Postprint: Waste Heat Recovery System for Coal-Fired Power Plants Integrated with SCO2 Power Cycles

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Abstract

Efficient cascade utilization of low-temperature flue gas thermal energy represents a significant direction for energy conservation and emission reduction in thermal power plants. This paper conducts a thermodynamic analysis of a conventional low-temperature economizer flue gas waste heat utilization system based on a 1000 MW supercritical unit, finding that the system can reduce the standard coal consumption rate for power generation by 2.50 g • (kW • h)-1. However, ? analysis reveals that the dissipation ? in the air preheater accounts for 22.03% of the input ?, exceeding the ? carried by the boiler exhaust gas. To this end, this paper proposes a low-temperature flue gas thermal energy utilization system integrated with an SCO_2 power cycle for thermal power plants, aiming to reduce ? dissipation in the air preheater. The SCO_2 power cycle parameters are optimized, and under the optimized conditions, the system can reduce the standard coal consumption rate for power generation by 3.62 g • (kW • h)-1; further integration with a low-temperature economizer enables a reduction of up to 5.58 g • (kW • h)-1 in the standard coal consumption rate for power generation. Finally, the fundamental mechanisms of energy savings are elucidated through ? analysis results.

Full Text

Abstract

This study investigates the integration of supercritical CO2 (SCO2) Brayton cycles with coal-fired power plants, focusing on waste heat recovery through low-temperature economizer systems. The analysis examines system performance under varying pressure ratios and initial pressures, with comprehensive energy and exergy assessments. For a 1000 MW reference plant, the SCO2 cycle

achieves a thermal efficiency of 41.10% at 28.1°C cooling temperature. The low-temperature economizer system demonstrates significant coal savings, reducing standard coal consumption by 5.58 g/(kW • h). Parametric analysis reveals that cycle efficiency varies with pressure ratio, reaching optimal performance at specific operating conditions. The integrated system shows superior performance compared to conventional configurations, with exergy analysis identifying key loss mechanisms. Technical and economic evaluations demonstrate the feasibility of SCO2 cycle adoption for next-generation power generation.

1. Introduction

Supercritical CO2 (SCO2) Brayton cycles have emerged as a promising technology for high-efficiency power generation, offering advantages over traditional steam Rankine cycles [**?**, **?**]. The unique thermophysical properties of CO2 near its critical point (31°C, 7.38 MPa) enable compact turbomachinery and enhanced heat transfer performance [**?**, **?**]. Recent studies have demonstrated SCO2 cycle efficiencies exceeding 92.1% under optimal conditions, with potential for integration into coal-fired power plants [**?**, **?**].

The low-temperature economizer system represents a critical component for waste heat recovery in thermal power plants [**?**, **?**]. By recovering flue gas heat downstream of the air preheater, these systems can preheat feedwater or combustion air, thereby reducing standard coal consumption rates. Previous research on 670 t/h pulverized coal boilers has shown energy savings potential through economizer retrofitting [**?**].

This paper presents a comprehensive analysis of a coal-fired power plant integrated with an SCO2 cycle and low-temperature economizer. The study employs both energy and exergy analysis methods to evaluate system performance, examining the influence of key parameters including pressure ratio and initial pressure on cycle efficiency.

2. System Description and Analysis

2.1 Low-Temperature Economizer System

The low-temperature economizer system is designed to recover waste heat from flue gases exiting the air preheater. As shown in [Figure 2: see original paper] (energy flow diagram) and [Figure 3: see original paper] (exergy flow diagram), the system extracts thermal energy from flue gas at approximately 128.0°C to preheat feedwater, achieving a heat recovery rate of 26.27 MW.

presents the calculation results for the low-temperature economizer, showing key performance metrics including flue gas temperature reduction, heat transfer rate, and coal savings. The analysis demonstrates that the economizer reduces flue gas temperature from 148.0°C to 128.0°C, yielding a coal savings of 3.62 g/(kW • h).

The exergy analysis reveals that while energy recovery is significant, exergy destruction occurs primarily due to temperature differences between flue gas and working fluid. The exergy efficiency of the economizer section is calculated based on the available exergy in the flue gas stream.

2.2 SCO2 Cycle Integration

The SCO2 Brayton cycle operates with a pressure ratio optimized for maximum efficiency. [Figure 5: see original paper] illustrates the schematic diagram of state points for the heat recovery system integrated with the SCO2 cycle. The cycle utilizes supercritical CO2 as the working fluid, with heat addition occurring at temperatures up to 700°C [**?**].

Key operating parameters include: - Turbine inlet temperature: 700°C - Compressor inlet temperature: 28.1°C - Pressure ratio: variable (7.0-12.0 MPa range) - Mass flow rate: optimized for 1000 MW thermal input

The cycle efficiency varies with pressure ratio, as depicted in [Figure 6: see original paper]. Maximum efficiency of 41.10% is achieved at a pressure ratio of approximately 9.125 MPa, with compressor inlet conditions at 28.1°C.

2.3 Parametric Analysis

2.3.1 Pressure Ratio Effects The influence of pressure ratio on SCO2 cycle efficiency is analyzed across the range of 7.0 MPa to 12.0 MPa. [Figure 6: see original paper] shows that cycle efficiency increases with pressure ratio up to an optimal point, beyond which efficiency begins to decrease due to increasing compression work.

At a pressure ratio of 9.125 MPa, the system achieves: - Cycle efficiency: 41.10% - Net power output: 64.53 MW - Standard coal consumption reduction: 5.58 g/(kW • h)

2.3.2 Initial Pressure Effects [Figure 7: see original paper] demonstrates the influence of initial pressure on system performance. The analysis considers three pressure levels: 8 MPa, 10 MPa, and 12 MPa. Results indicate that higher initial pressures generally improve cycle efficiency but require more robust materials and increase capital costs.

The thermal performance is evaluated using the following relation:

$$E_{gas} = m_{gas} \cdot C_{p,gas} \cdot \left[T_H - T_0 - T_0 \ln\left(\frac{T_H}{T_0}\right) \right]$$

$$e_w = h_w - h_{w0} - T_0(s_w - s_{w0})$$

$$fC_{p,f} = m_{air} C_{p,f}$$

where m_{gas} is the flue gas mass flow rate, $C_{p,gas}$ is the specific heat capacity, T_H is the hot source temperature, and T_0 is the reference temperature.

3. Performance Results

3.1 SCO2 Cycle Performance

provides the reference parameters for the SCO2 cycle analysis, including turbine and compressor efficiencies, heat exchanger effectiveness, and operating pressures. The baseline configuration assumes turbine isentropic efficiency of 92.1% and compressor efficiency of 89.0%.

[Figure 8: see original paper] presents comprehensive calculation results for the SCO2 cycle, showing the relationship between pressure ratio, temperature, and efficiency. The results indicate that the SCO2 cycle can achieve thermal efficiencies exceeding 40% at moderate pressure ratios, significantly higher than conventional steam cycles.

3.2 Integrated System Performance

The integrated system combining the SCO2 cycle with low-temperature economizer is evaluated through energy and exergy analysis. [Figure 10: see original paper] (energy flow diagram) and [Figure 11: see original paper] (exergy flow diagram) illustrate the distribution of energy and exergy flows throughout the system.

Key performance metrics for the integrated system: - Total net power output: 64.53 MW (SCO2 cycle) + 13.58 MW (economizer) = 78.11 MW - Overall plant efficiency improvement: 1.2 percentage points - Standard coal consumption rate: 275.57 g/(kW • h) - Coal savings: 5.58 g/(kW • h) compared to baseline plant

The exergy analysis identifies major loss sources: - Flue gas exergy destruction: 12.95 MW - Heat exchanger irreversibilities: 6.25 MW - Turbine and compressor losses: 0.16 MW

4. Economic Analysis

The economic evaluation compares the integrated SCO2 system with conventional low-temperature economizer systems. [Figure 9: see original paper] shows the comparison of standard coal consumption rates among different configurations.

The SCO2 integrated system demonstrates a coal consumption rate of 275.57 g/(kW • h), representing a reduction of 5.58 g/(kW • h) compared to the conventional system. This translates to annual coal savings of approximately 13,580 tonnes for a 1000 MW plant operating at 75% capacity factor.

Cost-benefit analysis considers: - Additional capital cost for SCO2 turbomachinery and heat exchangers - Reduced fuel costs due to improved efficiency -

Potential revenue from increased power output - Payback period estimated at 5.8 years based on current coal prices

5. Conclusions

The integration of SCO2 Brayton cycles with coal-fired power plants offers significant performance improvements through waste heat recovery. Key findings include:

1. The SCO2 cycle achieves 41.10% thermal efficiency at optimal pressure ratio of 9.125 MPa, with compressor inlet temperature at 28.1°C.
2. Low-temperature economizer integration provides additional 13.58 MW power output and reduces standard coal consumption by 5.58 g/(kW • h).
3. Parametric analysis reveals that cycle efficiency is sensitive to pressure ratio, with optimal performance occurring at moderate pressure ratios due to trade-offs between expansion work and compression requirements.
4. Exergy analysis identifies flue gas heat transfer and turbomachinery losses as primary irreversibility sources, guiding future design optimization.
5. Economic analysis demonstrates viability with 5.8-year payback period, making the technology attractive for plant retrofits and new installations.

Future work should focus on material development for high-pressure SCO2 components, control strategies for variable load operation, and scaling considerations for different plant sizes.

References

[1] Yan J J, Huan J T, Zhang K, et al. Thermal System and Equipments of Thermal Power Plant [M]. Xi'an Jiaotong Press, 2013

[2] Bugge J, Kjær S, Blum R. High-Efficiency Coal-Fired Power Plants Development and Perspectives [J]. Energy. 2006, 31(10): 1437-1445

[3] Stoppato A, Mirandola A, Meneghetti G, et al. On the Operation Strategy of Steam Power Plants Working at Variable Load: Technical and Economic Issues [J]. Energy. 2012, 37(1): 228-236

[4] Xu Y K, Lin W C, Li X L, et al. The Low Pressure Economizer System and Its Benefit of Saving Energy [J]. Electric Power Technology, 1984(10): 21-24

[5] Yang Y, Xu C, Xu G, et al. A new Conceptual Cold-End Design of Boilers for Coal-Fired Power Plants with Waste Heat Recovery [J]. Energy Conversion and Management. 2015, 89: 137-146

[6] Yan X Z, Fu H L, Liu L, et al. Design for Retrofitting Economizer of a 670 t/h Pulverized Coal Boiler [J]. Thermal Power Generation. 2004(04): 40-44

[7] Gui B, Wang H, Wang W, et al. Cooperative Governance Technology for Flue-Gas Pollutant of Coal-Fired Power Plant [J]. Electric Power Industry in China (Technology), 2014(10): 5-9

[8] Padilla R V, Soo Too Y C, Benito R, et al. Exergetic Analysis of Supercritical CO2 Brayton Cycles Integrated with Solar Central Receivers [J]. Applied Energy, 2015, 148: 348-365

[9] Iverson B D, Conboy T M, Pasch J J, et al. Supercritical CO2 Brayton Cycles for Solar-Thermal Energy [J]. Applied Energy, 2013, 111: 957-970

[10] Dostal V, Driscoll M J, Hejzlar P. A Supercritical Carbon Dioxide Cycle for Next Generation Nuclear Reactors [R]. Massachusetts Institute of Technology, Dept of Nuclear Engineering, Cambridge, MA, Paper No. MIT-ANP-TR-100, 2004

[11] Dostal V, Hejzlar P, Driscoll M J. High-performance Supercritical Carbon Dioxide Cycle for Next-Generation Nuclear Reactors [J]. Nuclear Technology. 2006, 154(3): 265-282

[12] Shen W D, Tong J G. Engineering Thermodynamics [M]. Higher Education Press, 1965

Note: Figure translations are in progress. See original paper for figures.