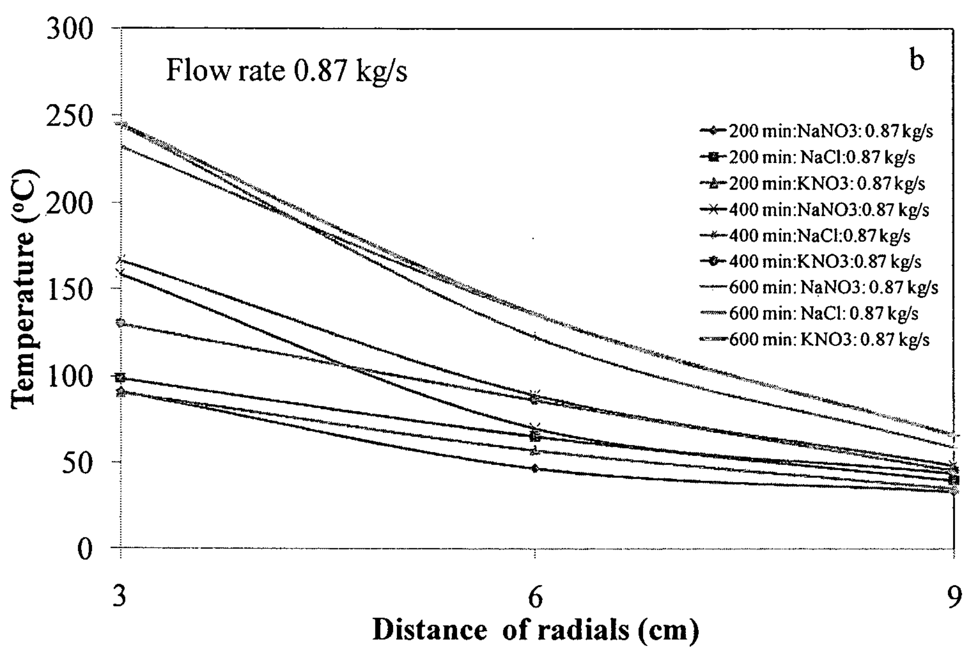
Temperature Distribution in Radius

The charging process was carried by applying HTF at 25-250 °C with a flow rates of 0.58-1.45 kg/s. Due to variation of heator sources are provided to maintain the temperature of HTF at 250 °C. The HTF is flowing through the storage tank then the temperature of HTF and NaCl, KNO_3, $NaNO_3$ have been noted for every 5 minutes once at three different levels. The period of time were in the range of 200, 400 and 600 minutes. The temperature profiles for NPCMs have been increase for each level as shown in Figure 21. 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. The radial temperature profile is averaged over the entire bed volume thus is the function of time only. The radial temperature profile rate of NaCl is more than that KNO_3 and $NaNO_3$ at 3, 6 and 9 cm on the every position. Figure 21 (a) comparison substance (NPCM) with a oil flow rate of 0.58 kg/s for NaCl are radial temperature profile of heat faster than KNO_3 and $NaNO_3$ on the every distances. The radial temperature profile of 3 cm was 85-233°C, 6 cm was 55-170°C and 9 cm was 24-48°C respectively. Figure 21 (b) comparison substance (NPCM) with a oil flow rate of 0.87 kg/s for NaCl are radial temperature profile of heat faster than KNO_3 and $NaNO_3$ on the every distances. The radial temperature profile of 3 cm was 90-244°C, 6 cm was 47-136°C and 9 cm was 36-46°C respectively. Figure 21 (c) comparison substance (NPCM) with a oil flow rate of 1.16 kg/s for NaCl are radial temperature profile of heat faster than KNO_3 and $NaNO_3$ on the every distances. The radial temperature profile of 3 cm was 99-259°C, 6 cm was 56-160°C and 9 cm was 34-51°C respectively. Figure 21 (d) comparison substance (NPCM) with a oil flow rate of 1.45 kg/s for NaCl are radial temperature profile of heat faster than KNO_3 and $NaNO_3$ on the every distances. The radial temperature profile of 3 cm was 107-270°C, 6 cm was 73-174°C and 9 cm was 36-113°C respectively.



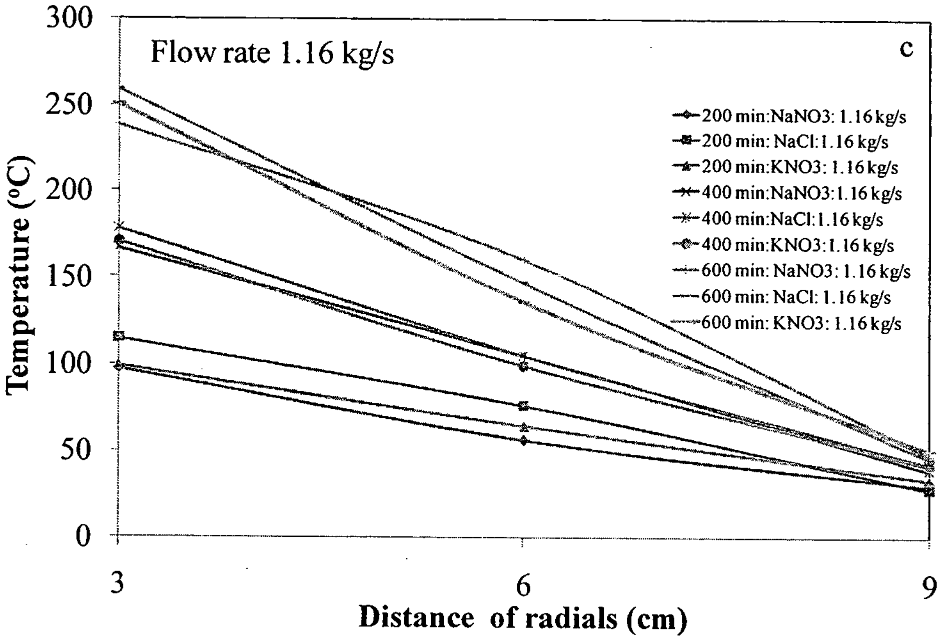
(a)

Figure 21 The temperature of radial temperature profile of 3, 6 and 9 cm of NaCl, KNO_3 and $NaNO_3$ at flow rate (a) 0.58 kg/s, (b) 0.67 kg/s, (c) 1.16 kg/s and (d) 1.45 kg/s



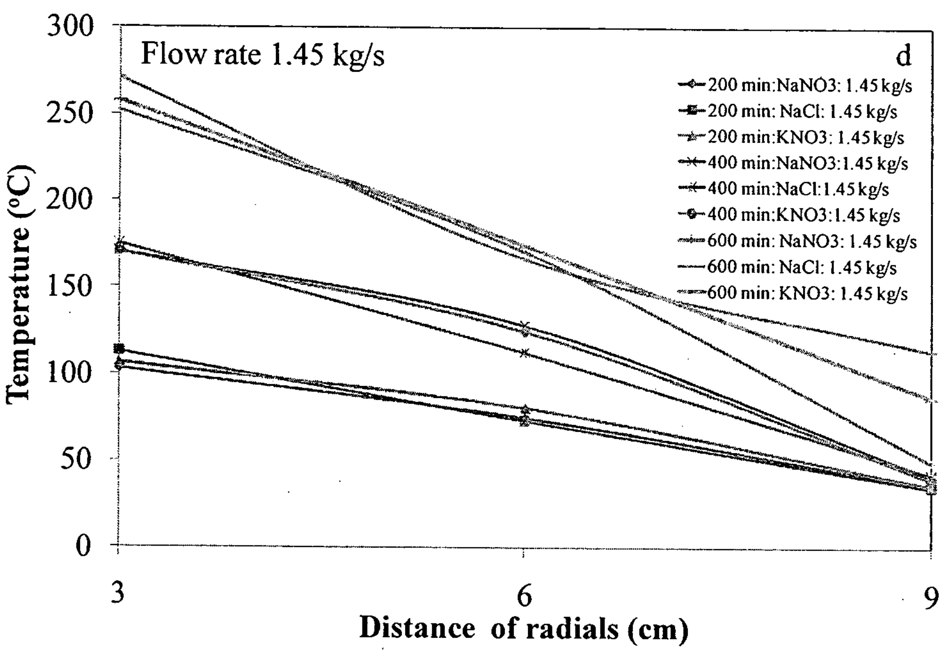
(b)

Figure 21 (cont.)



(c)

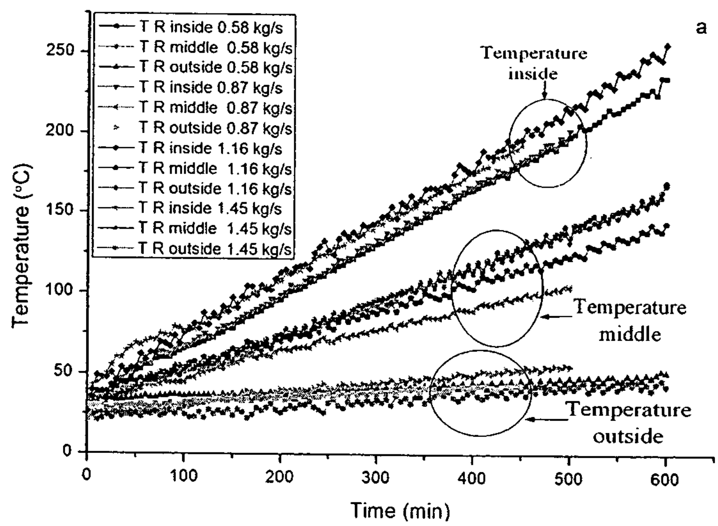
Figure 21 (cont.)



(d)

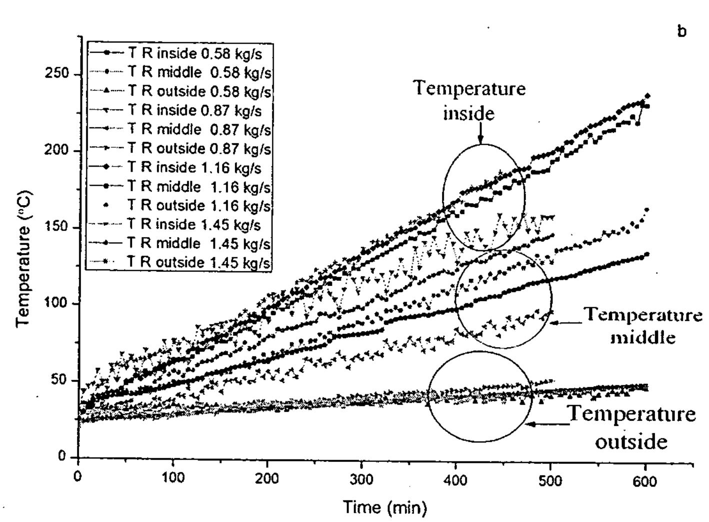
Figure 21 (cont.)

The study of the radial thermal distribution for thermal energy storage was using the three non-phase change materials that were selected for experimental investigations: NaNO, KNO_3 and NaCl. The motor speed was adjusted to obtain the oil flow rates of 0.58, 0.87, 1.16 and 1.45 kg/s respectively. The radial flow rate of 1.45 kg/s was faster than of 1.16, 0.87 and 0.58 kg/s respectively, as shown in Figure 22. Figure 22(a) comparing the thermal distribution of temperature radial of the NaCl for TR inside the radial thermal distribution of temperature in the range of 185-220°C, TR middle the thermal distribution of temperature in the range 95-150 °C and TR outside the thermal distribution of temperature in the range of 25-50°C for experimental results compared at a time 500min. Figure 22(b) comparing the thermal distribution of temperature radial position of the KNO_3 for TR inside the thermal distribution of temperature in the range of 150-200°C, TR middle the thermal distribution of temperature in the range 55-125°C and TR outside the thermal distribution of temperature in the range of 25-45°C for experimental results comparison at a time 500min. Figure 22(c) comparing the thermal distribution of temperature radial position of the $NaNO_3$ for TR inside the thermal distribution of temperature in the range of 125-200°C, TR middle the thermal distribution of temperature in the range 65-125°C and TR outside the thermal distribution of temperature in the range of 25-40 °C for experimental results compared at a time 500 min. The thermal distribution of radial for thermal energy storage as follows: Thermal distribution radial of NaCl for TR inside, TR middle and TR outside were optimum of temperature down to $NaNO_3$ and KNO_3 respectively, due to the higher heat capacity and low thermal conductivity. Oil flow rates have resulted in the heat transfer for thermal distribution radial and physics properties of NPCM.



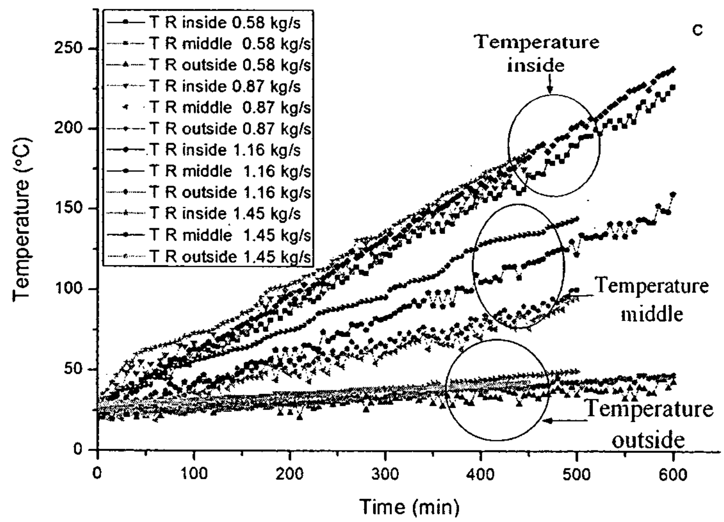
(a)

Figure 22 Flow rates and radial thermal distribution for thermal energy storage (a) NaCl, (b) KNO_3 and (c) $NaNO_3$.



(b)

Figure 22 (cont.)



(c)

Figure 22 (cont.)

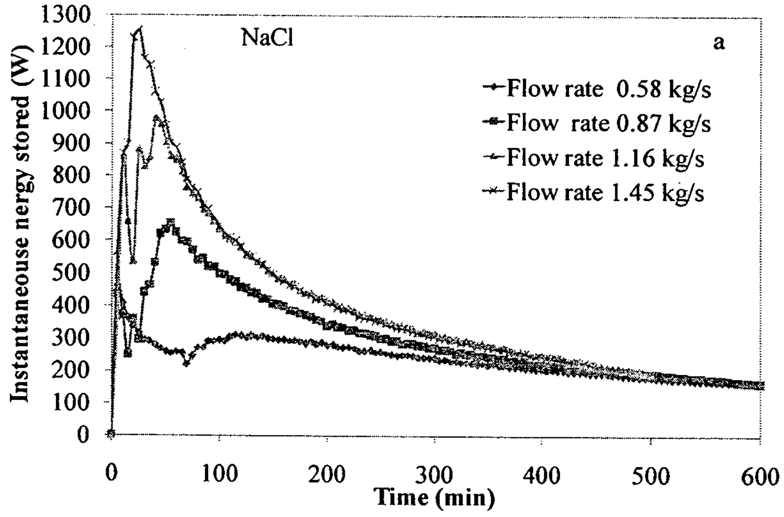
Energy stored

The thermal energy storage rates at the bed of the system for the sodium nitrate ($NaNO_3$), potassium nitrate (KNO_3) and sodium chloride (NaCl) was shown in Figure 23-25. The amount of thermal energy stored in the storage materials at their respective charging times is calculated using [Eq. 47]. Comparison of flow with the energy stored of NaCl, KNO_3 and $NaNO_3$ from figure were shown that the flow rate of 1.45 kg/s reached to time of TES faster than the rates in 1.16, 0.87 and 0.58 kg/s respectively for charging at 400 minutes. The thermal energy stored for experimental results were get with along the KNO_3, $NaNO_3$ and NaCl respectively.

Figure 23 (a) shows the instantaneous energy stored in the storage tank during the charging process for various mass flow rates of HTF with NaCl. This is estimated based on the instantaneous inlet and outlet temperatures of the HTF. It was observed that during the initial period of charging the instantaneous energy stored is high and decreases till 25-200 min. This drop in heat stored is due to the decrease in temperature difference between the HTF and the temperature of the storage tank. Figure 23(b) shows the cumulative energy stored in the storage tank for the case of NaCl. It is seen that the time required for storing 5,769 kJ is 600, 520, 360 and 340 min for mass flow rates of 0.58, 0.87, 1.16 and 1.45 kg/s respectively, and at average charging rates of 160, 162, 192 and 217 W respectively. It is observed from the figure that the mass flow rate has significant effect on the average charging rate. This is due to higher heat extraction rate of HTF from the heater when the flow rate is increased.

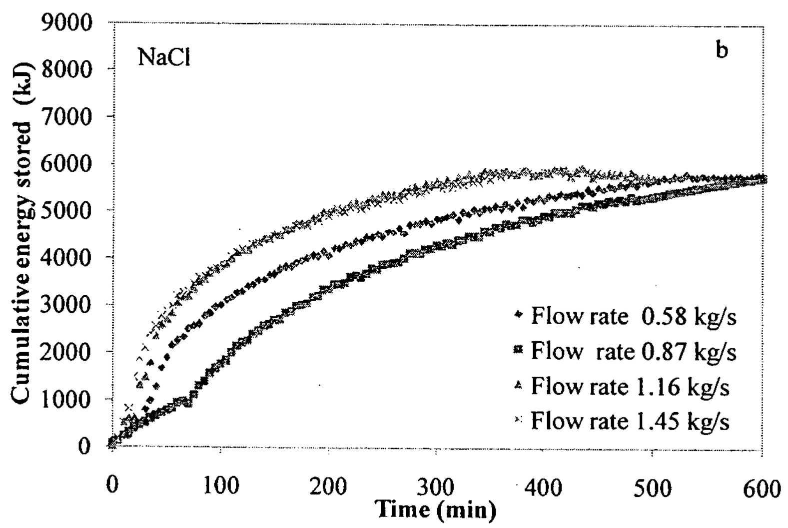
Figure 24(a) shows the instantaneous energy stored in the storage tank during the charging process for various mass flow rates of HTF with KNO_3. This is estimated based on the instantaneous inlet and outlet temperatures of the HTF. It was observed that during the initial period of charging the instantaneous energy stored is high and decreases till 30-200 min. Figure 24(b) shows the cumulative energy stored in the storage tank for the case of KNO_3. It is seen that the time required for storing 5,769 kJ is 270, 235, 180 and 145 min for mass flow rates of 0.58, 0.87, 1.16 and 1.45 kg/s respectively, and at average charging rates of 316, 353, 465 and 545 W respectively.

Figure 25(a) shows the instantaneous energy stored in the storage tank during the charging process for various mass flow rates of HTF with $NaNO_3$. This is estimated based on the instantaneous inlet and outlet temperatures of the HTF. It was observed that during the initial period of charging the instantaneous energy stored is high and decreases till 30-200 min. Figure 25(b) shows the cumulative energy stored in the storage tank for the case of $NaNO_3$. It is seen that the time required for storing 5,769 kJ is 365, 335, 250 and 245 min for mass flow rates of 0.58, 0.87, 1.16 and 1.45 kg/s respectively, and at average charging rates of 253, 287, 384 and 394 W respectively.



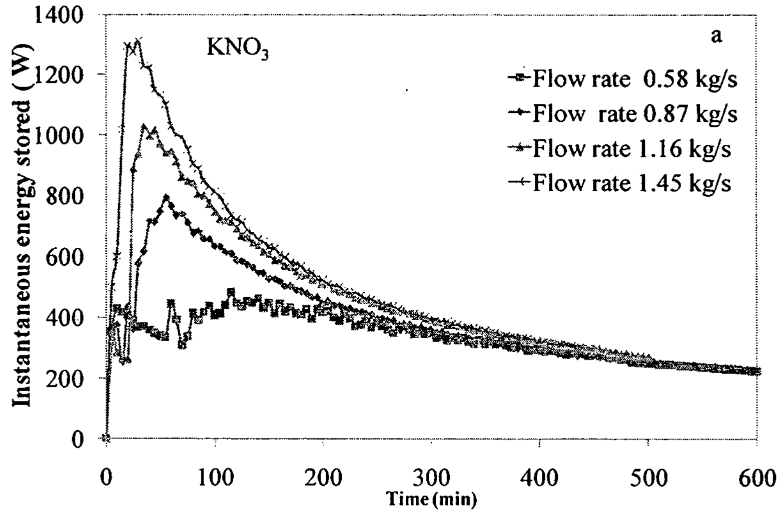
(a)

Figure 23 Instantaneous (a) and cumulative (b) energy stored during the charging process for NaCl.



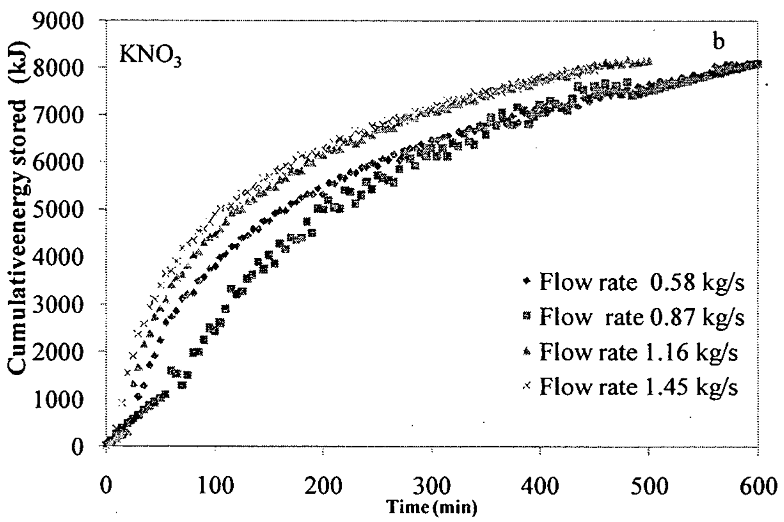
(b)

Figure 23 (cont.)



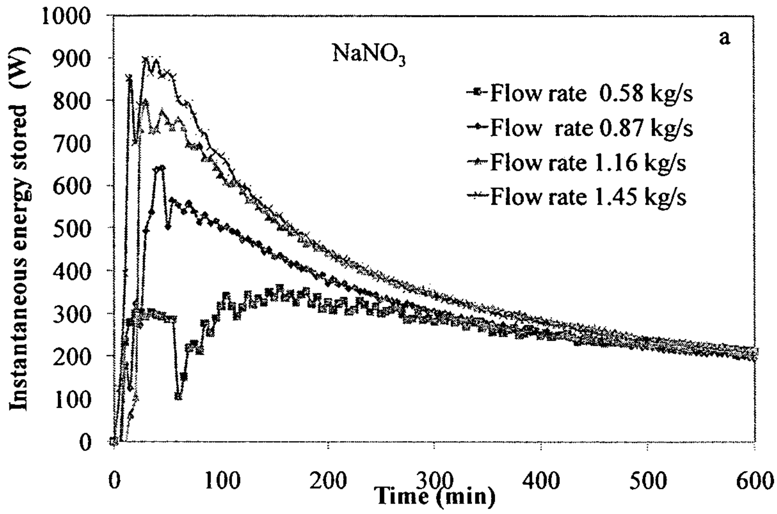
(a)

Figure 24 Instantaneous (a) and cumulative (b) energy stored during the charging process for KNO_3.



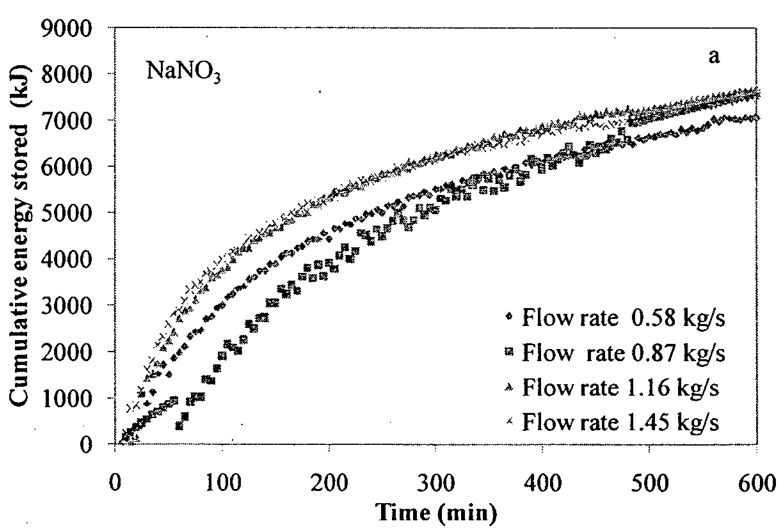
(b)

Figure 24 (cont.)



(a)

Figure 25 Instantaneous (a) and cumulative (b) energy stored during the charging process for $NaNO_3$.



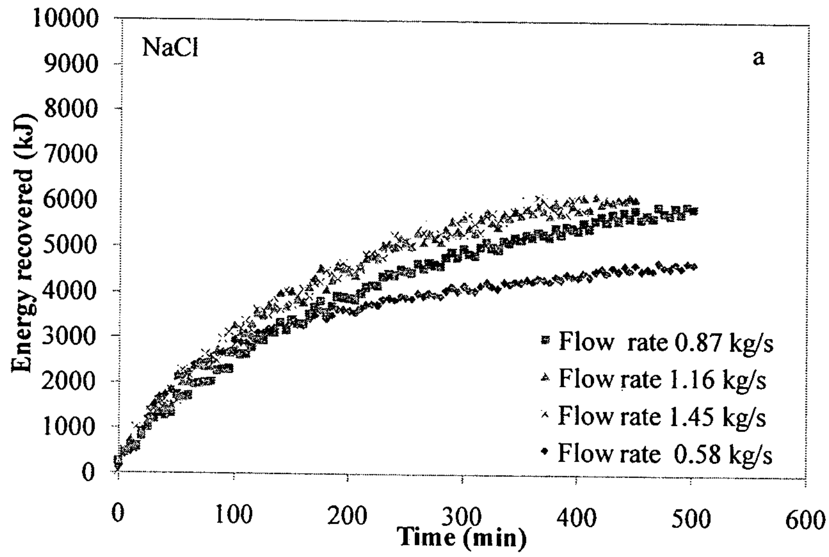
(b)

Figure 25 (cont.)

Energy recovered

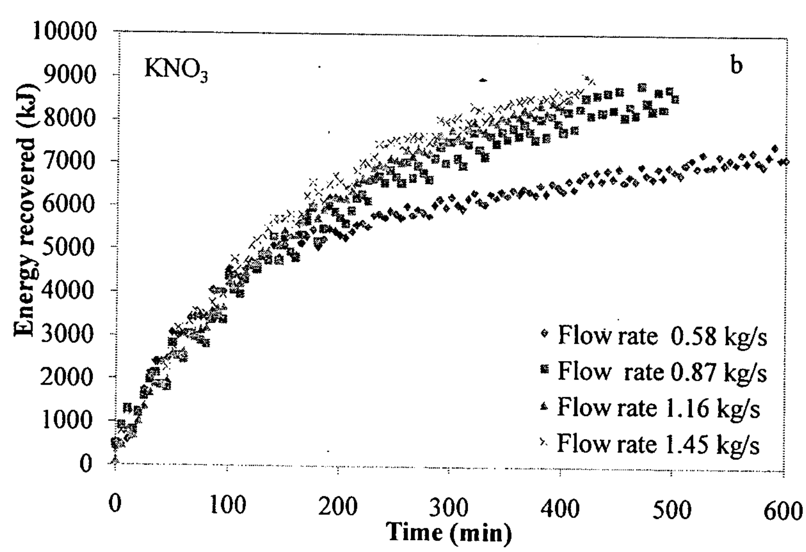
The thermal energy discharge rates at the bed of the system for $NaNO_3$, KNO_3 and NaCl bed was shown in Figure 35. The amount of thermal energy recovered from storage bed of different materials at their respective discharging time was calculated using [Eq.48]. The charging time are compared at 400 minutes. Figure 26(a) comparison of flow with the energy recovered of NaCl from figure was shown that the flow rate of 1.45 kg/s reached to time of TES faster than the rates in 1.16, 0.87 and 0.58 kg/s respectively. The energy recovered flow rate 1.45 kg/s was 6,028 kJ, the flow rate of 1.16 kg/s was 5,790 kJ, the flow rate of 0.87 kg/s was 5,412 kJ and flow rate of 0.58 kg/s was 4,332 J respectively. For Figure 24b comparison of flow with the energy recovered of $NaNO_3$ from figure was shown that the flow rate of 1.45 kg/s reached to time of TES faster than the rates in 1.16, 0.87 and 0.58 kg/s respectively. The energy recovered flow rate 1.45 kg/s was 6,887 kJ, the flow rate of 1.16 kg/s was 8,268 kJ, the flow rate of 0.87 kg/s was 7,922 kJ and a flow rate of 0.58 kg/s was 6,367 J respectively. For Figure 24c comparison of flow with the energy recovered of KNO_3 from figure was shown that the flow rate of 1.45 kg/s reached to time of TES faster than the rates in 1.16, 0.87 and 0.58 kg/s respectively. The energy recovered flow rate 1.45 kg/s was 7,620 kJ, the flow rate of 1.16 kg/s was 7,417 kJ, the flow rate of 0.87 kg/s was 6,743 kJ and flow rate of 0.58 kg/s was 5,453 kJ respectively.

For the thermal energy recovered of NPCM that compared for flow rate 1.45 were summarized as follows: flow rate, faster charging are optimum of flow rates 1.16, 0.87 and 0.58 kg/s respectively. The thermal energy recovered of NaCl was lain from 4332-6028 kJ, KNO_3 was lain from 6367-6887 kJ and $NaNO_3$ was lain from 5453-7620 kJ respectively. The thermal energy recovered for experimental results of KNO_3 more than that were $NaNO_3$ and NaCl respectively.



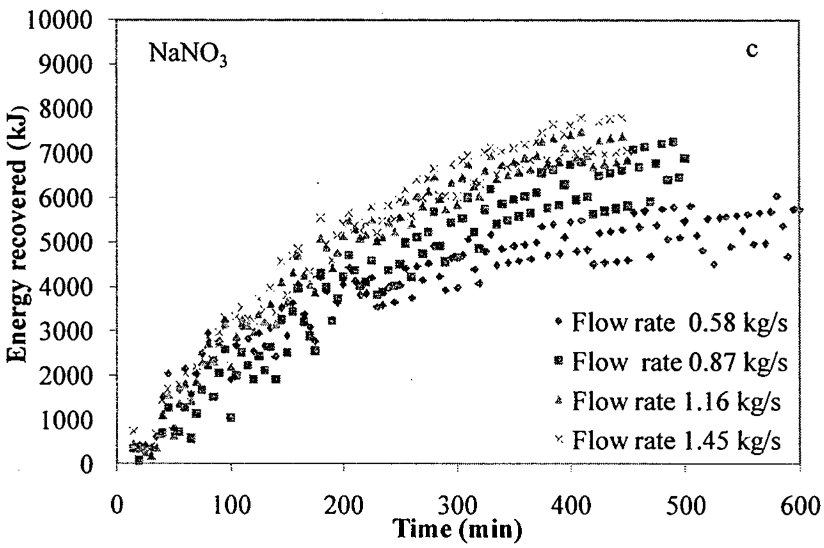
(a)

Figure 26 Flow rates of energy recovered in (a) NaCl, (b) KNO_3 and (c) $NaNO_3$.



(b)

Figure 26 (cont.)

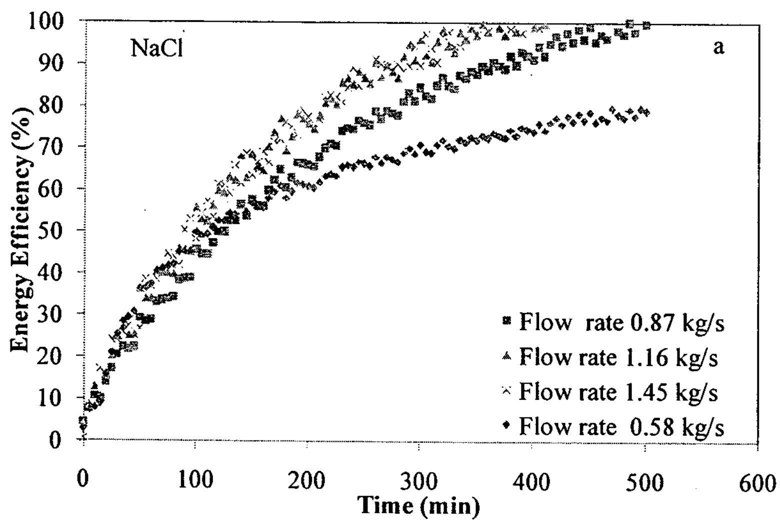


(c)

Figure 26 (cont.)

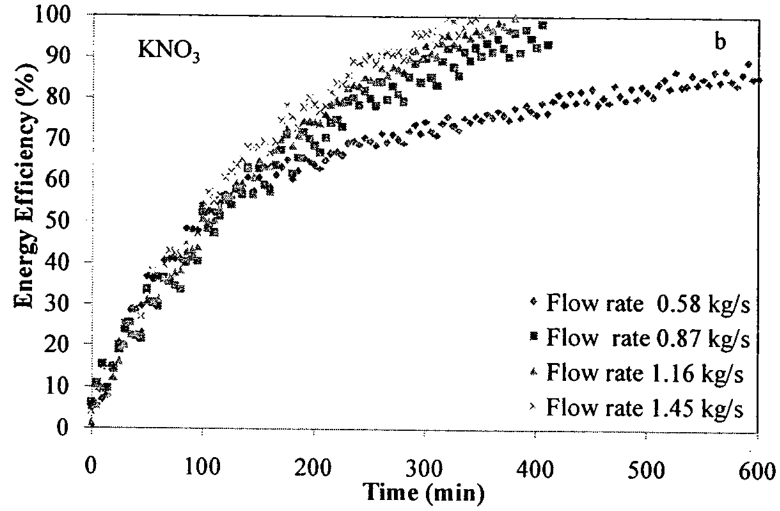
Energy efficiency

The energy was degraded in the process of storage since it was extracted at a temperature lower than that it was previously stored. The energy efficiency of storage beds was evaluated using [Eq. 49]. Energy efficiency variation with bed temperature difference during discharging cycle was shown in Figure 27 it was increased to 270-250 °C, a turning point, and then decreased to 100 °C, the final point of discharge. Figure 27(a) comparison of oil flow with energy efficiency of NaCl for a flow rate of 1.45 kg/s reached to time of energy efficiency faster than the rates in 1.16, 0.87 and 0.58 kg/s for discharging at a temperature of 100°C. Energy efficiency of flow rate 1.45 kg/s was 66 % at 165 minutes, the flow rate of 1.16 kg/s was 70 % at 165 minutes, flow rate 0.87 kg/s was 68 % at 210 minutes and a flow rate of 0.58 kg/s was 67 % at 275 minutes, respectively. Figure 27(b) comparison of oil flow with energy efficiency of $NaNO_3$ for a flow rate of 1.45 kg/s reached to time of energy efficiency faster than the rates in 1.16, 0.87 and 0.58 kg/s for discharging at a temperature of 100°C. Energy efficiency of flow rate 1.45 kg/s was 66 % at 40 minutes, the flow rate of 1.16 kg/s was 70% at 45 minutes, flow rate 0.87 kg/s was 68 % at 105 minutes and a flow rate of 0.58 kg/s was 67% at 60 minutes, respectively. Figure 25c comparison of oil flow with energy efficiency of KNO_3 for a flow rate of 1.45 kg/s reached to time of energy efficiency faster than the rates in 1.16, 0.87 and 0.58 kg/s for discharging at a temperature of 100°C. Energy efficiency of flow rate 1.45 kg/s was 66 % at 40 minutes, the flow rate of 1.16 kg/s was 70 % at 40 minutes, flow rate 0.87 kg/s was 68 % at 40 minutes and a flow rate of 0.58 kg/s was 67 % at 40 minutes respectively. For the thermal energy efficiency of NPCMs that compared for flow rate 1.45 were summarized as follows: flow rate, faster charging were optimum of flow rates 1.16, 0.87 and 0.58 kg/s respectively. The thermal energy efficiency of NaCl, KNO_3 and $NaNO_3$ were in the range of 66-70% for discharging at a temperature of 100°C.



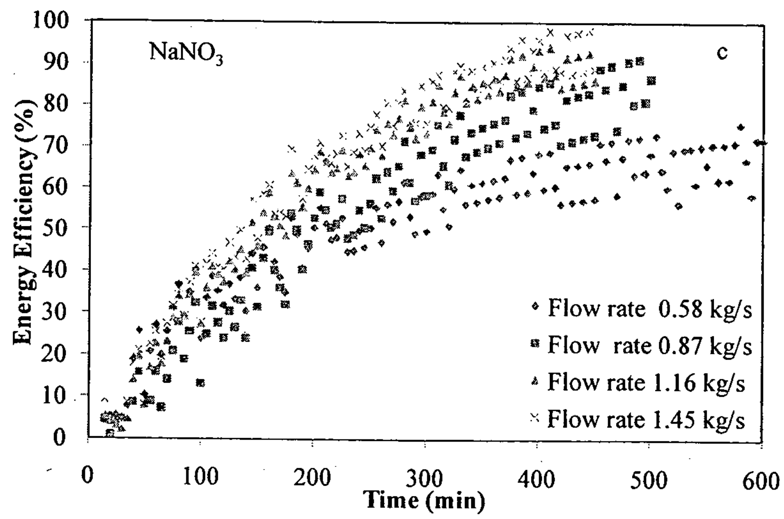
(a)

Figure 27 Variation of energy efficiency with bed temperature difference during discharging cycle in (a) NaCl, (b) KNO_3 and (c) $NaNO_3$.



(b)

Figure 27 (cont.)



(c)

Figure 27 (cont.)