Exergetic-Economic analysis and optimization of solar assisted heat pump using Multi-objective Genetic Algorithm

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Abstract. This study proposes the use of two-stage heat pump systems (SAHPs) for high temperature applications, 105°C. This system integrates solar thermal collectors and heat pumps into a hybrid system to meet the 400 kW heating load. The aim of this research is providing a method to deliver heat with sustainable energy resource, than to improve the performance of the system which is indicated by low exergy destruction. The model creation, performance evaluation and the optimization of solar assisted heat pump system are discussed in this paper. This system used R1234ze (E) as working fluid. A genetic algorithm is employed to optimize operation condition of the system. To ensure that the optimal solution obtained from the proposed method is an optimum condition, including evaporation temperatures, condensing temperatures and compressor temperatures while exergy destruction and total cost as the objective functions. The result showed that the system has an optimum condition at evaporating temperature of 317 K, Flash Tank temperature of 353.6 K and condensing temperature of 380.4 K with exergy destruction of 70.21 kW and total cost of 63,441 US$.

1. Introduction
Heat pumps are device that can upgrade heat from low to high temperature level by integrated it with external energy source such as solar energy [1,2]. Heat pumps can greatly reduce the use of energy in the system while producing adequate heating performance [2,3]. Nowadays, heat pumps are available for low temperature applications (below 60°C) in the residential sector, but have yet in industry applications (above 90°C) [4]. To make heat pumps more attractive for industrial applications, it is important to demonstrate their potential.

Some studies have been conducted on analysis of high temperature heat pump. Chaturvedi et al., investigated the capability of two stage heat pump system of meeting required heating load. They used R134a for the refrigerant and one-cover solar collector. The result showed that thermal performance of the system had an improvement by using two stage systems with high condensing temperature [5]. Another research has been carried out by Wu XK [6]. They evaluated the systems for heating process in industry with 80-90°C target temperature. The result showed the COP of the system reached 5.0. It indicates that heat pump is very promising in high temperature application.

In addition, optimum condition of SAHP systems such as good performance and total cost efficient is important to assure. Studies on the optimal condition for SAHP systems are helpful in increasing the performance of the systems. Khorasaninejad performed solar assisted heat pump optimization using
particle swamp [7]. Daley and Redlund found possibilities for improving the heat pump system performance by modeling and doing an optimization using MATLAB [8].

Therefore, this paper presents an optimization method by using multi objective Genetic Algorithm (GA). GA is employed to optimize the system in terms of exergy destruction and total cost. This study has been set three constraint, including temperature in evaporator, compressor and condenser to ensure that the optimal condition can be obtained.

2. Methodology

2.1. Model Description

A schematic diagram of solar assisted heat pump cycle which is discussed in this paper is demonstrated in figure 1.

![Figure 1. Schematic diagram of Solar Assisted Heat Pump.](image)

The system consists of solar thermal collector and heat pump system. Evacuated tubular solar collector help the heat pump system to absorb energy from the sun in order to raise the temperature of refrigerant in evaporator. The heat pump system consists of evaporator, two compressors, high temperature compressor and low temperature compressor, condenser and two expansion valves. The evaporator absorbs heat from solar thermal collector in the evaporating temperature $T_E$. The condenser delivers heat to raise the temperature of water up to 105º C at condensing temperature $T_C$. The heat rejected from the condenser is equal to the sum of the heat absorbed by evaporator and the work of two compressors.

R1234ze(E) working fluid is used as a working fluid in this system. The reason for selecting R1234ze(E) as a refrigerant for this system is because of its thermodynamic properties and their effect for environment. The critical temperature of R1234ze is suitable for a high temperature heat pump, up to 110ºC and R1234ze (E) has been nominated as an alternative for R134a, because it has a low GWP of around 6 [9].
2.2. Thermodynamic and exergetic analysis

Thermal modeling includes mass, energy and exergy balance are very important to improve system efficiency [10-12]. In this paper, components modeling are using some assumptions as follows:

1. The system operates under steady state condition.
2. The pressure and heat loss in pipe lines of the system are neglected.
3. Saturated refrigerant occurs at the exit of evaporator and condenser.
4. The kinetic and potential energies are not considered for the exergy analysis.

2.2.1. Energetic and Exergetic Analysis. The energy and exergy balance in the system components are list in table 1.

| Component | Mass | Energy | Exergy destruction |
|-----------|------|--------|--------------------|
| Evaporator | \( m_1 = m_8 \) | \( Q_{evap} = m_{ref,LT} (h_1 - h_8) \) | \( \text{Ex}_{D,\text{evap}} = [m_{ref,LT} (\text{Ex}_1 - \text{Ex}_8)] + [m_8 (\text{Ex}_{\text{win}} - \text{Ex}_{\text{w,out}})] \) |
| Compressor | \( m_2 = m_1 \) | \( W_{\text{LT,comp}} = m_{ref,LT} (h_2 - h_1) \) | \( \text{Ex}_{D,\text{LTt}} = [m_{ref,LT} (\text{Ex}_1 - \text{Ex}_2)] + [W_{\text{LT,comp}}] \) |
| HT | \( m_3 = m_4 \) | \( W_{\text{HT,comp}} = m_{ref,HT} (h_4 - h_3) \) | \( \text{Ex}_{D,\text{HTe}} = [m_{ref,HT} (\text{Ex}_1 - \text{Ex}_3)] + [W_{\text{HT,comp}}] \) |
| Condenser | \( m_4 = m_5 \) | \( Q_{\text{cond}} = m_{\text{ref,HT}} (h_4 - h_5) \) | \( \text{Ex}_{D,\text{cond}} = [m_{\text{ref,HT}} (\text{Ex}_4 - \text{Ex}_5)] + [1 - T_w/T_e] \) |
| Valve | \( LT \) | \( m_5 = m_6 \) | \( h_5 = h_6 \) | \( \text{Ex}_{D,\text{LTv}} = [m_{\text{ref,LT}} (\text{Ex}_4 - \text{Ex}_5)] \) |
| HT | \( m_7 = m_8 \) | \( h_7 = h_8 \) | \( \text{Ex}_{D,\text{HTv}} = [m_{\text{ref,HT}} (\text{Ex}_7 - \text{Ex}_8)] \) |

The coefficient of performance and the exergy efficiency [13] are calculated as follows:

\[
\text{COP} = \frac{Q_{\text{cond}}}{W_{\text{comp,LT}} + W_{\text{comp,HT}}} \quad (1)
\]

\[
\text{Ex}_{\text{in}} = W_{\text{HT,comp}} + W_{\text{LT,comp}} + Q_{\text{solar collector}} \quad (2)
\]

\[
\text{Ex}_{D,\text{tot}} = \text{Ex}_{D,\text{evap}} + \text{Ex}_{\text{D,comp,LT}} + \text{Ex}_{\text{D,comp,HT}} + \text{Ex}_{\text{D,cond}} + \text{Ex}_{\text{D,vale,LT}} + \text{Ex}_{\text{D,vale,HT}} \quad (3)
\]

\[
\text{Ex}_{\text{eff}} = 1 - \frac{\text{Ex}_{D,\text{tot}}}{\text{Ex}_{\text{in}}} \quad (4)
\]

2.2.2. Economic Analysis. The influence of the price of each component of the heat pump system greatly affect the election in consideration of solar assisted heat pump system as the best option for process heating. Total Annual Cost (TAC) will represent the economic value of the system, while TAC consists of investment costs, operating electrical appliances. Before calculating the cost components, it is necessary to do the following assumptions:

1. Age-made systems (lifetime, \( n \)) for 20 years.
2. Total operating time (H) for 7000 hours per year.
3. The cost of electricity (Cel) amounted to 0.08 US$ per kWh.
4. Interest rates (interest rate, \( i \)) 12%.

The equation for calculating the components of the overall cost of the system can be described as follows [14]:

\[
C_{\text{total}} = C_{\text{investment}} + C_{\text{operational}} \quad (5)
\]

\[
C_{\text{investment}} = \left[ \left[ C_{\text{inv,cond}} + C_{\text{inv,evap}} + C_{\text{inv,comp}} + C_{\text{inv,coils}} \right] \times \text{CRF} \right] \quad (6)
\]

\[
C_{\text{operational}} = \left[ C_{\text{elec}} \cdot \left[ \left(C_{\text{comp}} + W_p \right) \right] \right] \quad (7)
\]

While Capital Recovery Factor (CRF) and cost for other components can be calculated as [14]:

\[
\text{CRF} = \frac{i(1+i)^n}{(1+i)^n-1} \quad (8)
\]
With the assumption of Cel is about 0.104 US$/kWh, operation hours 6570, lifetime of operation 20 years and interest rate 0.12 per year.

2.3. Multi-objective Optimization

To determine the optimal operation conditions of heat pump system, the optimization method is developed. This study uses Genetic Algorithm (GA) to optimize the system, where constraints with value: 313 \( \leq T_{\text{evap}} \leq 318 \), 350 \( \leq T_{\text{compHT}} \leq 355 \) and 379 \( \leq T_{\text{cond}} \leq 382 \). The GA parameters used for the optimization procedure are: number of generations = 600, population size = 50, crossover probability = 0.7 and mutation probability = 0.2.

3. Result and Discussion

In this study, low GWP and ODP working fluids, R1234ze(E) is selected. The proposed optimization method was applied for modeling and optimizing the SAHP system. Exergy destruction and total cost are two objective functions in this optimization procedure. Low exergy destruction indicates that the system has a good performance, while as exergy destruction decrease, total cost of the system increases. To minimize exergy destruction and total cost, multi objective genetic algorithm (MOGA) was applied. Figure 2 shows pareto front as multi-objective optimization result.

![Figure 2](image-url)  
**Figure 2.** Decision making method.

The result showed that any change in decision variables that decreases the exergy destruction, leads to an increase in total cost and vice versa. Figure 2 gives an optimum condition of the system based on thermodynamic and economic. Due to so many optimum points offer by Pareto front as illustrated in figure 2 and the difficulties to choose the optimum if both thermodynamic and total cost are consider, a selection of a single optimum point is needed. Two common types of decision-making method, TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) and LINMAP (Linear Programming Technique for Multi-dimensional Analysis of Preference) are applied for selecting the optimum point. TOPSIS method was considered as one of the best method for selecting the optimum value of a number of optimum solutions. The optimum point is determined by selecting a point farthest to the non-ideal point and the point that is closest to the ideal point. The point selected by using the TOPSIS method was chosen as the point with optimum operating conditions. While LINMAP method chooses the best point by considering the distance from ideal point. The point that has a minimum distance from ideal point is selected as optimum point. Figure 4 and table 3 gives information about the optimum point selected by using both TOPSIS and LINMAP method.
Table 2. Optimum point from Pareto Front.

| Parameter                      | TOPSIS Method | LINMAP Method |
|--------------------------------|---------------|---------------|
| Evaporating Temperature (K)   | 317.95        | 317.90        |
| HT Compressore inlet (K)      | 353.64        | 353.60        |
| Condensing Temperature (K)    | 380.42        | 380.38        |
| COP                            | 3.58          | 3.56          |
| Exergy Destruction (kW)       | 70.207        | 70.183        |
| Total Cost (US$)              | 63,444        | 63,577        |

From Table 2 it can be seen that both decision-making methods lead to the same values for exergy destruction but 100 US$ difference in total cost. Hence, the selected point by LINMAP method was considered as the final optimal design point. Table 4 shows the result of system optimization with single-objective function I (thermodynamic), single-objective function II (economic) and multi-objective (both thermodynamic and total cost).

Table 3. Single-objective vs Multi-objective.

| Parameter                      | Single Objective I (Thermodynamic) | Single Objective II (Economic) | Multi-Objective |
|--------------------------------|-----------------------------------|--------------------------------|-----------------|
| Evaporating Temperature (K)   | 318                               | 317.4                          | 317.6           |
| HT Compressore inlet (K)      | 353.66                            | 353.14                         | 353.64          |
| Condensing Temperature (K)    | 380.26                            | 380.67                         | 380.42          |
| COP                            | 3.58                              | 3.54                           | 3.56            |
| Ex,des evaporator (kW)        | 0.925                             | 1.11                           | 1.03            |
| Ex,des condenser (kW)         | 48.08                             | 49.39                          | 48.50           |
| Ex,des LT comp (kW)           | 7.03                              | 7.03                           | 7.11            |
| Ex,des HT comp (kW)           | 5.34                              | 4.44                           | 5.48            |
| Ex,des LT valve (kW)          | 4.96                              | 4.92                           | 5.03            |
| Ex,des HT valve (kW)          | 6.82                              | 7.27                           | 6.94            |
| LT Compressor (US$)           | 46,774                            | 46,687                         | 46,971          |
| HT Compressor (US$)           | 44,807                            | 45,771                         | 45,129          |
| Condenser (US$)               | 18,288                            | 17,375                         | 17,911          |
| Evaporator (US$)              | 25,152                            | 17,028                         | 18,916          |

The results show that the highest amount of exergy destruction occurs in condenser (48.08 kW, 49.39 kW and 48.50 kW for minimizing objective function I, objective function II, and optimization with multi-objective functions I and II respectively). Compressors and valves had the next highest amount of exergy destruction. Then, for economic point of view, LT compressor has the highest cost (46,774 US$, 46,687 US$ and 46,971 US$ for minimizing objective function I, objective function II, and optimization with multi-objective functions I and II respectively) while the condenser has the lowest cost. As is shown, the total cost of the system obtained from objective function I had the highest amount, while the total cost obtained from objective function II had the lowest amount, and the total cost obtained from both objective functions was in between the above two limits. Therefore, in
multi-objective optimization technique, simultaneous analysis of economic and thermodynamic aspects was performed. Thus, this approach gives a reasonable trade-off between the first and the second objectives.

4. Conclusion
The optimization of solar assisted heat pump for high temperature application has been investigated in this paper. The aim of the research is to determine operating condition to make an optimum system both in thermodynamic and economic point of view. In optimization procedure there are three decision variables including evaporating temperature, flash tank temperature and condensing temperature. The result showed that Genetic Algorithm is a good solver to obtain the optimum condition of the system. The system has an optimum condition at evaporating temperature of 322 K, outlet compressor LT temperature of 348 K and condensing temperature of 379 K with 40% exergy efficiency, exergy destruction of 56.74 kW and total cost of 47,716 US$.

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