Cycle layout studies of S-CO_2 cycle for the next generation nuclear system application

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1. Introduction

As the interest on the development of advanced reactors is increasing, the need for the alternative power conversion systems is also increasing. As the efficiency of current water-cooled reactor is lower than other power plants, the operating temperature of the next generation nuclear reactors is generally higher than the current water-cooled reactors. According to the second law of thermodynamics, the next generation nuclear reactor system efficiency can potentially be increased with higher operating temperature.

Fig.1 shows several power conversion system efficiencies and heat sources with respect to the system top operating temperature. As shown in Fig.1, the steam Rankine and gas Brayton cycles have been considered as the major power conversion systems more than several decades..

In the next generation reactor operating temperature region (450 - 900^{o}C), the steam Rankine and gas Brayton cycles have limits due to material problems and low efficiency, respectively. Among the future power conversion systems, S-CO_2 cycle is receiving interests due to several benefits including high efficiency under the mild turbine inlet temperature range (450-650^{o}C), compact turbomachinery and simple layout compared to the steam Rankine cycle. As CO_2 behaves more like an incompressible fluid near the critical point, S-CO_2 cycle can achieve higher efficiency under relatively low turbine inlet temperature compared to the general Brayton cycle.

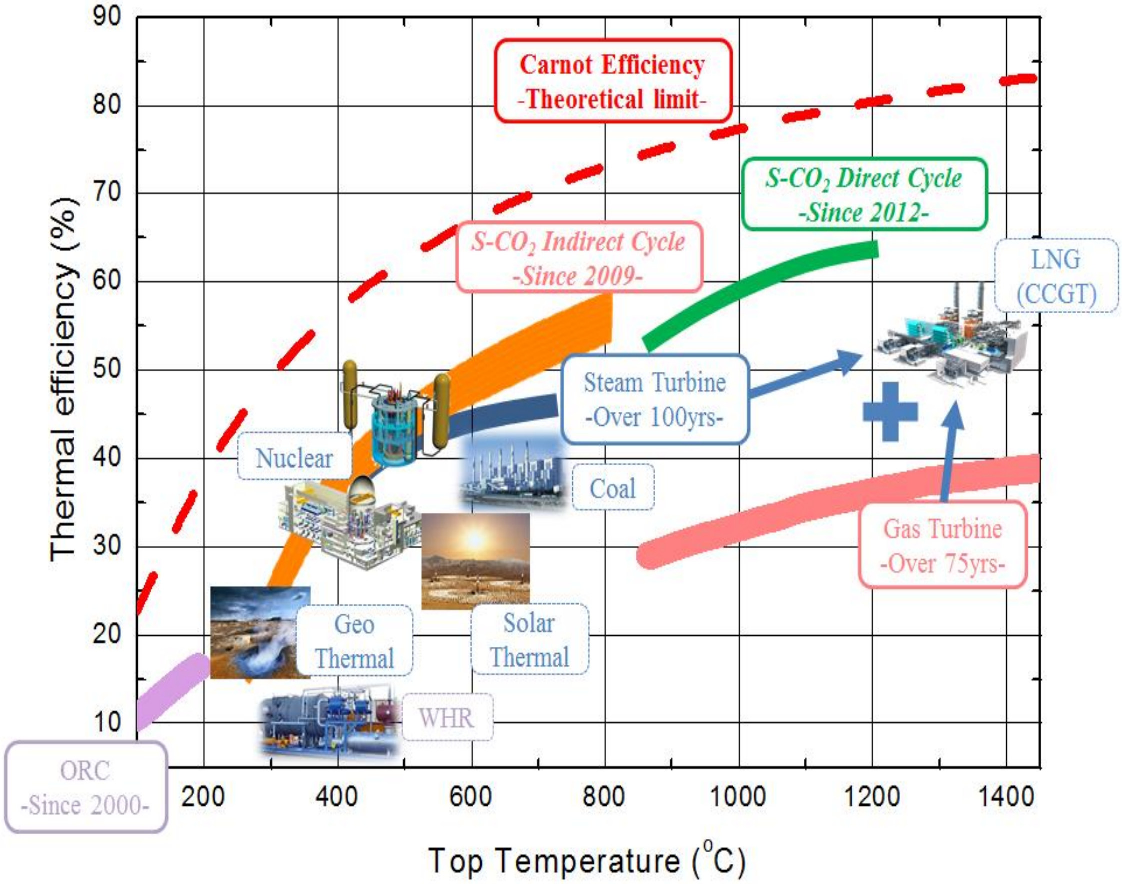

Fig. 1. Power cycle efficiencies

2. Various layouts of S-CO_2 Cycle

2.1 Literature Review

The studies on the supercritical cycle was firstly done in the United States by Feher [1]. The critical condition of various fluids is compared and the critical temperatures of some candidates such as NO_2, xenon and CO_2 are close to the atmospheric temperature. However, NO_2 is a chemically reactive gas and xenon is a monoatomic gas which favorable characteristics of non linear property change near the critical point are not observed.

Several layouts of S-CO_2 cycle are suggested and compared by Angelino [2]. His original work focused on the condensation cycle but some layouts including recompression cycle, partial cooling cycle and pre-compression cycle are still used in the S-CO_2 cycle research. He showed that the efficiency of recompression cycle with 650^{o}C turbine inlet temperature is competitive to the reheat steam Rankine cycle. He summarized his work on the CO_2 condensation cycle with two applications; one is for the mild temperature range (450-550^{o}C) with the benefits of simple layout and compactness, the other is for the high temperature range (650-800^{o}C) with the high efficiency as well as the simplicity and compactness.

Dostal revitalized the S-CO_2 cycle for the nuclear application and designed the recompression cycle with the turbine inlet temperature 550-750^{o}C [3]. For the S-CO_2 heat exchangers, he designed PCHE and estimated the size of a S-CO_2 cycle. After Dostal's work, S-CO_2 cycle researches on various heat sources including the concentrated solar power (CSP), fuel cell and gas turbine exhaust, waste heat recovery system and alternative power conversion system of current power plants were conducted [4, 5, 6, 7]. Most studies referred and adopted the recompression cycle which is known as the most efficient layout for the S-CO_2 cycle. However, relatively small specific work of recompression cycle can limit the system performance especially on the waste heat recovery systems. Kimzey referred the current CO_2 waste heat recovery systems and compared the S-CO_2 bottoming cycle that can maximize the usable work from the exhaust gas of current gas turbines [8]. Bae designed the cascade CO_2 system that consists of topping S-CO_2 recuperation cycle and bottoming CO_2 Rankine cycle for the bottoming cycle application of fuel cells [5]. Some S-CO_2 cycle layouts from Angelino's work were compared by Martin [9]. This study reviews the overall S-CO_2 layouts including the primary and bottoming cycle application and suggests the S-CO_2 layout classification to develop innovative systems.

2.2 S-CO_2 Cycle Layout Classification

Several S-CO_2 cycles have been analyzed in the previous studies. However, the general classification of S-CO_2 cycles is not discussed in the previous studies in much detail. Although some advanced S-CO_2 layouts were suggested from various literatures, these suggested layouts is simply a combination of several commonly utilized processes in power plant engineering such as intercooling, reheating and recuperation. Therefore, this study is attempted to suggest general layout classification for analysis and compare various S-CO_2 cycles' performance in a fair way.

In the closed Brayton cycle design, the recuperation process is usually required to improve the cycle efficiency by minimizing the waste heat. Therefore the recuperation cycle can be considered as the reference layout in the S-CO_2 cycle design.

The overall layouts of S-CO_2 cycle (only considered in the basic layouts) are shown in Fig. 2. The CO_2 flow can be separated depending on the heat source condition. Therefore the cycle can be divided whether the flow is split. The single (non-split) flow layouts are composed of intercooling, reheating, pre-compression, inter-recuperation, and split expansion cycles. The intercooling and reheating layouts are adopted to minimize or maximize the compression or expansion work, respectively. As the exhaust CO_2 temperature in the turbine is still high due to the low cycle pressure ratio, the heat can be recuperated in several ways. In the single flow layouts, the inter-recuperation, pre-compression and split expansion layouts are suggested depending on the recuperation processes.

The split flow layouts are composed of recompression, preheating and turbine split flow 1, 2, 3. The difference of recompression layout and the others is the recuperation processes. In the recompression layout, the heat is recuperated in High Temperature and Low Temperature Recuperators. To maximize the cycle efficiency, the heat recuperation is maximized. The temperature difference in IHX is maximized in other layouts. The additional heater is used in the preheating layout. The expansion processes are added in the turbine split flow 1-3 layouts.

2.3 Performance comparison of S-CO_2 cycle layouts

To compare the cycle performance, the design condition of the layouts is listed in Table 1. The pressure drop is ignored in this study. The cycle efficiency and specific work ratio (compared to the recuperation cycle) of S-CO_2 layouts are compared in Fig. 3. For the next generation nuclear reactor applications, the cycle efficiency is the main design target for the power conversion system design. Among the discussed layouts, the recompression layout efficiency is superior to other layouts. However, the specific work of recompression cycle is lower than other layouts and other layouts also can be considered in other applications such as waste heat recovery systems. Further studies on the layout comparison are required to design a better performing cycle.

Table I: S-CO_2 Cycle design conditions

Layout	Recuperation	Intercooling	Reheating	Inter-recuperation	Pre-compression	Split-expansion
Turbine inlet temperature, ^oC	500					
IHX inlet temperature, ^oC	278.7	251.9	352.0 / 428.3	302.5	284.4	272.7
Compressor inlet temperature, ^oC	32					
Compressor inlet & outlet pressure, MPa	7.5 / 25					
urbine & compressor isentropic efficiency,	90 / 85					
(HT/LT) Recuperator effectiveness, %	95	95	95	95 / 60	95 / 95	95

Layout	Recompression	Preheating	Turbine split flow 1	Turbine split flow 2	Turbine split flow 3
Turbine inlet temperature, ^oC	500				
IHX inlet temperature, ^oC	338.3	99.3	148	185.1	99.3
Compressor inlet temperature, ^oC	32				
Compressor inlet & outlet pressure, MPa	7.5 / 25				
urbine & compressor isentropic efficiency,	90 / 85				
(HT/LT) Recuperator effectiveness, %	93.3 / 95	95	95 / 89	52 / 95	95 / 95
Flow split ratio (m_H/m_T)	69.24	50	55.84	59.96	51.55

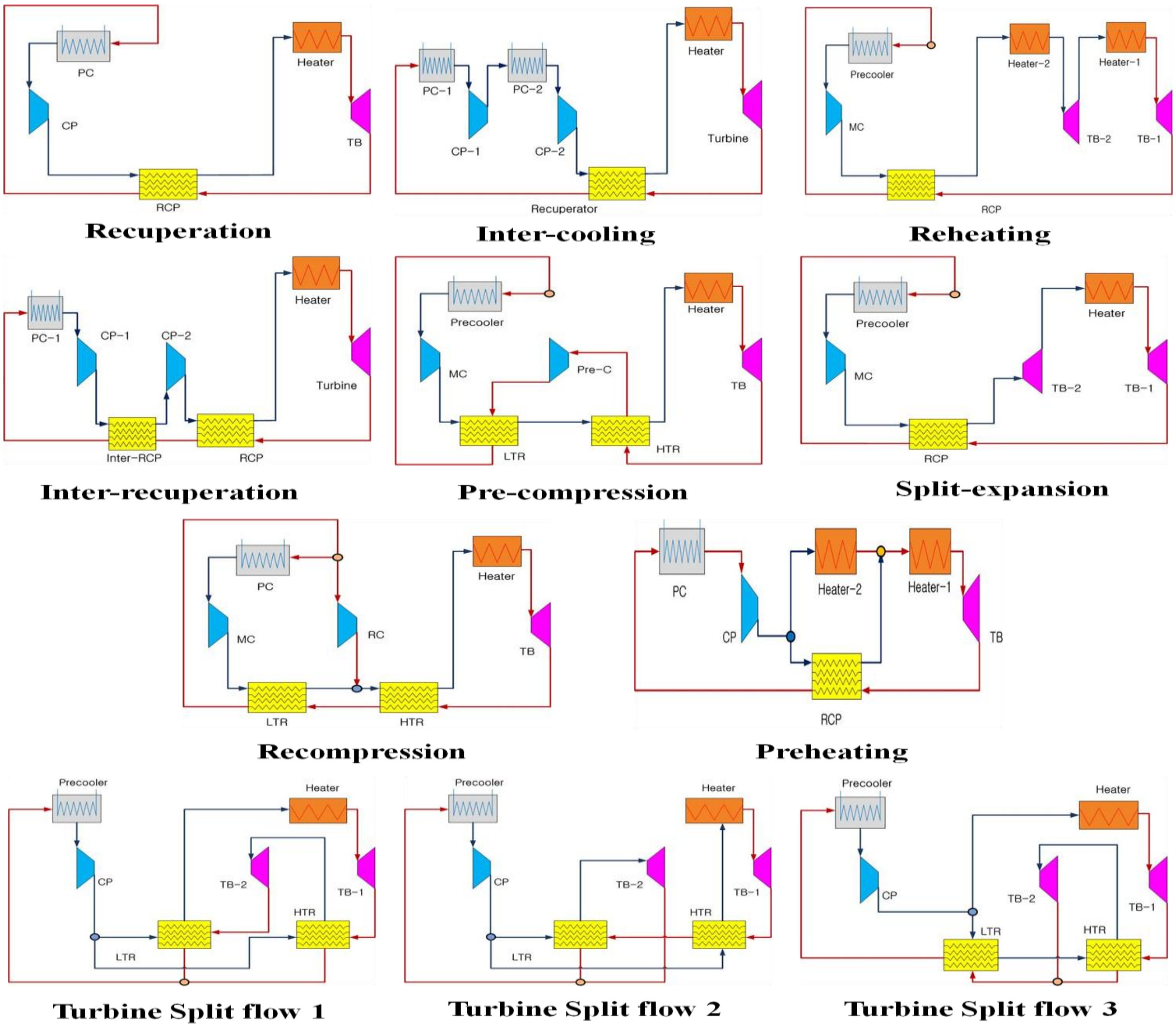

Fig. 2. S-CO_2 Cycle layouts

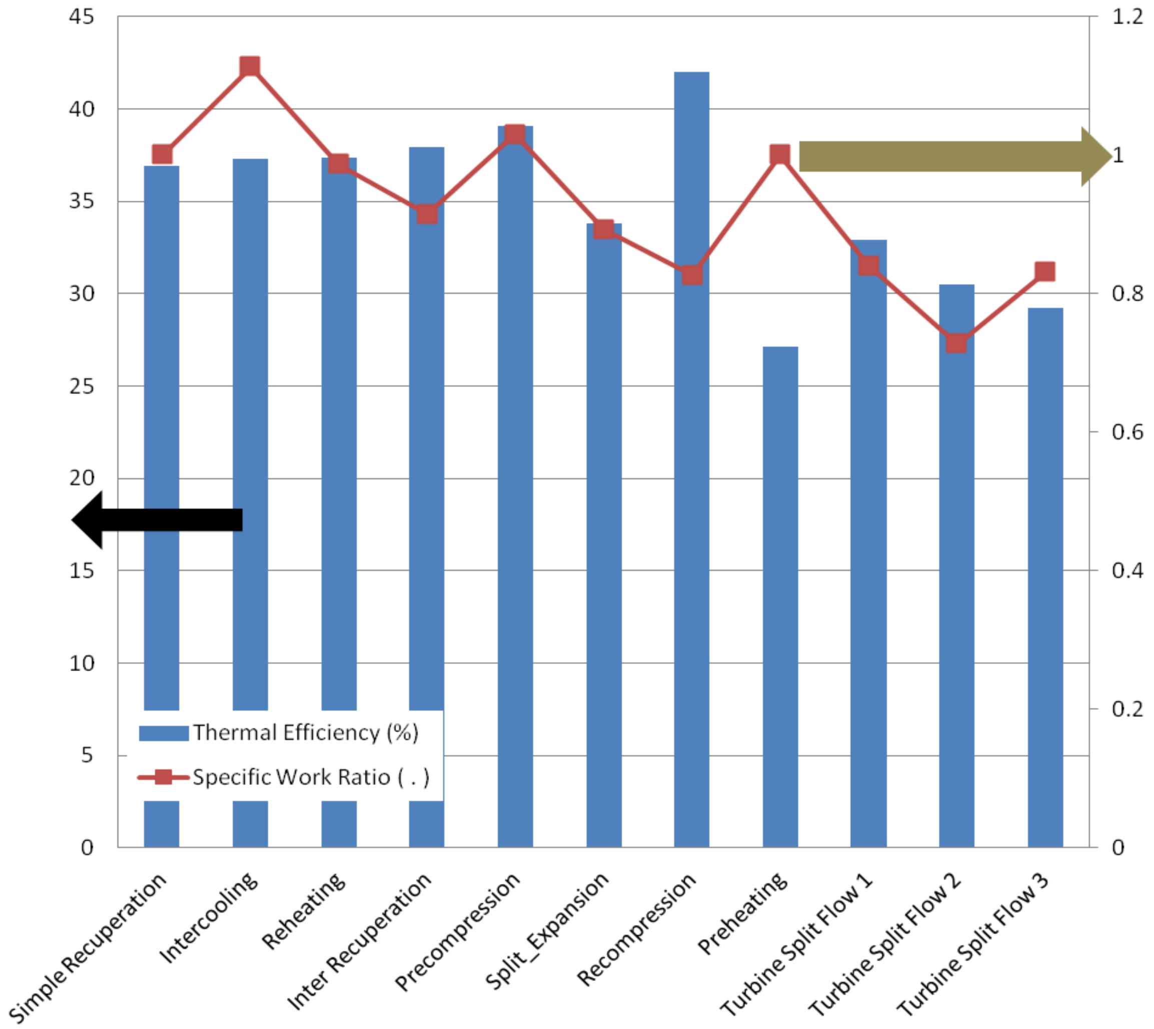

Fig. 3. Performance comparison of $S\text{-}CO_2$ Cycle layout

3. Summary and further works

$S\text{-}CO_2$ cycle can show relatively high efficiency under the mild turbine inlet temperature range (450-600^oC) compared to other power conversion systems. The recompression cycle shows the best efficiency among other layouts and it is suitable for the application to advanced nuclear reactor systems. As $S\text{-}CO_2$ cycle performance can vary depending on the layout configuration, further studies on the layouts are required to design a better performing cycle.

ACKNOWLEDGMENT

Authors gratefully acknowledge that this research is financially supported by the Korean Ministry of Education, Science and Technology and by the Korean Atomic Energy Research Institute

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