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Experimental Analysis of Binary Salt Mixture of $NaNO_3$: KNO_3 for Low-Grade Waste Heat Recovery System

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Abstract

Objective: To find out how energy storage capacity and energy holding capacity changes at different concentration and the effects of each salt on these factors. **Method/Statistical Analysis:** This system utilises a mixture of nitrate salts in water as primary medium for storing sensible heat.A mixture (300 gm) of Sodium Nitrate ($NaNO_3$) and Potassium Nitrate (KNO_3) at different wt% (60/40, 50/50, 40/60) in 1 litre of distilled water were used for experiments. Each sample was heated until its boiling point was reached and time was noted for each 1-degree rise. **Findings:** In this study a Thermal Energy Storage system for low-grade heat recovery is being proposed. As the atomic size of salt increases calorific value of mixture decreases & overall energy storage capacity decreases. But temperature increment of system is faster. But, for energy holding capacity KNO^3 has shown better results than $NaNO_3$. Its reason could be the atomic weight of the salt molecule. Among all 50 : 50 solutions have the maximum amount of energy stored and 60 : 40 solution has the slowest rate of heat loss among all. **Applications/Improvements:** This system can be used for applications like space heating, water heating etc. and for power generation also in conjunction with Organic Rankine Cycle (ORC) turbines which can operate at temperatures as low as 70°C.

Keywords: Heat Capacity, Heat Loss Rate, Low-Grade Heat, Specific Heat Capacity, Waste Heat Recovery, KNO_3, $NaNO_3$

1. Introduction

Everyday enormous amount of heat is rejected to the atmosphere by industries and households. This heat contributes to global warming, which is humanities biggest concerns about environment. A solution to this problem is a low grade thermal energy storage system. We need an effective way to store the excess heat produced during day to day operations and should be able to utilise that heat energy for various applications like space and water heating for buildings, offices and industries. A TES system can also be used to store solar energy for power generation using organic Rankine cycle plants. Molten salt TES systems are used around the world to store energy but they have their drawbacks, for example, very large storage tanks are required to safely store molten mixture of salts, acres of field is acquired to install parabolic trough mirrors to concentrate solar energy, the plant need to be far away from society because of safety hazards but this leads to need for long distance transmission lines which affects overall efficiency, this system can only be used for high grade heat which means it cannot be used for waste heat recovery. Heat is stored in two forms namely: Sensible Heat and Latent Heat. Sensible heat is stored when the energy is used to rise the temperature of the fluid whereas latent heat is stored when the material is undergoing a phase change, no change in temperature occurs during phase change. In this study we will focus on sensible heat storage.

Water is a very good medium to store sensible heat energy as it is readily available and environment friendly but, because of its high vapour pressure water cannot be used above 90°C temperature. This limits its

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application as working fluid in a TES system. But a change in its thermal properties is recorded when mixed with salts. Salts have lower vapour pressure, high melting and boiling point, higher thermal conductivity when compared with water. In this research three mixtures of Sodium Nitrate ($NaNO_3$) and Potassium Nitrate (KNO_3) are used. The concentrations used of $NaNO_3$: KNO_3 are as follows: 60 : 40, 50 : 50, 40 : 60. Three different samples of each were prepared by mixing 300 g in 1 L of distilled water.

A study conducted on a binary salt mixture of 30wt% of KNO_3 and 70wt% of $NaNO_3$ having a melting rage between 223°C – 260°C shows that this mixture has cyclic stability of 90 days[1]. A new method was invented to develop optimised salt systems by studying thermal properties and thermal decomposition of salts[2]. A new formulation method was studied to formulate different molten nitrate/nitrate salts consisting $LiNO_3$, KNO_2, KNO_3 and $NaNO_2$ that exhibits properties like low melting point and high specific heat capacity[3]. Another study shows that the long term thermal stability of eutectic $LiNO_3$-$NaNO_3$-KNO_3 mixture was limited at 500°C when tested under atmospheres of different gasses of Ar, N, O and air[4]. A review of thermal conductivity of molten salts revealed that a correlation exists between the thermal conductivity at the melting point and the mean ionic weight of a univalent molten salt[5]. Phase Change Materials (PCM) can be used to improve the thermal energy storage system for low-grade waste heat recovery[6]. Nitrates acts as corrosion inhibitors. Adding 3wt% of $NaNO_3$ in concrete mix significantly inhibits corrosion of steel rebars[7]. A storage tank with PCM having capacity of 345.121 kJ/hr was investigated and validated for a solar thermal plant to make use of renewable energy[8].

Specific heat capacity, heat capacity, energy holding capacity heat loss rate are some factors which significantly affect the performance and efficiency of a TES system. These properties were measured by performing experiments and are presented in the form of graph plots.

2. Experimental Setup

Apparatus consists of two concentric aluminium vessels of 3 mm wall thickness, with an air gap of 2 cm in between those vessels. For heating a 250 watt heating coil is fitted in a horizontal manner with the help of U-shape aluminium attachment. Ends of heating coils are covered by silicone to avoid any transfer of electricity to the system. For measurement of temperature increment a K-Type thermocouple probe is inserted via lid.For experiments three samples of salt mixture were prepared with ratios 40 : 60, 50 : 50, 60 : 40. With each sample weighting 300 gm.These samples were then added to 1 L water and mixed thoroughly. The solution was gradually heated till it reached its boiling point. Time was noted down for every 1-degree temperature rise till boiling started. For Energy holding capacity calculation, time was noted down for every 1-degree of temperature drop.

3. Results and Discussions

Heat capacity, specific heat capacity, heat loss rate are the important factors that greatly affects the efficiency of a TES system.

3.1 Specific Heat Capacity (Cp)

Figure 1 depicts Temperature vs Specific heat graph for all three ratios of KNO_3 : $NaNO_3$. Specific heat of any substance is the amount of heat required to raise its temperature by 1 degree per unit mass. Graphs clearly indicates that the increment in the concentration of KNO_3 increases Cp of the system. For a Thermal Energy Storage system 60 : 40 ($NaNO_3$: KNO_3) ratio seems to be the best option. Cp was calculated using the equation:

$$Cp = Q / (m \times \Delta T)$$

Where,
Cp = specific heat capacity
Q = heat added
m = mass
ΔT = Time taken for 1°C temp. rise

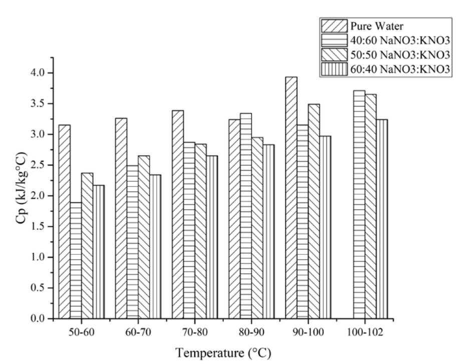

Figure 1. Temperature vs Cp.

3.2 Total Energy (Q)

Total energy is the actual amount of energy that a TES system can store without changing phase. In this case heat was provided to the solution till the boiling point is reached. It is determined by calculating the amount of energy provided to reach the boiling point.

Figure 2 clearly indicate that significant increase in total energy of samples as compared to water. 50 : 50 appears to have the maximum amount of energy stored.

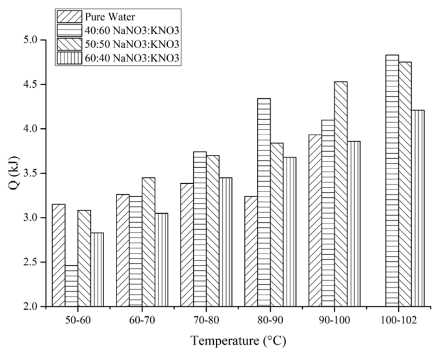

Figure 2. Temperature vs Q.

3.3 Heat Capacity (C)

Heat capacity is the capacity of the system to store sensible heat. It is a theoretical value which can be calculated at any point in the system. It is the ratio of total heat added to the total change in its temperature. Again, 50 : 50 appears to give the best results as shown in Figure 3. It is determined using following equation:

$$C = Q / (Tf - T\infty)$$

Where,
C = Heat capacity
Tf = Final temp
Ti = Initial temp

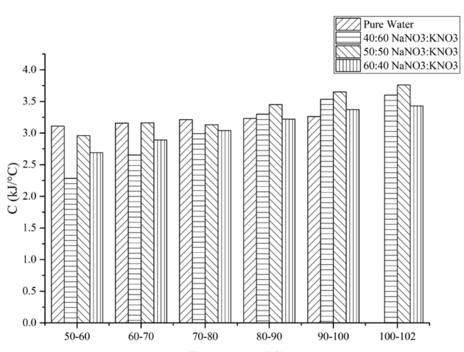

Figure 3. Temperature vs C.

3.4 Heat Loss Rate (Qloss)

As the name suggests it is the rate at which the TES system is able to reject heat or is capable to withhold the energy for specific amount of time. It must be minimum for TES system but, for a working fluid it is desirable to have a fast dissipation rate to have maximum effectiveness.

It is evident from the Figure 4 that all the three solutions are better than water and 60 : 40 solutions has the slowest rate of heat loss among all.

Qloss = (T - T∞) / RTotal
Where,
Qloss = Heat loss rate
T = Internal temp
T∞ = Ambient temp
Rtotal = Total thermal resistance of the container

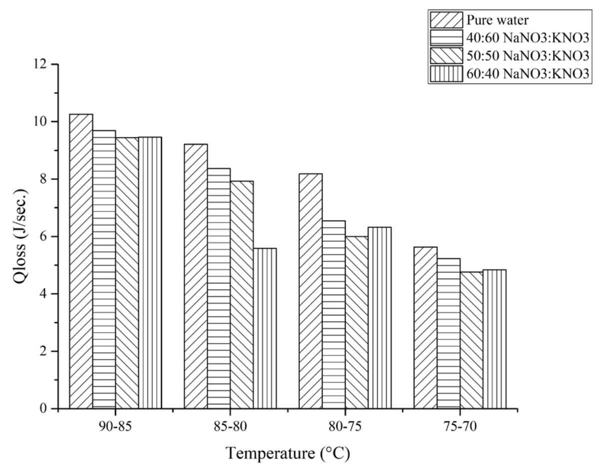

Figure 4. Temperature vs Qloss.

4. Conclusions

This study was to check the feasibility of a mixture of (Nitrate salt+Water) as a possible Thermal Energy Storage system for low grade waste heat recovery. Two different types of salts utilized for experiments were $NaNO_3$ and KNO_3. Reason for selecting these two was their low cost & easy availability. Based on performed experiments following conclusions can be drawn out.

1. Fabrication and usage of nitrate salt based Thermal energy system is feasible.
2. As the atomic size of salt increases calorific value of mixture decreases and overall energy storage capacity decreases. But temperature increment of system is faster.

3. As for energy holding capacity KNO_3 has shown better results than $NaNO_3$. Its reason could be the atomic weight of the salt molecule.
4. As the molecule weight and size increases its random motion decreases, hence low energy transfer during intermolecular collision and better holding capacity.
5. Energy holding capacity also implies heat transfer rate of the system. Better holding capacity means low heat transfer rate.

It is clear from the study that above solutions may be used as TES system or as a working fluid in heat exchanger for low-grade heat applications.

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