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Heat Transfer Performance of Quaternary Molten Nitrate Salt Mixture for Heat Transfer Application

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Abstract: Previous, study has shown that synthetic oil and water are the best medium that can act as heat transfer fluid in heat transfer application. However, in the context of transferring energy, these medium are insufficient for operating at high temperature range due to its characteristic such as low melting point. The use of high temperature molten salt mixture in various industries has resulting big changes in transferring of heat energy. It is proven that the molten salt mixture can carry more heat from one place to another. This study shows the effect of quaternary molten salts mixture consisting of four different salts which are Sodium Nitrate, ($NaNO_3$), Potassium Nitrate, (KNO_3), Lithium Nitrate, ($LiNO_3$), and Calcium Nitrate, ($Ca(NO_3)_2$) that can enhance the heat transfer rate in heat transfer application. New line of quaternary nitrate salt mixtures ($NaNO_3$ - KNO_3- $LiNO_3$ – $Ca(NO_3)_2$) were prepared through mixing process. Those mixtures were then heated inside the box furnace at 150ºC for four hours and rose up the temperature to 400ºC for eight hours to homogenize the mixtures. The temperature was then dropped for several hours until it reaches 115ºC before removing the mixture from the furnace. After that, the quaternary molten salt has been placed inside the boiler for heat transfer performance test. The quaternary molten salt was heated inside the boiler and transferred the heat to the working fluid through the copper coil. The inlet and outlet temperatures were recorded by reading the measuring devices that installed at the inlet and outlet of the boiler. At the boiler temperature of 200ºC, it is shown at time of 25 minutes, sample 5 with composition of 10wt% $NaNO_3$, 60wt% KNO_3, 10wt% $LiNO_3$ and 20wt% $Ca(NO_3)_2$ gives the highest value of heat transfer rate which was 2.65kW, meanwhile at boiler temperature of 100ºC, sample 2 with composition of 22wt%$NaNO_3$, 40wt%KNO_3, 23wt%$LiNO_3$ and 15wt%$Ca(NO_3)_2$ gives the lowest value of heat transfer which was 0.37kW. In the nut shell, by replacing the previous heat transfer fluid to quaternary molten salt mixture can increase the heat transfer rate in heat transfer application.

Keywords: Quaternary molten salt; Nitrate mixture; Heat transfer fluid; Heat transfer application

1. Introduction

The application of molten salt in the context of heat transfer fluid has been widely used in huge industries such as concentrated solar power. It can act as a high temperature heat transfer medium [1] that can help life more comfortable. Besides, molten nitrate salts have already acted as thermal energy storage (TES) medium for solar energy applications. Due to these advantages, molten salt is extensively used in the solar energy applications.

Heat transfer can be defined as shifting heat from one source to another. Any systems that have a higher temperature than the surrounding will undergo heat transfer phenomenon from system to the surrounding. Heat transfer plays an important role in design, performance and operating costs in different engineering systems. The solar power plant, generate electricity, cooling or heating a building, power generation and thermal storage are some examples that applying heat transfer application [2].

From previous study, molten nitrate salt such as $NaNO_3$, KNO_3, $LiNO_3$ and $Ca(NO_3)_2$ has been used in generating new composition that can be a good heat carrier in designated system. Judith *et. al.*, [3] state that a lower melting point in the range of 60–120 °C and a degradation temperature above 500°C were preferred because the selected fluid would enhance the overall efficiency of the plants by utilizing less energy to keep the salt in the liquid state and by producing superheated

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steam at higher temperatures in the Organic Rankine cycle. Another researcher found out that a eutectic line of $LiNO_3$ – $NaNO_3$ – KNO_3 – $NaNO_2$ has been used as a heat transfer medium. This quaternary mixture has a low melting point which is 99.02ºC. Through Differential Scanning Calorimeter testing (DSC), this quaternary salt mixture give a high specific heat capacity compared to that of conventional solar salt and HITEC salts, ($NaNO_3$ – KNO_3 – $NaNO_2$) under controlled variable. The higher the specific heat capacity will increase the thermal energy storage of quaternary molten salt [4]. As the storing capability of quaternary molten salt mixture increase, the heat transfer rate will also increase.

The heat transfer performance test has been done in order to determine the rate of heat transfer from various compositions of quaternary molten nitrate salt mixtures.

2. Experimental Setup

Preparation of Material. Four pure salts consisting of $NaNO_3$, KNO_3, $LiNO_3$ and $Ca(NO_3)_2$, were mixed together to produce various composition of quaternary molten nitrate salt [5]. In order to find the best formulation of quaternary molten nitrate salt that gives a high heat transfer rate, several compositions have been made with the range of composition as shown in Table 1.

Table 1 Range of compositions (%wt)

Molten Salts	Weight (wt%)	Melting point (ºC)
$LiNO_3$	13-21	256.7 [1]
$NaNO_3$	9-18	307.0 [6]
KNO_3	40-52	337.0 [6]
$Ca(NO_3)_2$	10-27	561.0 [7]

The compositions of quaternary molten nitrate salt were prepared according to Table 1. At the beginning of the preparation, each pure salt has been weighed and mixed inside a crucible.

After that, the mixture was heated inside the box furnace for four hours at 150˚C. The temperature was then increased to 400˚C to homogenize the mixture for eight hours. After eight hours, the mixed molten nitrate salts remained inside the furnace until the temperature inside the furnace reached 115˚C. Next, the mixture has been placed into the boiler for heat transfer performance test. The size of the boiler used in this research is 139.7 mm × 127.0 mm × 76.2 mm. It is approximately about 1.5 kg of quaternary molten salt needed to occupy the boiler so that the heat transfer process will occur between the copper coils and working fluid, (water).

Table 2 shows the composition of quaternary molten salt that being testified for heat transfer performance test.

Table 2 The composition of quaternary molten salt

Sample	Weight (wt%)			
	$NaNO_3$	KNO_3	$LiNO_3$	$Ca(NO_3)_2$
Sample 1	20	48	22	10
Sample 2	22	40	23	15
Sample 3	10	50	20	20
Sample 4	14	48	13	25
Sample 5	10	60	10	20
Sample 6	10	50	20	20
Sample 7	10	40	30	20
Sample 8	10	30	40	20

The analysis on the effect of $Ca(NO_3)_2$ has been done by comparing Sample 1, Sample 2, Sample 3 and Sample 4 whereas the analysis on the effect of $LiNO_3$ has been done on Sample 5 until Sample 8 due to constraint composition of $Ca(NO_3)_2$.

Heat Transfer Performance Test. In order to investigate the heat transfer rate, a designated system has been set up for heat transfer performance test as shown in Fig. 1. The flow process of the working fluid, (water) and heat transfer fluid, (quaternary molten nitrate salt mixture) are two crucial mixtures for the system to operate.

The flow of water started from the tank to the whole system with the aid of water pump. At the same time, the quaternary molten nitrate salt was heated inside the boiler and transferring the heat to the working fluid through the copper coil. The inlet and outlet temperature was recorded by reading the measuring devices that has been installed at the inlet and outlet boiler. The change of temperature is the keyword in heat transfer analysis. The analysis has been done by utilizing the table of saturated water temperature to record the value of enthalpy at certain temperature.

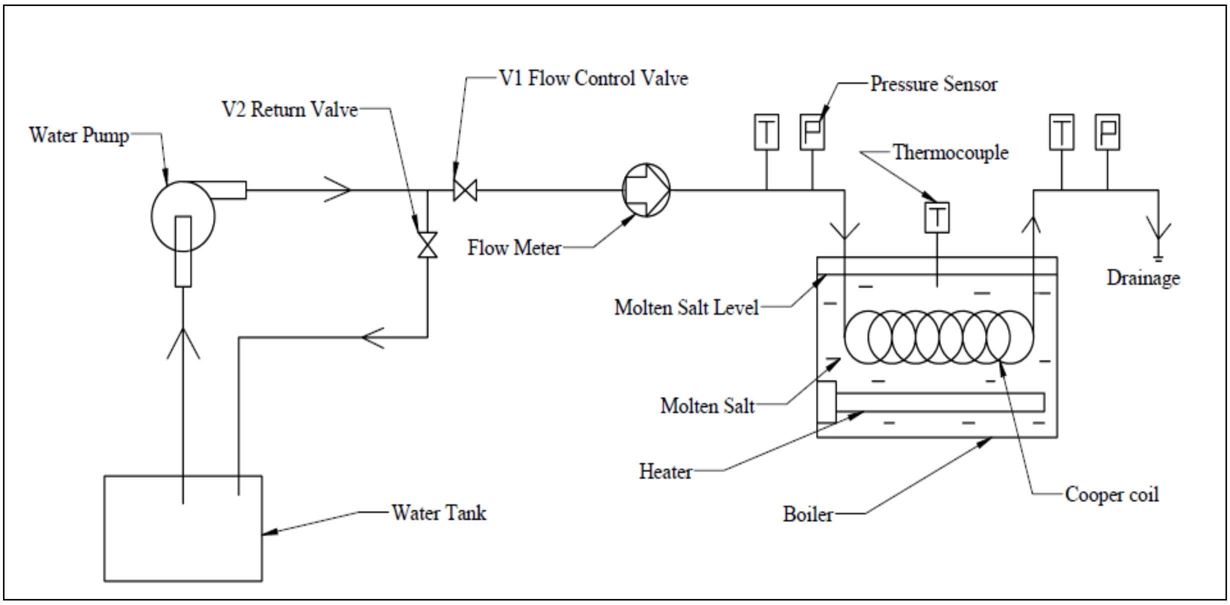

Fig. 1 Experimental diagram for heat transfer performance test

The system has a heat source produced by the electrical heater to the quaternary molten salt inside the boiler. The electrical heater was used to control the heat inside the boiler and avoid quaternary molten salt from freezing. The parameters that have been recorded for this test were working fluid temperature at inlet and outlet of the boiler, mass flow rate of working fluid, enthalpy change and heat transfer rate.

3. Results and Discussion

Heat transfer or more likely known as natural convection is all about the carrying heat from one source to another. Considering any system that consists of high temperature compared to the surrounding, there will be transfer of heat energy from the system to the surroundings. Heat transfer performance test has been conducted by using a designated system of heat transfer performance to evaluate the efficiency of heat transfer fluid of quaternary molten salt nitrate mixture. Through that system, quaternary molten nitrate salt mixture that can transfer heat inside the system has been determined. By using formula Eq. 1, the value of heat transfer of each quaternary molten nitrate salts has been calculated.

$$\dot{Q} = \dot{m}\,(h_2 - h_1) \quad (1)$$

Where $\dot{m}$=Mass flow rate, h_2=Enthalpy at outlet temperature, T_2, h_1=Enthalpy at inlet temperature, T_1.

From Eq. 1, it is shown that the value of enthalpy difference will affect the efficiency of heat transfer itself. The values of enthalpy, h_2 and h_1 can be found by referring table of saturated water temperature using the value of T_2 and T_1. The result of heat transfer rate were tabulated as shown in Table 3, Table 4 and Table 5 for all samples at boiler temperature of 100˚C, 150˚C and 200˚C respectively.

All data for heat transfer performance were recorded and analyzed by using line graph. The graphs were constructed using the value of heat transfer rate against time. Fig. 2 shows the rate of heat transfer for eight samples for boiler temperature of 100˚C.

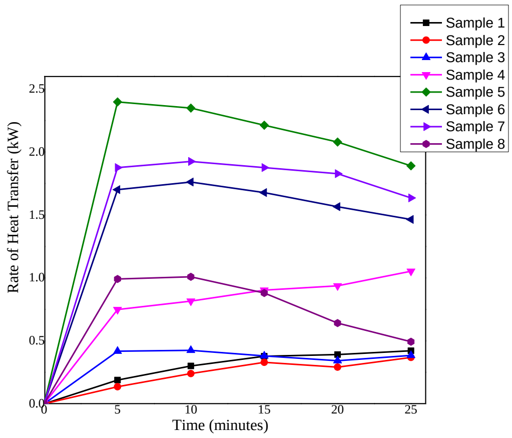

Fig. 2 Rate of heat transfer at boiler temperature of 100˚C

Table 3 Heat transfer rate at boiler temperature of 100°C

Time, min	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7	Sample 8
0	0	0	0	0	0	0	0	0
5	0.19	0.14	0.42	0.75	2.40	1.70	1.88	0.99
10	0.30	0.24	0.42	0.82	2.35	1.76	1.93	1.01
15	0.38	0.33	0.38	0.90	2.21	1.68	1.88	0.88
20	0.39	0.29	0.34	0.94	2.08	1.57	1.83	0.64
25	0.42	0.37	0.38	1.05	1.89	1.46	1.64	0.49

Table 4 Heat transfer rate at boiler temperature of 150°C

Time, min	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7	Sample 8
0	0	0	0	0	0	0	0	0
5	0.64	0.62	0.60	1.94	2.74	2.30	2.32	1.58
10	0.82	0.61	0.63	1.84	2.89	2.31	2.26	1.68
15	0.90	0.70	0.75	2.01	2.88	2.12	2.22	1.6
20	0.88	0.82	0.74	1.87	2.86	2.10	2.22	1.66
25	1.03	0.76	0.66	1.92	2.74	2.12	2.13	1.57

Table 5 Heat transfer rate at boiler temperature of 200°C

Time, min	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7	Sample 8
0	0	0	0	0	0	0	0	0
5	1.70	2.12	1.94	2.09	2.86	2.79	2.71	2.25
10	1.92	2.15	2.14	2.14	2.74	2.65	2.60	2.04
15	1.93	2.11	1.93	2.10	2.74	2.67	2.72	2.07
20	1.97	2.11	2.14	2.07	2.74	2.60	2.67	2.06
25	2.01	2.15	2.01	2.09	2.65	2.55	2.60	2.07

Based on Fig.2, it is observed that at the end of experiment, Sample 5 gives the highest rate of heat transfer performance which was 1.89 kW whereas Sample 2 gives the lowest rate of heat transfer which was 0.37 kW. Based on Table 2, it can be seen that the change of composition in $LiNO_3$ has affected the rate of heat transfer. As reported by Wang *et. al*., that the melting point of $LiNO_3$ is the lowest which was 256.7°C and has a low specific heat capacity [8,9]. As the composition of $LiNO_3$ increase, the average of specific heat capacity decreases. Therefore, the ability of quaternary molten nitrate salt to store energy decreases due to low specific heat capacity. When the ability of storing heat is decrease, the capability of quaternary molten salt mixture to carry heat will also decrease. According to Venegas *et. al*., the higher the composition of $LiNO_3$ in quaternary molten salt mixtures, the lower the values of heat transfer rate [10]. Hence, by lowering the composition of $LiNO_3$ in quaternary molten salt mixtures, it will improve the value of heat transfer rate.

Next, Fig. 3 shows the rate of heat transfer for all samples at boiler temperature of 150°C. It is shown that sample 5 has the highest rate of heat transfer value which was 2.74 kW compared to sample 3 that gives the lowest rate of heat transfer, 0.66 kW.

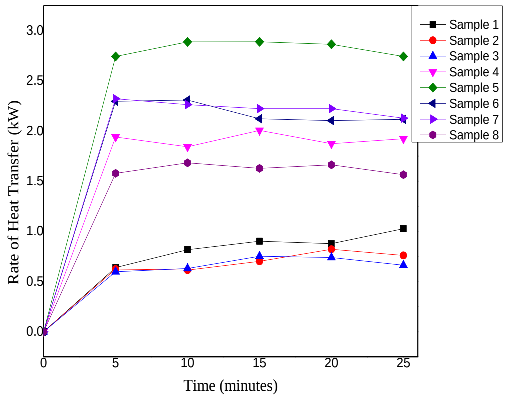

Fig. 3 Rate of heat transfer at boiler temperature of 150˚C

Fig. 4 shows the rate of heat transfer for all samples for boiler temperature of 200˚C. At the end of the experiment, it is shown that sample 5 has the highest rate of heat transfer value which was 2.65 kW. Meanwhile, at 200˚C, sample 1 gives the lowest rate of heat transfers which were 2.01 kW.

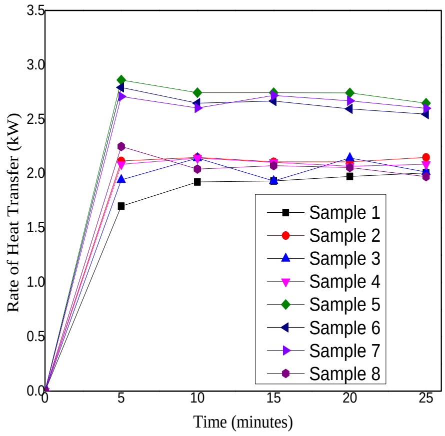

Fig. 4 Rate of heat transfer at boiler temperature of 200˚C

From Table 2, as the composition of $Ca(NO_3)_2$ increased, the rate of heat transfer increased. It is reported that the melting point of $Ca(NO_3)_2$ is 561˚C [7]. Hence, the higher the composition of $Ca(NO_3)_2$ in quaternary molten salt mixtures, the higher the rate of heat transfer. From the data collected, the enthalpy difference at boiler temperature of 200˚C was bigger compared to 100˚C.

In overall, the rate of heat transfer at boiler temperature of 200˚C was higher compared to the rate of heat transfer at boiler temperature 150˚C and 100˚C.

4. Conclusion

As a conclusion, heat transfer rate were experimentally determined by conducting the heat transfer performance test. It is proven that the higher the composition of $Ca(NO_3)_2$ in quaternary molten nitrate salt mixture has increased the value of heat transfer rate. At boiler temperature of 200˚C, Sample 5 has the highest heat transfer rate which was 2.65 kW at the end of experiment. Meanwhile, by lowering the composition of $LiNO_3$ has given a better heat transfer rate. It is proved at boiler temperature of 100˚C that by increasing the composition of $LiNO_3$ will lowered the value of heat transfer rate. It can be seen that Sample 2 with the highest composition of $LiNO_3$ presents the lowest value of heat transfer rate which is 0.37 kW. By lowering the composition of $LiNO_3$ will increase the rate of heat transfer of quaternary molten salts mixture.

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