Design of Supercritical CO_2 Waste Heat Recovery System for Shipboard Applications

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Introduction

As the global climate change becomes substantial, there has been increasing interest to utilize the waste heat from conventional power source to reduce the fuel consumption. Among various power conversion systems, supercritical CO_2 cycle is considered as one of the most promising candidates with the benefits: 1) high efficiency in the mild turbine inlet temperature range (450-650℃), 2) simple layout configuration and 3) small footprint incorporated with compact heat exchangers and turbomachineries. These characteristics can be more distinct when the supercritical CO_2 waste heat recovery (WHR) system is installed in the shipboard application. The supercritical CO_2 WHR design concept and preliminary component design is discussed in this paper.

History of Supercritical CO_2 Cycle Development

The concept of supercritical CO_2 cycle has been originally introduced in 1948 by [1], Switzerland. The distinct benefit of supercritical cycle is to increase the turbine inlet temperature without phase change while reducing the compression work when the inlet condition approaches to the critical point. Among several candidates, CO_2 is selected as the most economical and stable material and the critical condition being close to the ambient temperature is an additional advantage of easy handling. Several designs of supercritical CO_2 cycle has been proposed by Feher, Angelino and Gokhstein [2], [3], [4]. Combs suggested a compact design concept of supercritical CO_2 system for the maritime application as well [5]. However, this innovative power system was not demonstrated due to the absence of compact heat exchangers and high-speed motors and generators.

The supercritical CO_2 cycle was revitalized by Petr, Dostal and Moisseytsev [6], [7] and [8]. Dostal suggested this innovative power conversion system for the advanced reactor application such as high temperature gas-cooled reactor (HTGR) and sodium-cooled fast reactor (SFR). He also provided the preliminary design parameters of turbomachineries and heat exchangers.

Some small-scale supercritical CO_2 systems are investigated and analyzed as well. Sandia National Lab (SNL) and Knolls Atomic Power Lab (KAPL) manufactured hundreds kW heat source supercritical CO_2 test loops and reported the experiment data [9], [10]. Echogen is making an effort to build a commercial power module of supercritical CO_2 system mainly for the waste heat application [11].

In Korea, supercritical CO_2 cycle designs were mainly proposed for the application of sodium-cooled fast reactor, fusion reactor main power systems and high temperature fuel cell, gas turbine waste heat recovery systems. In this paper, supercritical CO_2 design mainly for the gas turbine exhaust heat utilization is investigated and analyzed depending on the operating condition and system size.

System Design Consideration

The heat source of WHR system is the exhaust heat from a gas turbine, LM2500 which is widely used in shipboard application. The overall system pressure ratio is 18 and the stage of compressor, HP and LP turbine is 16, 2 and 6, respectively. The composition of flue gas is listed in Table I.

Table I : Gas turbine (LM2500) flue gas condition

Power	MW	25
Flue gas temperature	℃	566
Flue gas flow rate	kg/s	70.5
Flue gas composition	%, mole fraction	N_2, 74.9 O_2, 13.7 Ar, 0.8 CO_2, 3.3 H_2O, 7.3

As the main purpose of WHR system is to maximize the usable work, large temperature gradient in WHR heat exchanger is more preferred. Therefore, recompression layout rather produces less work than simple recuperated layout in WHR system. In this manner, simple recuperated layout is selected for the heat recovery system. Component design variables are based on the manufacturing capability. Several layout studies considering the split flow option show large usable work in WHR system but additional turbomachineries and heat exchaners (cooler or recuperator) are required which increases the capital cost [Kimzey].

Table II : Supercritical CO_2 cycle performance

Turbine efficiency	%	80
Compressor efficiency	%	70
Waste heat exchanger effectiveness	%	80
Recuperator effectiveness	%	90
Heat exchanger pressure drop	%	1

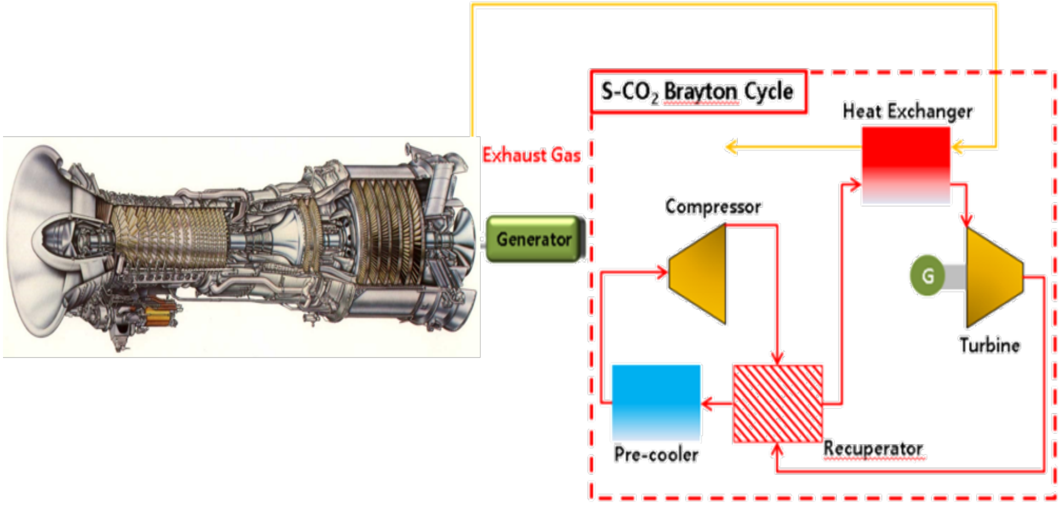

Fig. 1. Supercritical CO_2 cycle layout

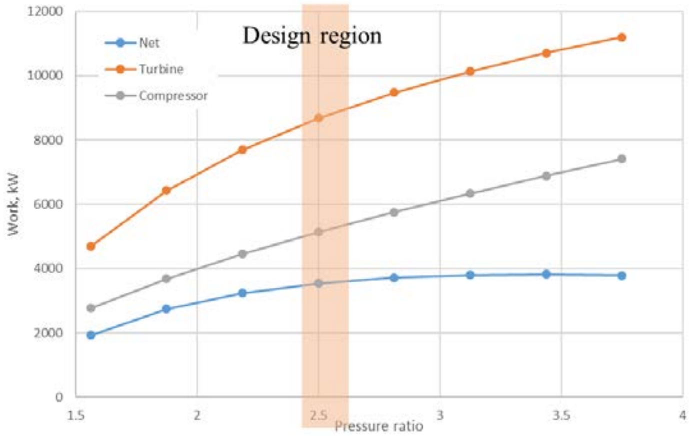

Fig. 2. Turbomachinery work in pressure ratio

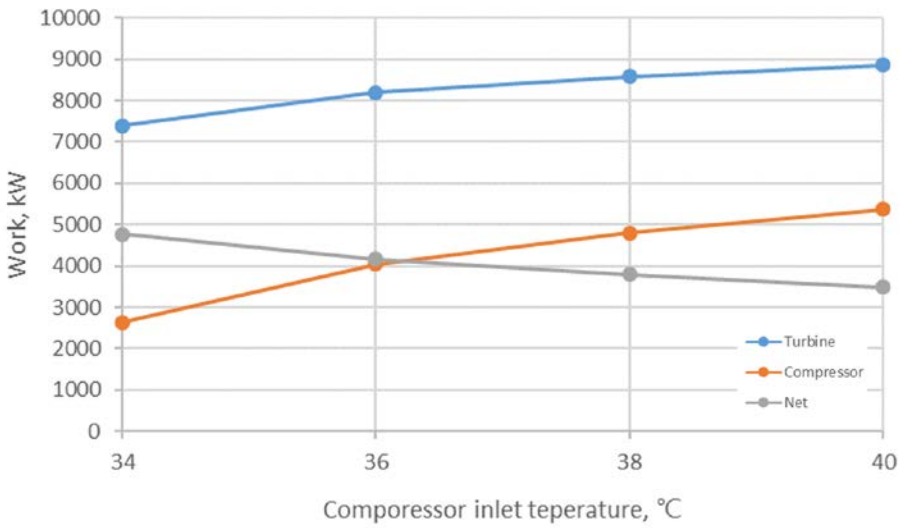

Fig. 3. Turbomachinery work in compressor inlet temperature

Cycle layout and design parameters are listed in Table II and Fig. 1. Turbomachinery performance is assumed based on the current technology. Heat exchanger effectiveness is highly related to the heat transfer area. The heat exchanger performance is reasonably assumed to balance the economic benefits. As the cycle pressure ratio increases, the turbine power and compressor power gradually increase as well. Fig. 2 shows that the design target of 2.5 pressure ratio is reasonable as high pressure causes the overall capital cost as well. Fig. 3 shows that the turbomachinery work in compressor inlet temperature. As the compressor inlet temperature increases, the compressor power increases significantly due to high incompressibility. The cooling pump power slightly changes but negligibly small compared to the turbine and compressor power.

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Summary and Conclusion

The recuperated layout of supercritical CO_2 cycle is designed and 16.7% marginal power can be potentially obtained through a heat recovery system. The corresponding component design will be performed in the future work.

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