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INTEGRATION AND OPTIMIZATION OF SOLAR ENERGY DRIVEN SUPERCRITICAL CO_2 CYCLE AND ORGANIC RANKINE CYCLE

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ABSTRACT

The increasing scarce of conventional energy resource and deteriorating environmental problem push the world toward more and more sustainable way in energy conversion and utilization. Close Brayton cycle using super-critical CO_2 as working fluid is a promising technology for coal-fired, renewable energy-driven, waste energy-driven power production. Heat integration inside the CO_2 power cycle or with external resources are effective way in improving the super-critical CO_2 power cycle (SCO_2) performance. In the present study, an integration system of solar thermal collector, SCO_2, and organic Ranking cycle (ORC) is proposed. An equation of state-based model is developed for the simulation and simultaneous optimization of the proposed integration system. A case study is elaborated to test the superiority of three integration systems with different SCO_2 structure and validate the effectiveness of the proposed optimization model. The working fluid of ORC are screened and sensitivity analysis of key parameters on the integration system performance are conducted.

Keywords: Super-critical CO_2, organic Rankine cycle, integration, optimization, solar energy

1. INTRODUCTION

With the increasing of energy price and deteriorating environmental pollution, the world is facing more and more severe energy and environmental challenges. These challenges force the world toward a more sustainable way in energy conversion and utilization. Super-critical CO_2 cycle is a promising technology for coal, nuclear, solar, and waste heat-driven power generation.

Much of previous research has focused on the cycle structure retrofitting, cycle simulation and optimization, component design and optimization for the SCO_2. The heat integration inside the SCO_2 has been well studied and significant performance improvement can be achieved via inner integration. Beside the inner integration, the external integration is also important to further improve the utilizing efficiency of energy resources. Ma et al. [1] presented an exergoeconomic optimization method for the integration system of recompression supercritical CO_2 Brayton cycle with main compression intercooling in solar power tower system. Hou et al. [2] conducted a performance optimization of combined supercritical CO_2 recompression cycle (RC-SCO_2) and regenerative organic Rankine cycle (ORC) using zeotropic mixture fluid. Song et al. [3] presented a performance analysis and parametric optimization of SCO_2 cycle with bottoming ORC. Akbari and Mahmoudi [4] conducted a thermoeconomic analysis and optimization of a combined SCO_2/ORC. These studies indicated that the integration of SCO_2 with ORC results in different degree of performance improvement. However, these previous studies mainly focus on the cycle integration and optimization, the integration and simultaneous optimization of SCO_2 with heat source and heat sink is not well investigated. In addition, these studies using REFPROP to obtain thermophysical properties of CO_2 and ORC, thus enable the cycle/system performance indicator a discrete or implicit function of cycle/system operation parameters. This limits the simulation and optimization strategy to the iteration or stochastic algorithm as demonstrated in the previous studies.

In this paper, an integration of SCO_2 with solar thermal collector, ORC, and heat sink is proposed. A mathematical model for the simultaneous optimization of heat source, SCO_2, ORC, and heat sink is formulated based on the accurate equation of state (EOS) for working fluid thermophysical properties. The advantage of the integration is validated by comparing three solar-SCO_2-ORC integration systems with their corresponding standalone cycles. The influence of solar collector parameter, working fluids, and heat sink parameters are also investigated through sensitivity analysis.

2. PROBLEM DESCRIPTION AND MODEL FORMULATION

2.1 *Integration system description*

As simple, recuperative and recompression are most promising cycles and therefore are mainly investigated as base cycles in this study. Fig. 1 presents three integration systems, namely, integration system of solar-driven simple SCO_2 and ORC ($SSCO_2$-ORC), integration system of solar-driven regenerative SCO_2 and ORC ($RSCO_2$-ORC), integration system of solar-driven recompression SCO_2 and ORC ($RCSCO_2$-ORC).

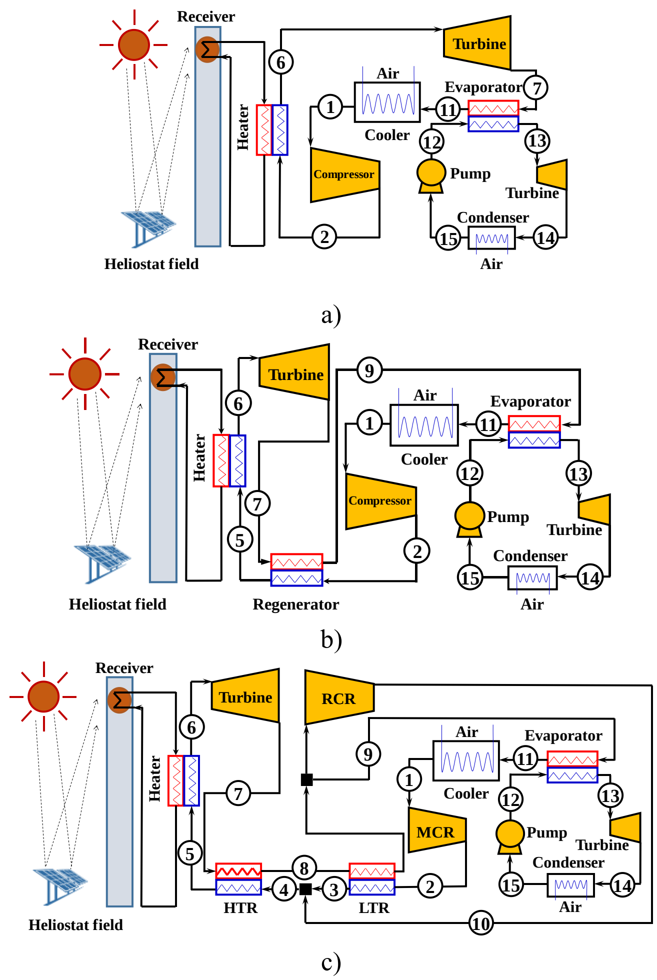

Fig. 1 Representation of three integration system: a) $SSCO_2$-ORC; b) $RSCO_2$-ORC; c) $RCSCO_2$-ORC

2.2 *Model formulation*

The model of the proposed systems consists of the objective function, the solar thermal collection, SCO_2, ORC, and EOS models.

2.2.1 Solar thermal collection model

In this paper, solar tower is used as solar energy collector. Eq. (1) shows the solar radiation energy Q_{solar} which is composed of receiving heat Q_{rec} and optical loss $Q_{opt,loss}$. Eqs. (2)-(5) give the detailed calculation model. Eq. (6) indicates that the receiver heat is divided into heat absorption of molten salt and heat loss in the receiver. Eq. (7) gives the molten salt heat absorption model.

$$Q_{solar} = A \cdot DNI = Q_{rec} + Q_{opt,loss} \tag{1}$$

$$DNI = [1367 \cdot [1 + 0.033 \cdot cos\left(\frac{2n\pi}{365}\right)] \cdot sin\, \alpha_s \,/(sin\, \alpha_s + 0.33)] \tag{2}$$

$$\alpha_s = sin^{-1}(cos\, \varphi\, cos\, \delta\, cos\, \omega + sin\, \varphi\, sin\, \delta) \tag{3}$$

$$\delta = 23.45 \cdot \pi \cdot sin(2\pi(284 + n)/365)/180 \tag{4}$$

$$\omega = 15\pi(\tau - 12)/180 \tag{5}$$

$$Q_{rec} = Q_{salt} + Q_{rec,loss} \tag{6}$$

$$Q_{salt} = C_{salt} M_{salt}(T_{rout} - T_{rin}) \tag{7}$$

2.2.2 SCO_2 model

As shown in Fig. 1c, the $RCSCO_2$ cycle is composed of the cooler (Cooler), low and high temperature recuperators (LTR and HTR), heater (Heater), main compressor (LTR), recompression compressor (HTR), and turbine (TUR). $RSCO_2$ and $SSCO_2$ are the particular cases of $RCSCO_2$. Converting $RCSCO_2$ into $SSCO_2$ by setting *sr*=0, Q_{LTR}=0, and Q_{HTR}=0 or RC-SCO_2 into R-SCO_2 by setting *sr*=0 and Q_{LTR}=0 is easy.

Eqs. (8)-(15) ensure the energy balance of the heater, turbine, HTR, LTR, MCR, RCR, and Cooler. Eqs. (16) and (17) calculate the net power output (NPO) and thermal efficiency. Eq. (18) ensures the minimum temperature difference of streams at the segmented heat exchanger.

$$M_{HSC} Cp_{HSC}(T_{HSC,in} - T_{HSC,out}) = M_{CO2}(h_6 - h_5) \tag{8}$$

$$W_{TUR} = M_{CO2}(h_6 - h_7) \tag{9}$$

$$h_5 - h_4 = h_7 - h_8 \tag{10}$$

$$h_4 = sr * h_{10} + (1 - sr)h_3 \tag{11}$$

$$(1 - sr)(h_3 - h_2) = h_8 - h_9 \tag{12}$$

$$W_{MCR} = M_{CO2}(1 - sr)(h_2 - h_1) \tag{13}$$

$$W_{MCR} = M_{CO2} sr(h_{10} - h_9) \tag{14}$$

$$M_{HSK} Cp_{HSK}(T_{HSK,out} - T_{HSK,in}) = M_{CO2}(1 - sr)(h_9 - h_1) \tag{15}$$

$$Wnet = W_{TUR} - W_{MCR} - W_{RCR} \tag{16}$$

$$EFF = (W_{TUR} - W_{MCR} - W_{RCR})/[M_{CO2}(h_6 - h_5)] \tag{17}$$

$$T_{i,n,hot} - T_{i,n,cold} \geq \Delta Tmin_i \;\; i \in I, n = 1,2, \dots, N + 1 \tag{18}$$

2.2.3 ORC model

A simple ORC consists of an evaporator, an expander, a condenser, and a pump. The ORC model includes mass and energy balance constraints. Eqs. (19)-(22) show the energy balance model for the evaporator, expander, pump, and condenser. Eq. (23) gives the heat transfer between ORC and SCO_2. Eqs. (24) and (25) calculates the NPO and thermal efficiency of the ORC.

$$Q_{e,ORC} = M_{ORC}(h_{13} - h_{12}) \quad (19)$$
$$W_{t,ORC} = M_{ORC}(h_{13} - h_{14}) \quad (20)$$
$$W_{p,ORC} = M_{ORC}(h_{12} - h_{15}) \quad (21)$$
$$M_{HSK,ORC}Cp_{HSK}(T_{HSK,out} - T_{HSK,in}) = M_{ORC}(h_{14} - h_{15}) \quad (22)$$
$$M_{CO2}(h_9 - h_{11}) = M_{ORC}(h_{13} - h_{12}) \quad (23)$$
$$W_{net,ORC} = W_{t,ORC} - W_{p,ORC} \quad (24)$$
$$\eta_{ORC} = W_{net,ORC}/Q_{e,ORC} \quad (25)$$

2.2.4 EOS model

In this paper, the EOS developed by Span and Wagner [5] based on sophisticated fitting and optimization procedures is used to obtain the CO_2 properties. As validated in [5], the EOS for CO_2 yields high accuracy covering the fluid temperature region from the triple-point temperature to 1100 K and the pressure up to 800 MPa. The specific enthalpy $h(p, T)$ and entropy $s(p, T)$ are achieved as functions of pressure and temperature through the EOS. The detailed model is not listed here due to the limited space and can be found in [5].

2.2.5 Objective function

The objective function is the maximization of the thermal efficiency of the integration solar power system as formulated by Eqs. (26) and (27), where W_{Gnet} is the total net power output of the integration system.

$$Max\ GEFF = W_{Gnet}/[M_{CO2}(h_6 - h_5)] \quad (26)$$
$$W_{Gnet} = W_{net} + W_{net,ORC} \quad (27)$$

The formulated model is a non-linear programming (NLP) model. The optimization variables are: inlet molten salt temperature, outlet molten salt temperature, CO_2 mass flowrate, hot side CO_2 pressure, cold side CO_2 pressure, CO_2 split ratio, inlet and outlet temperatures of segmented heat exchangers, ORC working fluid mass flowrate, ORC evaporation pressure, and ORC condensing pressure. The number of variables is much larger than that in previous cycle integration problem and is difficult to solve using traditional iteration or stochastic algorithm. Since the EOS is embedded in the model, deterministic algorithm can be used to solve the model. In this study, the NLP model is formulated in GAMS 23.6 [6] on a 3.0 GHz Intel(R) Core (TM) 2 PC, and CONOPT is used as an NLP solver.

3. RESULTS AND DISCUSSION

The systems' parameters are listed in Table 1. Fig. 2 shows the *T-H* diagrams of three SCO_2-ORC integration systems and the corresponding ORC with the molten salt at an inlet temperature of 300°C.

Table 1 The system parameters

Parameter	Value
Isentropic efficiency for turbine	0.9[7]
Isentropic efficiency for compressor	0.85[7]
ΔT_{min} for heat exchanger (K)	15
Area of mirror field (m^2)	30000
Component of molten salt	60%$NaNO_3$/40%KNO_3[8]

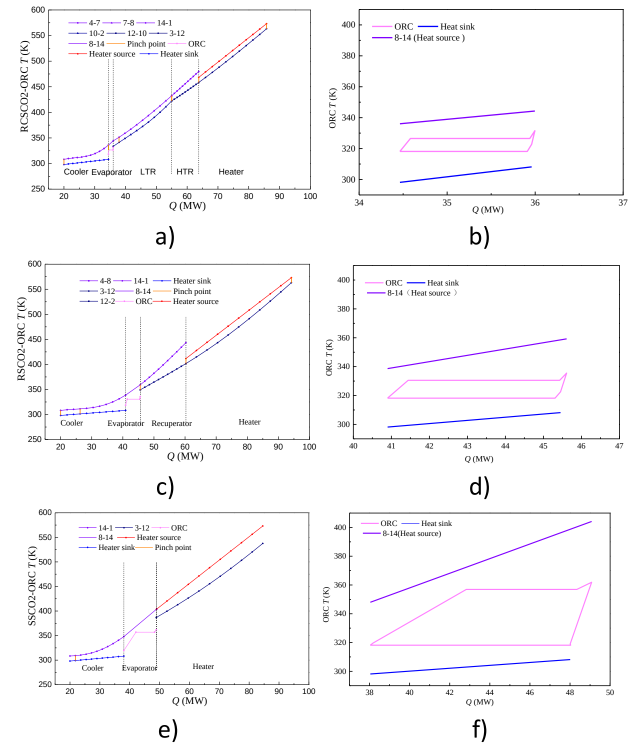

Fig. 2 *T-H* diagramof three integration system: a-b) $RCSCO_2$-ORC; c-d) $RSCO_2$-ORC; e-f) $SSCO_2$-ORC

The thermal efficiencies of $RCSCO_2$-ORC, $RSCO_2$-ORC, and $SSCO_2$-ORC are 27.57%, 25.01%, and 21.04%. The efficiencies of the integration systems are 0.72%, 1.99%, and 13.97% higher than those of standalone SCO_2 system, indicating the effectiveness of external heat integration. Fig. 3 shows the influence of working fluid on the integration cycle and ORC cycle. The results indicate that the ORC performances are heavily influenced by working fluid. Only $SSCO_2$-ORC performance is remarkably influenced by the working fluid while the performance of $RCSCO_2$-ORC and $RSCO_2$-ORC are only slightly influenced.

Fig. 4 illustrates the impact of the receiver outlet temperature on the thermal efficiency and NPO of $RCSCO_2$-ORC and $RCSCO_2$. It shows that the thermal efficiency of both integration and standalone system increase with the receiver outlet temperature. However, the net power outputs first increase and then decrease with the receiver outlet temperature.

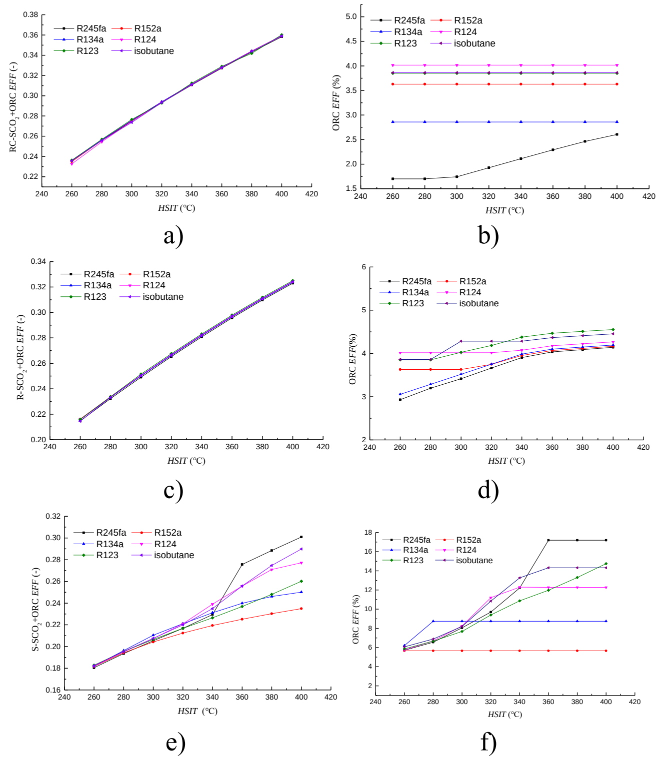

Fig. 3 Efficiency of different working medium system: a-b) $RCSCO_2$-ORC; c-d) $RSCO_2$-ORC; e-f) $SSCO_2$-ORC

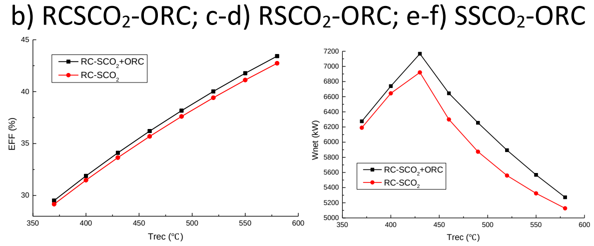

Fig. 4 Sensitivity analysis of receiver outlet temperature

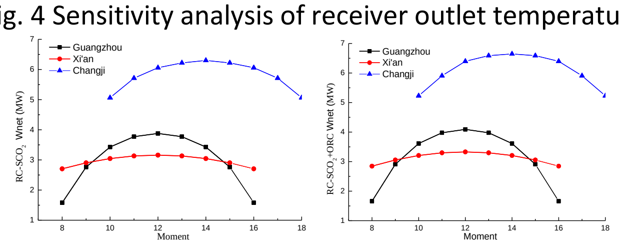

Fig. 5 Comparison of NPO in different regions

Fig. 5 gives the net NPO of both integration system and standalone system at different area. The NPO of both systems first increases and then decreases with time on a typical day. The NPO at Changji is significantly higher than those at Xian and Guangzhou.

4. CONCLUSION

A conceptual integration of solar collector, SCO_2, and ORC is proposed. A simultaneous optimization model of the proposed system is developed and solved using deterministic algorithm thanks to the application of EOS for working fluid thermophysical properties calculation. Following conclusions are drawn. The efficiencies of $RCSCO_2$-ORC, $RSCO_2$-ORC, and SCO_2-ORC are 0.72%, 1.99%, and 13.97% higher than those of corresponding standalone cycles. The working fluid has significant impact on the ORC performance and notable influence on SCO_2-ORC. However, the influence of working fluid on $RCSCO_2$-ORC and $RSCO_2$-ORC is negligible. The thermal efficiencies of $RCSCO_2$-ORC and $RCSCO_2$ increase along with the receiver temperature. The performance of the integration system and standalone system is sensitive to the solar field region.

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REFERENCES

[1] Ma Y, Morozyuk T, Liu M, Yan J, Liu J. Optimal integration of recompression supercritical CO_2 Brayton cycle with main compression intercooling in solar power tower system based on exergoeconomic approach. Appl Energ. 2019;242:1134-54.

[2] Hou S, Cao S, Yu L, Zhou Y, Wu Y, Zhang F. Performance optimization of combined supercritical CO_2 recompression cycle and regenerative organic Rankine cycle using zeotropic mixture fluid. Energ Convers Manage. 2018;166:187-200.

[3] Song J, Li X, Ren X, Gu C. Performance analysis and parametric optimization of supercritical carbon dioxide (S-CO_2) cycle with bottoming Organic Rankine Cycle (ORC). Energy. 2018;143:406-16.

[4] Akbari AD, Mahmoudi SMS. Thermoeconomic analysis & optimization of the combined supercritical CO_2 (carbon dioxide) recompression Brayton/organic Rankine cycle. Energy. 2014;78:501-12.

[5] Span R, Wagner W. A New Equation of State for Carbon Dioxide Covering the Fluid Region from the Triple-Point Temperature to 1100 K at Pressures up to 800 MPa. J Phys Chem Ref Data. 1996;25(6):1509-96.

[6] GAMS: a user's guide. Washington DC: GAMS Development Corp. 2008.

[7] Kim S, Cho Y, Kim M S. Characteristics and optimization of supercritical CO_2 recompression power cycle and the influence of pinch point temperature difference of recuperators. Energy. 2018;147:1216-1226.

[8] Li X, Kong W, Wang Z, Chang C, Bai F. Thermal model and thermodynamic performance of molten salt cavity receiver. Renewable Energy, 2010;35(5):981-988.