Parametric evaluation of the combined solar driven pre-compression supercritical CO₂ cycle and organic Rankine cycle using ultra low global warming potential fluids

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Abstract. In this paper, thermodynamic parametric analysis of solar driven pre-compression cycle combined with super critical CO₂ and organic Rankine cycle using zero ozone depletion (ODP) and ultra low global warming potential (GWP) fluids have been carried out. The thermal model for the above system was developed using low global warming potential fluids and it was found that the thermal performance of the system is increased with the concentration ratio, fluid velocity, and with solar irradiation while decreased with receiver emittance. In terms of thermal performance parameters the R1224yd(E) gives highest performance Maximum exergy efficiency, thermal efficiency and output power were increased from 36.73% to 58.52%, 34.16% to 54.42% and 183kW to 293.5kW respectively when DNI (direct normal irradiation) increased from 0.4 kW/m² to 0.95 kW/m² based on R1224yd(E) fluid. R1224yd(E) recommended for the better performance.

Keywords: Ultra-low global warming potential fluids, Performance computation, organic Rankine cycle, pre-compression super critical CO₂ cycle, solar power tower.

1. Introduction
Energy is the important factor for living slandered. It is important to analyze the energy problems in the world. Since conventional energy resources are depleting continuously. Therefore, it is necessary to develop a power system which utilizes the renewable energy source. Solar energy is the best option to provide the content source of pollution free electricity [1]. To harvest the solar energy solar power tower (SPT) system is used. It provides the high temperature heat which used to produce the electricity for commercial purpose [2]. Supercritical carbon dioxide (sCO₂) operated cycle are compact and highly efficient at high temperature without taking much amount of work for compression [3].

A few researchers did the work in the direction of sCO₂ cycle driven operated by solar energy such as Khan and Mishra [1] carried out the study on solar driven partial heating sCO₂ cycle combining with the organic Rankine cycle (ORC) for performance improvement. They found that ORC improved the thermal performance by 4.47% of existing cycle. Khan and Mishra [4] also did the thermal performance evaluation of the pre-compression sCO₂ cycle driven by SPT, further they used the ORC. They examined that the performance was improved with the ORC. After the analysis it was also found that R227ea is best performing fluid. Khan and Mishra [5] performed a thermo economic analysis of the sCO₂ cycle also they combined the system with the ORC. They found that R1336mzz(Z) have the lowest investment cost and also best performing fluids on environmental, economic, and thermal point of view. Khan and Mishra [6] performed analysis of the SPT driven recompression cycle having intercooling at main compressor. They combined with parallel double evaporator ORC (PDORC)
system to recover the heat simultaneously from the intercooler and after the low temperature recuperator. Pre-compression cycle generally used to prevent the pinch issue which occurs with the simple sCO₂ Brayton cycle. Also, if this cycle is carefully optimized efficiency will improve almost by 6% [7].

Also, various working fluids were used in ORC system for better performance of the combined system such as Yu, Feng and Wang [8] considered eight hydro fluoro carbon working fluids for various source driven ORC and observed that the system’s thermal performance extremely depends on sort of working fluids. They considered the deferent types of the HFC fluid such as they generally selected HFC working fluids (such as R601, R600a, R600, R245fa, R236ea, R236fa, R601a and R227ea) and also found the highest thermal efficiency using by the R601 fluid.

It was found from the literature review that performance of the sCO₂ cycle can be improved with the low GWP and ODP fluids. This study deals with the use of low global warming potential fluids. Further parametric analysis was performed and effects of solar parameters (such as concentration ratio, solar irradiation, velocity of fluids, and receiver emittance) were discussed on the performance of the system (thermal efficiency, exergy efficiency and power output). Equations were solved in the EES [13] software.

2. Description of proposed model
The combined system consist the three loops first solar loop, second sCO₂ loop and third is ORC loop. Solar loop supplies the heat to the sCO₂ cycle where system gave the power output. Exhausted heat or wasted heat is utilized by the bottoming ORC system where also extra power is obtained as displays in figure 1 and corresponding T-s graph is given in figure 2.

![Figure 1. Combined cycle driven by SPT [4].](image-url)
3. Thermodynamic evaluation

3.1 Assumptions:
The assumptions are assumed to be as following (1) Kinetic and potential energy are ignored. (2) All considered equation was developed at steady state conditions. (3) Friction and heat loss are neglected in each component. (4) Input parameters for simulation are given in table 1.

3.2 Mathematical modeling:
Complete mathematical modeling of the current system has been given in reference [4] here only some useful equations have been taken from reference [4] for better understanding.
Total solar heat incidence on the heliostats [4]

\[
\frac{Q_{solar}}{g_{2922}} = \frac{(G_{g_{2912}} \cdot A_{g_{2918}} \cdot N_{g_{2918}})}{1000} \quad (1)
\]

Where,
- \( G_{g_{2912}} \) is the solar irradiation (W/m^2),
- \( A_{g_{2918}} \) heliostat state area (m^2) and
- \( N_{g_{2918}} \) number of heliostats.

Exergy balance equation is given as;

\[
\sum_{i} \left(1 - \frac{T_{g_{2910}}}{T_{g_{311}}} \right) \dot{Q}_{i} - \sum \dot{W}_{c,v} - \sum (\dot{m}_{i} E_{i}) - \sum (\dot{m}_{e} E_{e}) - \dot{E}D = 0 \quad (2)
\]

Where, \( \dot{E}D \) is the rate of exergy destruction. Exergy of solar is calculated as [4, 5,10];

\[
\dot{E}_{solar} = \left( \frac{Q_{r}}{\eta_{h} \cdot \eta_{r}} \right) E_{s} \quad (3)
\]

Where, \( E_{s} \) is the dimensionless maximum useful work and expressed in the references [5], \( \eta_{h} \) and \( \eta_{r} \) are heliostat and receiver efficiency,

Heat given to the combined cycle;

\[
\dot{Q}_{r} = \dot{Q}_{HX1} = \dot{m}_{ms} \cdot C_{Pms} (h_{b} - h_{a}) = \dot{m}_{SCO2} \cdot (h_{1} - h_{b}) \quad (4)
\]

Thermal efficiency of the solar operated combined cycle is determined as;

\[
\eta_{th} = \frac{W_{net}}{Q_{solar}} \quad (5)
\]

Exergetic efficiency of combined system can also be defined as [2]
\[ \eta_{\text{ex}} = 1 - \frac{E_{\text{total}}}{E_{\text{solar}}} \]  \hspace{1cm} (6)

The combined cycle’s thermal efficiency can also be defined as [9]:

\[ \eta_{\text{th}} = \eta_{\text{ex}} \cdot \eta_{\text{Carnot}} \]  \hspace{1cm} (7)

### 3.3 Selection for working fluids

Working fluid selection is an important factor to decide the thermal performance. In this study, a mixture of magnesium chloride and potassium chloride is selected as a heat transfer fluid in the solar cycle. The low GWP and ODP fluids were chosen for the bottoming cycle. Eight low GWP fluids were considered in the ORC system such as R1336mzz(Z), R1234ze(E), R1243zf, R1234yf, R1233zd(E), R1225ye(Z), R1224yd(E), and R1234ze (Z). Thermophysical properties of the considered fluids are given in Table 2.

### Table 1. Input parameters for considered system [4,5].

| Input parameters for the system | Value |
|--------------------------------|-------|
| Main turbine inlet pressure    | 25 MPa [14] |
| Main turbine inlet temperature | 650 °C [14] |
| Inlet pressure of Pre-compressor | 5.6 – 6.8 MPa [14] |
| Main compressor’s inlet pressure | 7 – 10.5 MPa [4] |
| Main compressor’s inlet temperature | 32 – 38 °C [14,5] |
| Main turbine’s isentropic efficiency | 88% [14] |
| Main compressor’s isentropic efficiency | 85% [14] |
| Pre-compressor isentropic efficiency | 85% [14] |
| Heat exchanger effectiveness | 95% [15] |
| Effectiveness of both recuperators | 95% [15] |
| sCO2 mass flow rate in topping cycle | 1.5 kg/s |
| Bottoming ORC Mass flow rate | 2.5 kg/s |
| ORC turbine inlet pressure | 3 MPa [4,5] |
| Isentropic efficiency of ORC pump | 70% [16] |
| Isentropic efficiency of ORC turbine | 80% [16] |

### Table 2. Properties of organic working fluids [1,4,5,11,12].

| Working substance | \( P_e \) (MPa) | \( T_e \) (°C) | Weight (Kg/Kmole) | Type | ODP | GWP | Lifetime (years) | Security group |
|-------------------|-----------------|---------------|------------------|------|-----|-----|------------------|----------------|
| R1234ze(Z)        | 3.53            | 150.1         | 114.04           | I    | 0   | <10 | -                | -              |
| R1224yd(Z)        | 3.33            | 155.5         | 148.5            | I    | 0.00023 | 0.88 | -                | A1             |
| R1225ye(Z)        | 3.335           | 106.5         | 130.5            | I    | 0.00012 | 0.87 | -                | -              |
| R1233zd(E)        | 3.57            | 165.5         | 130.5            | I    | 0.00024 | 1   | -                | A1             |
| R1234yf           | 4.597           | 94.7          | 114.04           | I    | 0   | <1  | -                | A2L            |
| R1243zf           | 3.518           | 104.44        | 96.05            | D    | 0   | <1  | -                | A2             |
| R1234ze(E)        | 3.64            | 109.4         | 114.043          | D    | 0   | 6   | 0.025            | A2L            |
| R1336mzz(Z)       | 2.903           | 171.3         | 164              | D    | 0   | 8.9 | 0.0602           | A1             |
3.4 Verification of model
Current model is verified with the previous study to precede further analysis. It was verified with previous study ref. [4] at same input conditions as listed in table 3.

| Baseline conditions | Reference Thermal efficiency [4] | Current model thermal efficiency |
|---------------------|----------------------------------|---------------------------------|
| $P_1=25\text{MPa}$, $T_1=650^\circ\text{C}$, $P_6=6.5$ MPa, $T_6 = 32^\circ\text{C}$, $P_{10} = 3$ MPa, $\eta_{\text{MC}}=0.85$, $\eta_{\text{MT}}=0.88$ | 44.52% | 44.75% |

4. Results and discussion
In this study thermodynamic analysis of the pre-compression sCO$_2$ cycle and ORC driven by SPT system using low GWP fluids has been carried out. Results were calculated with computational technique considering assumptions and listed data in table 1.

4.1 Influence of the solar irradiation on the system performance
The basic condition for sun irradiation in the Indian climate in Mumbai was 850 W/m$^2$. The impacts of DNI on the efficiency of the system consequently need to be examined, since the current integrated system is driven by a SPT system. The exergy efficiency of the combined system was steadily raised with DNI. This is explained by the efficient use of increased solar irradiation on the solar concentrate field. This correlates to an increase the inlet exergy of combined cycle.

Power output and thermal efficiency and power of the system have also increased with DNI. At 950 W/m$^2$ of DNI, R1224yd(Z) achieved the highest exergy efficiency, thermal efficiency and net power output of 58.52% and 54.43% and 293.50 kW, respectively, as indicated in the Figures 3-5 followed by the fluids R1243zf, R1336mzz(Z), R1233zd(E), R1225ye(Z), R1234ze(Z) and R1234ye(Z) and R1234yf. The curve for thermal efficiency and power output has the same pattern as the curve for exergy efficiency. The explanation behind this is that thermal efficiency is directly linked to exergy efficiency. Increase in solar irradiation from 0.4 kW/m$^2$ to 0.95 kW/m$^2$, the exergy efficiency, thermal efficiency and power out of the system were increased from 36.73% to 58.52%, 34.16% to 54.42% and 183kW to 293.5kW respectively by R1224ye(Z).

![Figure 3. Variation of Exergy efficiency with DNI](image-url)
4.2 Influence of concentration ratio on the system performance

Another receiver design parameter to consider is the concentration ratio, which has an impact on the combined system's performance. As illustrated in Figures 6-8, increasing the concentration ratio increases the exergy efficiency and thermal efficiency of combined cycle. As the concentration ratio rises, the receiver efficiency rises, causing the HTF outlet temperature to rise, as the turbine inlet temperature is inversely proportional to the receiver outlet temperature. As a result, the combined cycle efficiency increased with turbine inlet temperature. The fluid R1224yd(Z) achieved the highest exergy efficiency, thermal efficiency and power output once again. Exergy efficiency, thermal efficiency and power output increased from 38.76% to 59.89%, 36.05% to 55.70% and 143.2kW to 342.7kW, respectively, based on R1224yd(Z) with concentration ratio that increased from 200 to 1400 as shown in figures 6-8.
Figure 6. Variation of exergy efficiency with concentration ratio

Figure 7. Thermal efficiency variation with concentration ratio

Figure 8. Variation of power output with concentration ratio
4.3 Influence of HTF velocity on system performance

Figures 9-11 show the effect of the HTF velocity in absorber tube on the exergy efficiency, thermal efficiency and power output. From figure it is observed that exergy efficiency and thermal efficiency increase with velocity. Reason for increase in second law efficiency with the velocity is that due to increases in velocity of fluid Reynolds number is increased consequently convective heat transfer coefficient increased so much heat is carried with heat transfer fluids so much heat available with HTF. This leads to increase in efficiencies. Highest exergy efficiency, thermal efficiency and output power were obtained for R1224yd(Z) and varies 56.60% to 58.0%, 52.63% to 54.03% and 289.7 to 292.3 kW respectively when velocity varies from 0.01(m/s) to 0.1(m/s) and while lowest values were obtained by the R1234yf among other considered working fluids, it varies from 47.83% to 48.88%, 44.48% to 45.45% and 242.5 to 243.2 kW respectively when it velocity varies from 0.01(m/s) to 0.1(m/s). It was seen that performance improvement slightly varied with the velocity due to effect of standalone cycle only. The performance of bottoming ORC did not affect significantly.

Figure 9. Variation of exergy efficiency with HTF velocity

Figure 10. Thermal efficiency variation with HTF velocity
4.4 Influence of receiver emittance on system performance

Receiver emittance is the important parameter to be examined because it affects the receiver performance. It is seen in figure 12-14, performance of the combined cycle decreases with the receiver emittance. Receiver’s surface temperature is the function of the receiver emittance. Receiver efficiency decreases with the receiver emittance. That means more heat loss to the surrounding, consequently less heat energy available to the combined cycle. This leads to decrease in the both efficiencies of the combined cycle. Increase in solar emittance from 0.05 to 0.2 reduces the exergy efficiency, thermal efficiency and output power of the system from 61.22% to 59.66%, 57.29% to 55.84% and 286.4kW to 278.8kW respectively based on the R1224yd(Z) as shown in Figures 12-14. Therefore, it becomes necessary to decrease the solar emittance while designing the SPT to get better performance of combined cycle for power generation.
5. Conclusions

Following conclusions were made from the results:

- Performance of the system increased with the DNI. Maximum performance of combined cycle were found with R1224yd(E) fluid followed by R1243zf, R1336mzz(Z), R1233zd(E), R1225ye(Z), R1234ze(Z), R1234ze(E), and R1234yf at present input conditions. Maximum exergy efficiency, thermal efficiency and power output were increased from 36.73% to 58.52%, 34.16% to 54.42% and 183 kW to 293.5 kW respectively when DNI increased from 0.4 kW/m² to 0.95 kW/m² based on R1224yd(Z) fluid.
- Increase in concentration ratio from 200 to 1400 increases the highest exergy efficiency, thermal efficiency and output power increased from 36.05% to 55.70%, 38.76% to 59.89%, and 143.2 kW to 342.7 kW with fluid R1224yd(Z).
- Performance of combined cycle increased with velocity of HTF in receiver. Highest exergy efficiency, thermal efficiency and power output were obtained for R1224yd(Z) and varies 56.60% to 58.1%, 52.92% to 54.4% and 289.7 to 292.3 kW respectively when velocity varies from 0.01(m/s) to 0.1(m/s).
- Apart from this R1224yd(Z) may be recommended for better performance of the combined cycle based on current input conditions.
• Current study limited to the parametric analysis and effects evaluation of few selected SPT design parameters on combined cycle. Further, this system can be analyzed with more SPT design parameters.

**Nomenclature**

- $A_h$: Single heliostat area (m²)
- $ED$: Exergy destruction rate (kW)
- $E_{\text{solar}}$: Exergy of solar (kW)
- $E$: Rate of exergy (kW)
- $Q$: Heat rate in (kW)
- $sCO_2$: Supercritical carbon dioxide
- $Q_{\text{solar}}$: Sun heat absorbed by heliostat field (kW)
- $\eta_h$: Heliostat efficiency
- $N_h$: Number of heliostat
- $\eta_{\text{th}}$: Thermal efficiency
- $s$: Specific entropy (kJ/kg-K)
- $m$: Mass flow rate (kg/s)
- $\eta_r$: Thermal efficiency of receiver
- $W$: Power (kW)
- $\eta_{\text{ex}}$: Exergy efficiency
- $T$: Temperature (K)

**Abbreviations**

- PC: Pre-compressor
- DNI: Direct normal irradiation (W/m²)
- Cond: Condenser
- GWP: Global warming potential
- HX2: Heat exchanger -2
- MC: Main compressor
- HX1: Heat exchanger -1
- MT: Main turbine
- LTR: Low temperature recuperator
- CR: Concentration ratio
- SPT: Solar power tower
- ORC: Organic Rankine cycle
- OT: ORC turbine
- HTR: High temperature recuperator

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