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Research Article

THERMODYNAMIC SIMULATION AND ECONOMIC ANALYSIS OF MOLTEN SALT THERMAL ENERGY STORAGE SYSTEM

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ABSTRACT:
This research focuses on applying thermal energy storage system using molten salt as a storage medium to the steam production system of a food processing factory. Parabolic trough solar collector was installed as a heat source for a hot oil steam generator which was used to produce steam for pasteurization. Previously, only fossil-fuel boilers were used to produce steam. In this work, two tank molten salt system was considered. The system consists of a cold tank and a hot tank to be used for steam production at night or when there is no sunlight for up to 4 hours per day instead of using fossil-fueled boilers. The process flow diagram of the existing steam production system was created in Aspen Hysys. Then it has been modified with the molten salt thermal energy storage system. Hot oil (PTT-Hitemp 500) is used an intermediary for receiving thermal energy from the solar collector to the steam generator, while molten salt (60% KNO_3 and 40% $NaNO_3$) acts as a thermal energy storage medium. The simulation result showed that the thermal energy storage could produce saturated steam at the pressure of 6 bar and 158 °C with sufficient flow rate to meet production's demand at 0.5 m^3/hr. Economic analysis of the molten salt thermal energy storage system has been performed and key performance indicators have been evaluated. All indicators show favorable result, thus, indicating that the molten salt thermal energy storage system is economically feasible.

Keywords: *Thermal energy storage, Thermodynamic analysis, Hot oil, Molten salt, Economic analysis*

1. INTRODUCTION

Solar energy is one of the world's largest renewable energy sources [1]. Technologies related to solar energy have been continuously researched and developed from past to present. To maximize solar energy utilization and to create long-term environmental and commercial benefits, it is possible to store the thermal energy during the day and use it at night [2]. Solar thermal energy storage can be divided into 2 categories:

1. Direct system is a process by which the working fluid directly receives thermal energy from sunlight and transfers its thermal energy via a heat exchanger to the desired substances for further end use [3, 4].

2. Indirect system involves two working fluids and heat exchangers. The primary working fluid receives thermal energy from sunlight, and then transfers its thermal energy to the secondary working fluid through a primary heat exchanger. The secondary working fluid heats up the desired substances in the secondary heat exchanger [3, 4].

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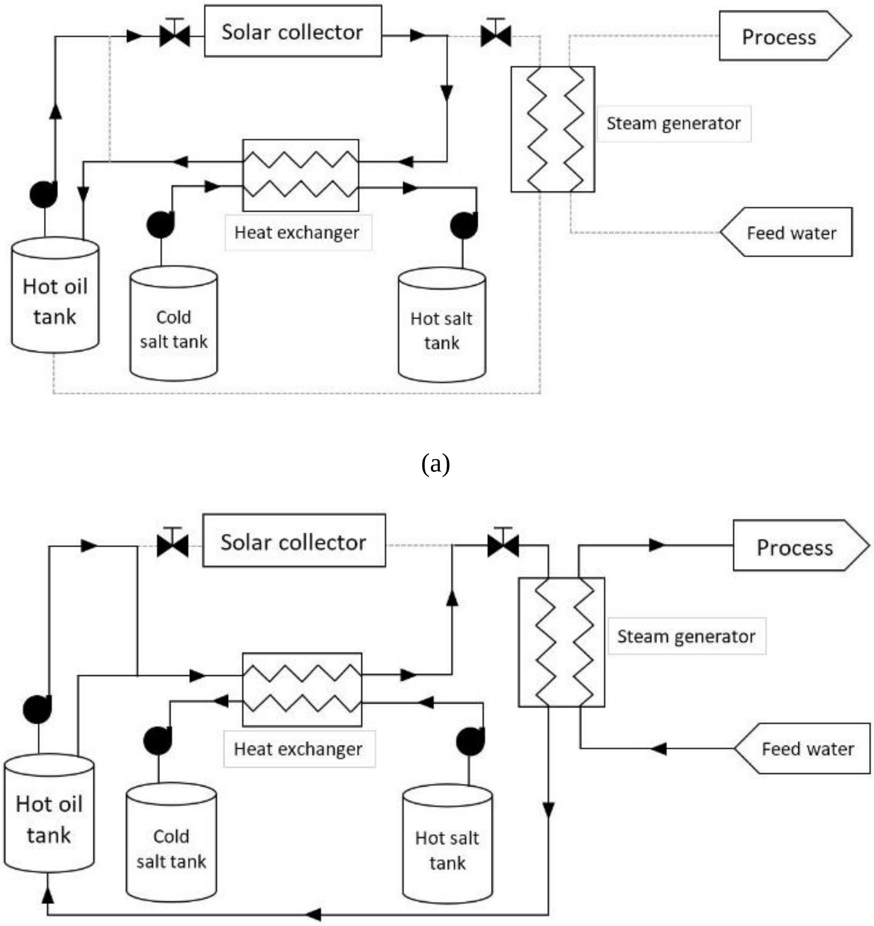
In this research, the concept of molten salt thermal energy storage is applied to the steam production process of a food processing factory that produces fruit and vegetable juices. At the factory, a parabolic trough solar collector was installed as a heat source for a hot oil steam generator which was used to produce steam for pasteurization. As a working fluid, the hot oil receives the heat from sunlight and passes through a steam generator to convert feedwater into steam. On the day when there is insufficient solar heat or when the production schedule is extended beyond daytime, fossil-fuelled boiler will be used as a supplementary heat source. The use of fossil fuel during these periods increases the operating cost and release pollutions to the environment. Therefore, in order to reduce the variability of the solar steam generation system and extend its serviceable hours during the night-time, the objective of this research is to investigate the technical and economic feasibility of installing a molten salt thermal energy storage added to the existing solar steam generation system. To minimize the plant interruption and the cost of retrofitting, the direct heating system between hot oil and water is retained. In this case, the hot oil will collect solar heat to melt the salt during charging process. At night during the discharging process, the molten salt is used to heat the hot oil instead of solar heat while the steam production rate is kept at a desirable flowrate. To achieve this objective, the process flow model representing the solar steam production system and the thermal energy storage system were created in Aspen Hysys. The time-dependent behavior of the system during charging and discharging was investigated and discussed in this paper. Finally, the economic analysis using various methods has been carried out to evaluate the economic worthiness of the thermal energy storage.

2. Verification of Simulation Tool and Process Flow Design

To analyze the operating condition and key performance indicators (pressure, temperature, flowrate, efficiency, etc.) of the molten salt thermal energy storage system, this research has created a thermodynamic model of the system in Aspen Hysys. Aspen Hysys is a well-known commercial process modeling tool capable of both steady-state and transient processes [2]. However, before applying this simulation tool to analyze the problem of interest, the reliability of Aspen Hysys needs to be verified. This task has been carried out by (1) selecting a representative experiment from published literature, (2) creating the model in Aspen Hysys, and (3) benchmarking its calculation results with reported experimental data so that the accuracy, reliability and uncertainty can be estimated. In this paper, the work by Peiró et al. entitled "Experimental analysis of charging and discharging processes, with parallel and counter flow arrangements, in a molten salts high temperature pilot plant scale setup" [5] has been chosen as the representative model for benchmarking. Details of the modeling and simulation processes were described elsewhere [2]. By comparing the simulation results from Aspen Hysys with the experimental results by Peiró et al., in general, the discrepancies between the calculated and measured results in most processes were less than 5% except one state point during the charging process which had around 30% error. Reportedly, this deviation was caused by uncertainty electrical power and temperature measurement. Overall, it can be concluded that Aspen Hysys is an effective and reliable tool suitable for modeling the molten salt thermal energy storage system.

After the reliability testing of Aspen Hysys, the next step was to design a process flow diagram. In this work, the thermal energy storage system was designed using two-tank system consisting of hot and cold molten salt tanks with solar energy as a heat source. This two-tank system has 2 modes of operation: charging process where molten salt receives heat and discharging process where the molten salt release stored thermal energy to the working fluid. In this design, the working fluid is hot oil PTT-Hitemp 500 and the molten salt is a mixture of 60% potassium nitrate and 40% sodium nitrate, commonly known as solar salt. A process flow diagram of both charging and discharging processes is shown in Fig. 1. The key equipment in the process are solar collector, cold and hot salt tanks, hot oil tank, heat exchanger, steam generator, and pumps.



(a)

(b)

Fig. 1. Process flow diagram of molten salt thermal energy storage (a) charging process and (b) discharging process

From Fig. 1a, the charging process begins by pumping the heat transfer fluid (hot oil) from hot oil storage tank into the solar collector to collect thermal energy from solar irradiation and then transfer to the molten salt from the cold salt tank via a heat exchanger. The molten salt at higher temperature is then kept in a hot molten salt tank while the hot oil flows back to the storage tank. The flow of hot oil to steam generator is closed during this mode of operation. During the discharging process, the hot oil receives thermal energy from the molten salt from hot salt tank via the heat exchanger then it flows to a steam generator to convert feedwater to steam. Finally, the hot oil flows back to the storage tank. Similarly, the molten salt is fed back to the cold salt tank after a heat exchanging process with hot oil. The flow of hot oil to solar collector is closed during discharging process. For the operation of fossil-fueled boilers, it was intended for use in the in the absence of sunlight, during inclement weather or seasonal peak demand. However, it is expected that when the thermal energy storage system is incorporated into the existing system, it can replace the need for fossil-fuelled boilers. In this work, the molten salt thermal energy storage was designed to store thermal energy sufficient for steam production up to 4 hours a day.

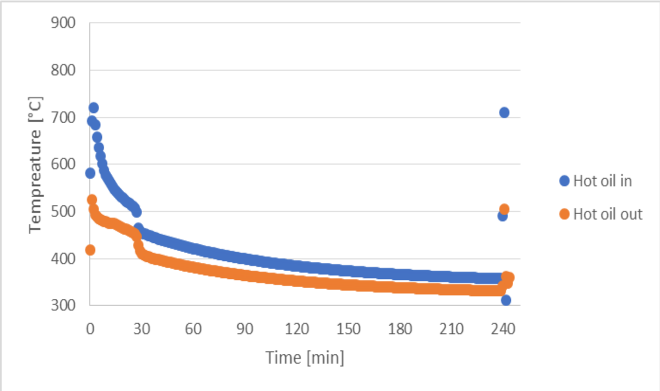
3. Simulation Results

From Fig. 1, the process flowsheet has been created in Aspen Hysys. One of the key input parameters that need to be defined is the steam demand volume. In this case, it has been set at 0.5 m^3/hr according to the factory demand for product pasteurization. Other importation parameter such as mass flow rate of hot oil and molten salt, temperature and pressure at different locations in the process were obtained from the factory. The simulation of the process begins in the transient state and over time it will reach a steady state. The simulation period is set to 4 hours or 240 minutes. The results obtained when a steady state condition is reached are shown in Table 1. Details description of the initial conditions, state parameters e.g. temperature, pressure, mass flowrate, enthalpy, entropy, and exergy are described elsewhere [2].

Table 1: Summary of process parameters obtained after steady-state condition.

Properties	Data	Unit
Temperature of hot oil inlet heat exchanger	280	°C
Mass flow rate of hot oil outlet solar collector	1.74	kg/s
Volume flow rate of molten salt	1.98	m^3/h
Heat flow to solar collector	2.936×10^6	kJ/h
Temperature inside hot salt tank	367	°C

From the simulation, time-dependent behavior of temperature of hot oil and molten salt (MS) is shown in Fig. 2(a) and 2(b), respectively. The amount of heat exchanged in kW between the hot oil and the molten salt is shown in Fig. 3(a) and 3(b), respectively.



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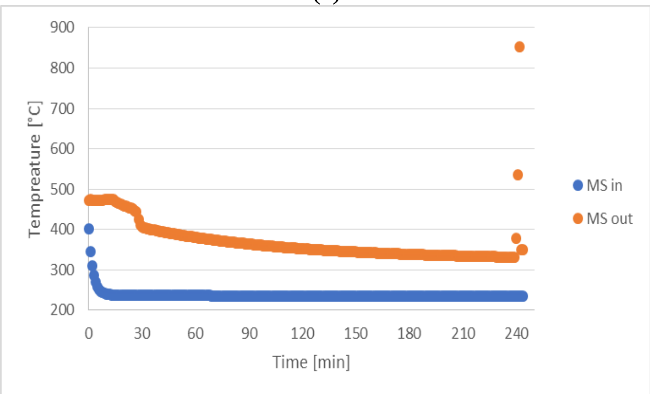
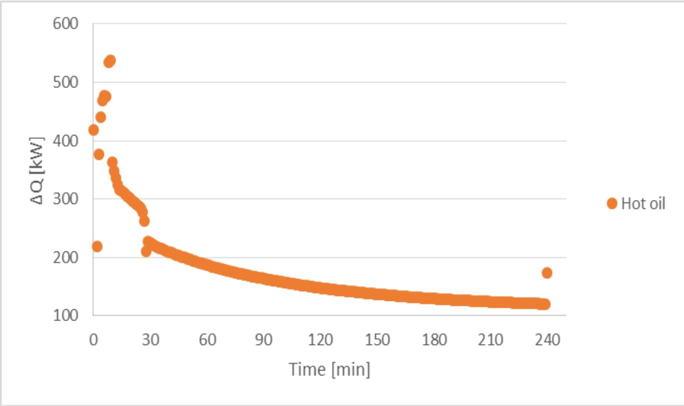


(b)

Fig. 2. Time-dependent behavior of temperature of (a) hot oil and (b) molten salt when passing through the heat exchanger during the charging process.



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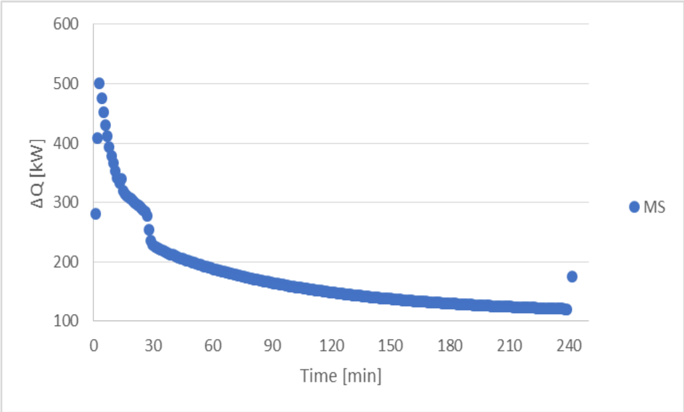
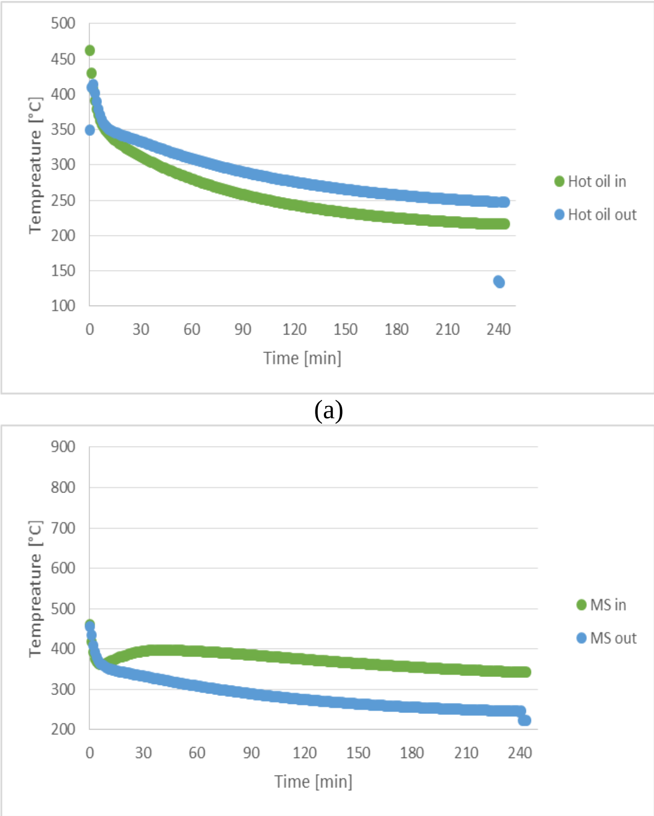


(b)

Fig. 3. Time-dependent behavior of heat exchanged of (a) hot oil and (b) Molten salt during the charging process.

Figures 2a and 2b show the temperature of the hot oil and molten salt at the inlet and outlet of the heat exchanger. Temperature fluctuation occurred at the beginning of the simulation because the system was in a transient state. After about 235 minutes near the end of simulation period, the system approached a steady state as the temperature profiles become smooth. The temperature of the hot oil at the inlet and outlet of the heat exchanger was approximately 380 ° C and 320 ° C, respectively. The temperature of the molten salt at the entrance and exit of the heat exchanger at steady state was approximately 220 ° C and 330 ° C, respectively. A sudden change in molten salt temperature at the outlet of the heat exchanger at the end of the simulation was caused by the constant charging of hot oil into the exchanger while the molten salt from cold salt tank was near depletion. The amount of heat exchanged between hot oil and molten salt was approximately 110 kW, as shown in Fig. 3a and Fig. 3b. Intuitively, the amount of heat exchanged between the hot and cold stream was higher at the beginning during a transient state. As the two fluids were trying to reach a thermal equilibrium, the amount of heat transferred gradually decreased until it reached an equilibrium value.

After the charging stage, the next task is to assess the performance of the energy storage system during the discharging. From the simulation, the time-dependent behavior of hot oil and molten salt temperatures as well as the amount of heat exchanged during the discharging are shown in Fig. 4 and 5, respectively.



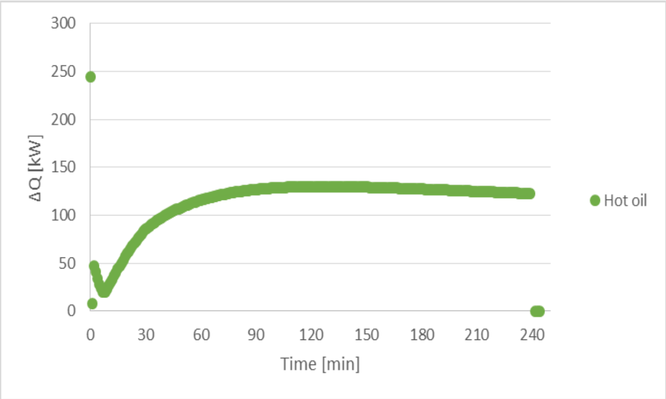
(a)

(b)

Fig. 4. Time-dependent behavior of temperature of (a) hot oil and (b) molten salt when passing through the heat exchanger during the discharging process.

Figures 4a and 4b show time evolution of hot oil and molten salt temperature at the inlet and outlet of the heat exchanger during the discharging process. Similar to the charging process, the system began in a transient state as both fluid streams gradually converged onto each other to achieve thermal equilibrium near the end of simulation. At the end of simulation, the temperature of hot oil at inlet and out was approximately 220 °C and 250 °C, respectively whereas that of molten salt was approximately 350 °C and 245 °C, respectively. The amount of heat exchanged was approximately 120 kW as the system approached a steady state as shown in Fig. 5a and Fig. 5b. A sudden drop in heat transfer and a decrease in hot oil temperature at the end of simulation were primarily caused by the depletion of molten salt from the hot salt tank as the flow rate of hot oil was kept constant.

Through simulations of both processes, the amount of steam produced is shown in Fig. 6. From the required operating conditions of (1) steam as a saturated vapor at the pressure of 6 bar and 158 °C, (2) a minimum volumetric flowrate of 0.5 m^3/hr, and (3) operating period of 4 hours, it can be clearly seen that the thermal energy storage system have simulated could meet the initial production demand with acceptable quantities.



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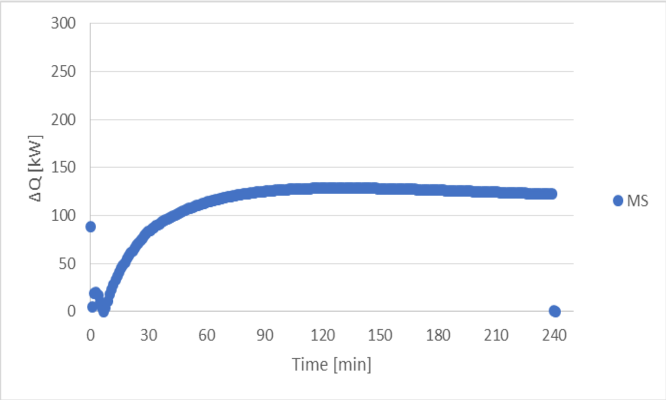

(b)

Fig. 5. Time-dependent behavior of heat exchanged of (a) hot oil and (b) Molten salt during the discharging process.

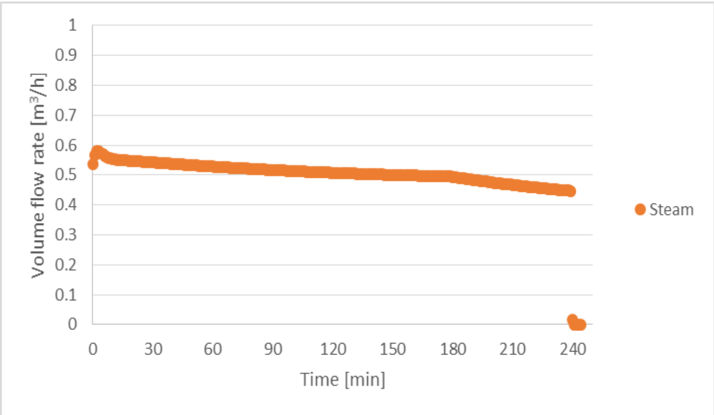

Fig. 6. The volumetric flowrate of steam produced from the discharging process.

From Fig. 2b, the outlet temperature at the molten salt during the first 10 minutes of simulation could increase as high as 400-480 °C which is inconsistently higher than the inlet temperature of hot oil in as can be seen from Fig. 2a. Similarly in Fig. 4a, the outlet temperature of hot oil could reach 380-420 °C during the first 10 minutes of simulation which is again inconsistently exceeds the temperature at the entrance of the molten salt as can be seen from Fig. 4b. From this occurrence, it can be described that as the system begins in transient state, the first 10 minutes of simulation involved a lot of changes in fluid temperature, flow path, and fluid flow rate by process control i.e. flow interference by valve opening and closing. The change in flow path is responsible for controlling the process operation. During the charging and discharging process, a flow path of hot oil is changed from the steam generator or solar collector to the molten salt heat exchanger. Once the flow switching is complete, the process resumed normal operation after 5 to 10 minutes.

4. THERMODYNAMIC AND ECONOMIC ANALYSIS

The simulation results can be further manipulated into various indicators representing the thermodynamic performance of the system.

4.1 Thermodynamic efficiencies [6]

The thermodynamic efficiencies of the molten salt thermal energy storage system can be divided into 3 parameters: thermal efficiency, exergy destruction, and exergy efficiency.

4.1.1 Thermal efficiency or the first-law efficiency

Thermal efficiency of the whole plant can be determined using Equation 1

$$\eta_I = \frac{\dot{m}_{water}(\Delta h)}{\dot{Q}_{solar\ collector}}$$
(1)

where η_I = first-law thermodynamic efficiency
$\dot{m}_{water}$ = mass flow rate of feedwater at steam generator (kg/h)
Δh = enthalpy difference at the outlet and inlet of the steam generator (kJ/kg)
$\dot{Q}_{solar\ collector}$ = rate of heat input to solar collector (kJ/h)

The results obtained from the simulation were calculated according to Equation (1), it can be concluded that first-law efficiency of this system is 28%. The detailed descriptions of the calculation were described elsewhere [2].

4.1.2 Exergy destruction

Exergy destruction or irreversibility can be calculated using Equation 2

$$\dot{X}_{destroyed} = \dot{m}\left(\dot{X}_2 - \dot{X}_1\right)$$
(2)

where $\dot{X}_{destroyed}$ = Exergy destroyed (kW)
$\dot{m}$ = Mass flow rate at the point of interest (kg/s)
$\dot{X}_2 - \dot{X}_1$ = Exergy difference between two state points (kJ/kg)

Exergy destruction can be calculated by taking the difference between the exergy values of each state point. Table 2 summarizes the exergy destroyed by each process equipment. It can be seen that the exergy destruction is largest when there is temperature difference or heat transfer involve either with the surrounding or with the other working fluid. In this case, the solar collector, the steam generator, and the heat exchanger have the highest exergy destruction. On a contrary, devices that involve pressure change and mass flowrate such as pump, valve, or pipe induce insignificant changes in the exergy of working fluids.

Table 2: Summary of exergy destroyed after each process equipment.

Equipment	Exergy destroyed	
	Charging Process	**Discharging Process**
Hot Oil Pump	0.33	0.33
Hot Oil Value	0.02	0.02
Hot Oil Pipe	1.53	2.80
Solar collector	298.51	-
Heat Exchanger	120.55	110.15
Steam Generator	-	150.88
Molten Salt Pipe	7.134	3.10
Molten Salt Pump	0.33	0.04

Molten Salt Value	0.02	-
Molten Salt Pipe	1.71	-

4.1.3 Exergy efficiency or the second-law efficiency

In this work, the second-law efficiency can be calculated only at the heat exchanger as it was the only equipment that was designed with a specific value of heat transfer coefficient, the surface area, the minimum temperature difference, etc. For all other equipment, there were assumed as reversible devices. So, the second-law efficiency is defined in Equation 3. The detailed descriptions of the calculation were described elsewhere [2].

$$\eta_{II}=\frac{Exergy\ recovered}{Exergy\ expended}=1-\frac{Exergy\ destroyed}{Exergy\ expended} \tag{3}$$

In summary, the second-law efficiency of the heat exchanger during the charging and discharging process were 90% and 87%, respectively, indicating a high-level of reversibility of the heat transfer between the molten salt and the hot oil can achieve given the initial assumption of no heat losses and pressure drops.

4.2 Economic Analysis [7]

The economic worthiness of the molten salt thermal energy storage has been estimated based on the assumption that the molten salt system could be used to reduce the operating hours of the existing steam boiler by 4 hours per day. The reduction in fuel consumption directly translates into a fuel cost saving. Based on the average steam production for 4 months in 2018 and 2019, the total cost saving per moth is summarized in Table 3.

Table 3: Estimated cost saving from molten salt thermal energy storage.

Condition	Value	Unit
Existing operating hours	286.3	hr/month
Reduced operating hours	94	hr/month
Fuel consumption rate	75.94	L/hr
Fuel cost (Heavy fuel oil)	18.5	Bath/L
Fuel cost saving	132,059.66	Bath/month
Electricity bill from electric heater and pump	38,200	Bath/year

From the information in Table 3, it can be concluded the fuel consumption will be reduced by 32.8% per month or approximately 132,000 baht per month. To incorporate the molten salt thermal energy storage into the existing solar collector system, the cost of new equipment must be assessed: (1) cold salt tank, (2) hot salt tank, (3) heat exchanger, (4) additional piping for molten salt and hot oil [8], (5) hot oil pumps and molten salt pump [9], additional electricity cost for salt heater [10]. The cost of two molten salt tanks and a custom designed heat exchanger obtained from local vendors is approximately 6,174,039 baht. Details of the cost estimation are described elsewhere [2]. Taking the cost of these major equipment and scale it with the cost of auxiliary equipment such as pumps, valves, and piping, the total cost of capital expenditure (CAPEX) and the cost of operating expenditure (OPEX) that calculated from are summarized in Table 4.

Table 4: Summary of expense and investment condition of the project

Expense	Value	Unit
Capital expense at year 0	7,745,568	Bath
Annual operating expense	580,390	Bath/year
Project lifetime	25	year
Minimum attractive rate of return (MARR)	10	%

To evaluate the economic feasibility of the molten salt thermal energy storage, first, the project lifetime and the minimum attractive rate of return (MARR) have to be assumed. In this case, they are initial specified at a lifetime of 25 years and the MARR of 10%. The economic feasibility has been analyzed by 5 different methods as follows: 1. Economic efficiency, 2. Net Present Value (NPV), 3. Payback Period (PB), 4. Internal Rate of Return (IRR), 5. Benefit-to-Cost Ratio. From the economic performance evaluation, the results of each evaluation method can be summarized in Table 5. In this work, the economic efficiency is defined as the ratio of expected revenue over required investment over project lifetime. Details of the calculations are described elsewhere [2].

Table 5: Summary of economic feasibility evaluation.

Method of analysis	Efficiency calculation	Minimum criteria for investment
Economic Efficiency	242.85%	Economic Efficiency > 100%
NPV	11,064,319	NPV > 0
PB	8.9 year	PB < Life-time
IRR	13%	IRR > MARR
B/C Ratio	2.428	B/C Ratio > 1

From the Table 5, it can be concluded that all economic performance indicators exceeds the minimum criteria for investment. This made it possible to consider that the molten salt thermal energy storage system project would be interesting for actual implementation.

5. CONCLUSION

A molten salt thermal energy storage system has been proposed as an additional system to the existing solar thermal system using parabolic trough solar collectors. The thermodynamic models of the existing solar collector and the enhanced thermal storage system have been created in Aspen Hysys. In the process flow simulation, a two-tank molten salt thermal energy storage system, consisting of a cold tank and a hot tank, has been designed in accordance to meet the steam demand. The process flow diagram has been designed to handle two modes of operation: charging and discharging processes. Working fluids were hot oil (PTT-Hitemp 500) and solar salt (60% KNO_3) and 40% $NaNO_3$). During the charging process, the hot oil receives heat from solar collect and transfers it to the molten salt when steam production is not yet needed. During the discharging process, hot oil heated by the molten salt is used to produce steam in the steam generator.

Simulation results indicated that the temperature and mass flowrate of the working fluids were in acceptable range and suitable for actual operation. The steam production during the discharging process was in the desirable range of around 0.5 m^3/hr. The first thermodynamic law efficiency is 28%, the second thermodynamic law efficiency is 90% during the charging process and 87% during the discharging process. The highest exergy destruction occurs in devices involving heat transfer and heat exchange.

From the economic analysis, it has been estimated that the fuel consumption could be reduced by 32.8% which could be translates to a cost saving of around 132,059.66 baht per month. The initial investment required was 7.8 million baht with the annual operating cost of approximately 580,000 baht with the economic efficiency of 242.85%, the net present value (NPV) of 11,064,319 baht, the payback period of around 9 years, the internal rate of return (IRR) of 13%, and the benefit cost ratio (BCR) of 2.428. All indicators show favorable result, thus, indicating that the molten salt thermal energy storage system is economically feasible.

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