

Exergy Destruction Analysis about S-CO₂ Power Cycle Applied In Marine Engine Heat Recovery System

Na-Wei SHEN^{a*}, Guang-Shen SHAO, Ming-Fa WU, Dong-Hui ZHANG

School of Energy and Power Engineering, Jiangsu University of Science and Technology,
Zhenjiang, 212003, China

^anwshen@just.edu.cn

*Corresponding Author

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Abstract. The S-CO₂ Brayton cycle is widely used in any fields now. It mainly consists of four components: compressor, condenser, evaporator and Turbine. The exergy destruction and irreversibility analysis about this kind of system was presented, which is applied in the marine engine heat recovery system. The objective of the present study was to find the component with primary irreversibility or exergy destruction in the system. The physical model is built. This paper Exergy analysis in this paper is based on the energy analysis method, a kind of the second law of thermodynamics. It reveals the status of available energy utilization from the aspects of the energy quality in the waste heat recovery system. Through the work of this paper, it also lays basic foundation for the design of a more reasonable s-CO₂ system for heat recovery.

Introduction

The supercritical carbon dioxide (S-CO₂) Brayton cycle has emerged as a promising method for high-efficiency power production. With growing interest in renewable energy sources, cycles with high efficiency are critical to achieving cost-parity with non-renewable sources. It is found that the small to medium gas turbine market makes sense for bottom cycling technologies such as the supercritical CO₂ based power cycle which can deliver smaller, more economical solutions for bottom cycling.

The original work about S-CO₂ cycle were suggested by Angelino [1]. He showed that the efficiency of the recompression cycle with 650 turbine inlet temperature is competitive to the reheat steam Rankine cycle. After Dostal et al's [2] work, S-CO₂ cycle research on various heat sources including concentrated solar power, fuel cells, gas turbine exhaust heat recovery systems, and so on. Turbine and compressor performance characterization and prototype system testing has been researched at Sandia National Laboratories within the Advanced Nuclear Concepts group [3]. System control problem on S-CO₂ system has been investigated at Argonne National Laboratory (ANL), specifically applied in the Lead Fast Reactors (LFRs) and sodium-cooled reactors [4]. Now various cycle configurations have been explored in great efforts. The Southwest Research Institute in Texas is also active in enabling S-CO₂ for solar energy and is pursuing turbo-expander and heat exchanger development for this purpose. In contrast to the cycle efficiency of a conventional power conversion system, which highly depends on the turbine inlet temperature and heat source, S-CO₂ cycle efficiency is influenced by the low temperature regions such as a precooler and a compressor. Therefore, the Korea Advanced Institute of Science and Technology (KAIST) [5] constructed a low pressure ratio compressor test loop, S-CO₂ Pressurizing Experiment.

In recent years, S-CO₂ power cycle was being considered to be applied in the marine engine heat recovery system. Some India scholars [6] explored the feasibility of this kind of system about recoverable energy from the exhaust gas of a typical engine installed in an offshore supply vessel. Their case study is adopted in our paper. On the basis of their research, further work about the exergy destruction analysis is discussed carefully.

Physical Model

As shown in the figure 1, it is the Marine engine exhaust waste heat recovering system. The gaseous Carbon dioxide is compressed adiabatically in the compressor, where its state changes into supercritical state. Then the carbon dioxide with the supercritical state flows into the evaporator, where the Carbon dioxide absorbs exhaust heat with constant pressure along the pipeline; Next, the gaseous Carbon dioxide enters the turbine, driving the turbine impeller to output work. The exhaust Carbon dioxide enters the condenser, after isobaric heat rejection process, then enter the compressor inlet for the next cycle.

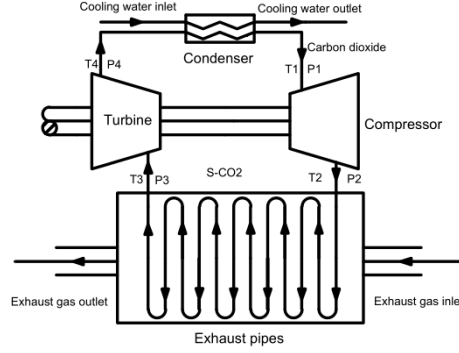


Fig.1 S-CO₂ Power Cycle for ship engine

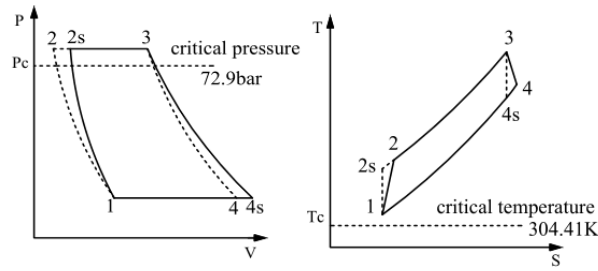


Fig.2 ideal & actual P-V and T-S diagram for S-CO₂ Power Cycle

Exergy Analysis Model

Exergy Definition. In the thermodynamics exergy (Ex [7]) is defined as the useful work that can be converted into the largest power under the condition of environment:

$$\sum E_{in} + P = \sum E_{out} + I \quad (1)$$

Enthalpy exergy is the largest useful power that working fluid of steady flow only with the environment. The calculation formula is:

$$E_{xH} = H - H_0 - T_0(S - S_0) \quad (2)$$

It is knowable that the exergy of exhaust gas and air consists of thermal exergy and pressure exergy approximately. The calculation formula is:

$$E_x = m \left[C_p(T - T_0) - T_0 C_p \ln \frac{T}{T_0} + T_0 R \ln \frac{P}{P_0} \right] \quad (3)$$

The process of energy transfer and conversion in the system or equipment, exergy efficiency is the ratio of exergy benefit and exergy expenditure.

$$\eta_{ex} = \frac{E_{x,gain}}{E_{x,pay}} \quad (4)$$

Exergy loss coefficient of systems or equipments:

$$\xi_{ex} = \frac{Ex,l}{E_{x,pay}} = \frac{E_{x,pay} - E_{x,gain}}{E_{x,pay}} = 1 - \eta_{ex} \quad (5)$$

Exergy Analysis Model. As shown in the Figure 3, it is the exergy analysis of each equipment.

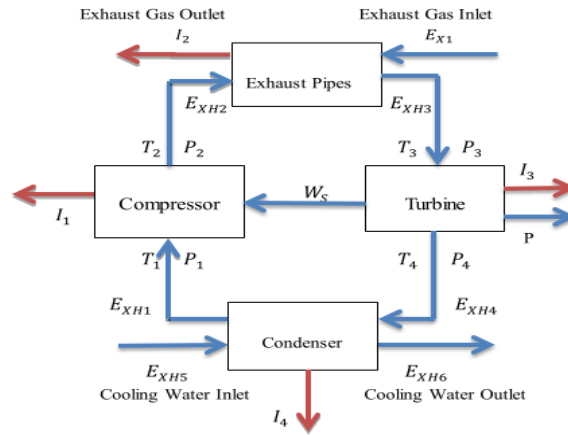


Fig.3 The exergy analysis diagram of each equipment

(1) Exergy flow equation of Exhaust Pipes:

$$E_x = m(C_p(T-T_0) - T_0 C_p \ln \frac{T}{T_0} + T_0 R \ln \frac{P}{P_0}) \quad (6)$$

$$E_{XH3} = m[H_3 - H_0 - T_0(S_3 - S_0)] \quad (7)$$

$$E_{XH2} = m[H'_2 - H_0 - T_0(S'_2 - S_0)] \quad (8)$$

$$I_2 = E_x + E_{XH2} - E_{XH3} \quad (9)$$

(2) Exergy flow equation of Turbine:

$$E_{XH4} = m[H'_4 - H_0 - T_0(S'_4 - S_0)] \quad (10)$$

$$Ws = Wc \times m_{co_2} \quad (11)$$

$$P = W_{ta} - W_s \quad (12)$$

$$I_3 = E_{XH3} - E_{XH4} - W_s - P \quad (13)$$

(3) Exergy flow equation of the condenser:

$$E_{XH1} = m[H_1 - H_0 - T_0(S_1 - S_0)] \quad (14)$$

$$E_{XH5} = Q_m C_p [(T - T_0) - T_0 \ln \frac{T}{T_0}] \quad (15)$$

$$E_{xH6} = Q_m C_p [(T - T_0) - T_0 \ln \frac{T}{T_0}] \quad (16)$$

The exergy equations of each equipment are shown in Table 1.

Tab.1 The exergy analysis of each equipment

Equipment Name	Exergy Equilibrium Equation	Benefit exergy	Expenditure exergy	Exergy efficiency	Exergy loss rate
Compressor	$W_S + E_{xH1} = E_{xH2} + I_1$	$E_{xH2} - E_{xH1}$	W_S	$\frac{E_{xH2} - E_{xH1}}{W_S}$	$\frac{I_1}{E_X}$
Exhaust Pipes	$E_{x1} + E_{xH2} = E_{xH3} + I_2$	$E_{xH3} - E_{xH2}$	E_X	$\frac{E_{xH3} - E_{xH2}}{E_X}$	$\frac{I_2}{E_X}$
Turbine	$E_{xH3} = E_{xH4} + W_S + P + I_3$	W_S, P	$E_{xH3} - E_{xH4}$	$\frac{W_S + P}{E_{xH3} - E_{xH4}}$	$\frac{I_3}{E_X}$
Condenser	$E_{xH4} + E_{xH5} = E_{xH1} + E_{xH6} + I_4$	$E_{xH6} - E_{xH5}$	$E_{xH4} - E_{xH1}$	$\frac{E_{xH6} - E_{xH5}}{E_{xH4} - E_{xH1}}$	$\frac{I_4}{E_X}$

Results

Initial conditions of carbon dioxide for each component are shown in table 2.

Tab.2 Initial conditions of carbon dioxide for each component

Equipment Name	Parameter Name	Unit	Numerical Value
Exhaust Pipes	Mass flow rate	Kg/s	4.81
	Exhaust inlet temperature/pressure	K/bar	700.15/1.015
	Exhaust outlet temperature/pressure	K/bar	322.15/1.015
Turbine	Mass flow rate	Kg/s	4.69
	Inlet/Outlet pressure	bar	14.78/73.9
	Output Power	kW	828.54
	Inlet temperature	K	478.31
Condenser	Cooling water inlet/outlet temperature	°C	20/90
	Cooling water mass flow rate	Kg/s	2.7
Compressor	Inlet temperature/pressure	K/bar	439.16/73.9
	Outlet temperature/pressure	K/bar	309.15/14.78

From the table 1 and equation (24) and equation (25), it can get the exergy efficiency and exergy loss rate of the equipments, as shown Figure 4, it is the exergy efficiency of equipments and the system.

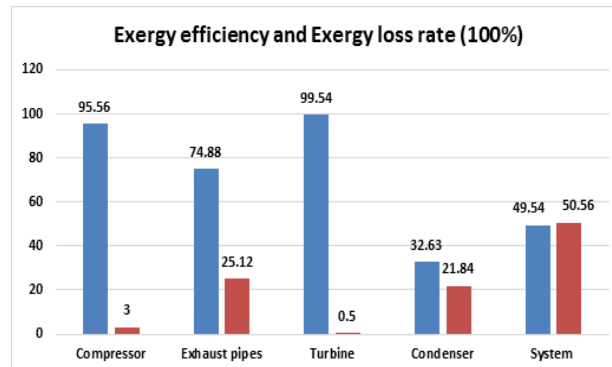


Fig.4 Exergy efficiency and Exergy loss rate for each component

Through analyzing the waste heat recovery system, system exergy flow diagram is shown in

figure 5 in detail. The overall exergy input rate from exhaust gas of the diesel engine is distributed as follows:

(1) Exhaust gas exchanges heat with working fluid-CO₂ in heat exchanger equipment. Along the exhaust gas pipe, the exergy value of the working fluid increases with the increase of the temperature after absorption of heat. Then the exhaust gas is discharged into the atmosphere;

(2) This part of the electrical work can supply power for some ship equipments, rather than consuming fuel, which means more economy and energy-saving. As the generating power can't meet the requirement of the waste heat steam turbine in ship, small-scale diesel generator in operation can be used to replace it;

(3) In the condenser, the heat of the cooling water can be reused in ship air conditioner or to heat the fuel cabin and so on. It can also reduce fuel consumption;

(4) The mechanical power consumed by the compressor is provided by the part of turbine shaft work.

From in the exergy flow diagram, the exergy destruction rate in evaporator is the largest in the heat transfer process due to large temperature difference, and the condenser is the second, next is compressor. Among four components, the exergy destruction rate of the turbine is the least. Therefore, in order to make use of the waste heat from exhaust gas, it must try to reduce the exergy loss rate of the evaporator and condenser first of all.

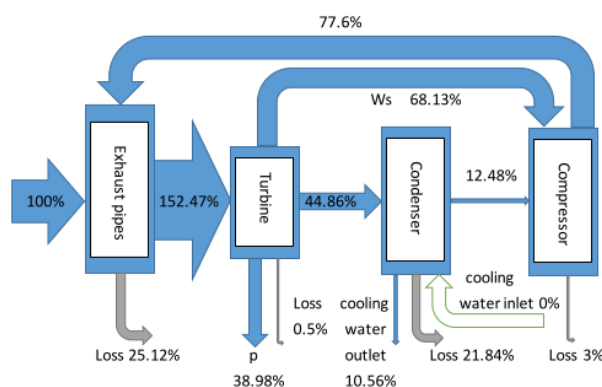


Fig.5 System exergy flow diagram

For this system, the waste heat is mainly used for the production of electric power in turbine and hot water in condenser, which accounts for about 49.54% of exergy input rate from exhaust gas. It both increases the energy utilization greatly and lower the emissions of sulphur, which reduces environment pollution.

Conclusion

Exergy analysis in this paper is based on the energy analysis method, a kind of the second law of thermodynamics. It reveals the status of available energy utilization from the aspects of the energy quality in the waste heat recovery system. This method also reflects the available energy loss of every process in the supercritical carbon dioxide (s-CO₂) Brayton cycle. Through the work of this paper, it also lays basic foundation for the design of a more reasonable s-CO₂ system for heat recovery.

Reference

- [1] G. Angelino, Carbon dioxide condensation cycles for power production, ASME Paper No. 68-GT-23, J. Eng. Power, 1968, 90:287-295.
- [2] V. Dostal, M.J. Driscoll, P. Hejzlar, A Supercritical Carbon Dioxide Cycle for Next Generation Nuclear Reactors, MITANPTR-100 [Internet], Massachusetts Institute of Technology, Cambridge (MA), 2004. Available from: <http://hdl.handle.net/1721.1/17746>.

- [3] S. A. Wright, R. Fuller, et.al., "Initial status and test results for a supercritical CO₂ Brayton cycle test-loop", Proceedings of International Congress on Advances in Nuclear Power Plants, June 8-12, Anaheim, California, 2008.
- [4] Gong, Y, et al. "Analysis of Radial Compressor Options for Supercritical CO₂ Power Conversion Cycles," MIT-GFR-034, June 2006
- [5] S.J. Bae, J. Lee, Y. Ahn, J.I. Lee, Preliminary studies of compact Brayton cycle performance for small modular high temperature gas-cooled reactor system, Ann. Nucl. Energy.75 (2015) 11e19.
- [6] Ramesh, Kalyani, Waste Heat Recovery Using (s-CO₂) Power Cycle -Applications for Maritime Industry
- [7] Cengel, Y.A., Boles, M.A.," Thermodynamics: An Engineering Approach", fifth ed.McGraw-Hill, New York. 2006.
- [8] <http://webbook.nist.gov/chemistry/fluid/>
- [9] [http://www.nsdrc.res.in/Publications/26.Waste%20Heat%20Recovery%20Using%20\(s-CO₂\)%20Power%20Cycle%20-Applications%20for%20Maritime%20Industry.pdf](http://www.nsdrc.res.in/Publications/26.Waste%20Heat%20Recovery%20Using%20(s-CO2)%20Power%20Cycle%20-Applications%20for%20Maritime%20Industry.pdf)