A comparative study of the He and CO_2 cycle for a small modular gas-cooled reactor

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1. Introduction

Since world energy consumption is gradually growing while the sources of energy such as fossil fuel, coal and natural gas are consistently decreasing, small-sized nuclear system is considered as one of the desirable power systems for future energy application. As a part of an effort to develop a small modular reactor (SMR) system, a high temperature gas-cooled reactor (HTGR) type SMR is actively under development.

The gas-cooled nuclear reactor with closed Brayton cycle is considered as an attractive power conversion system because it can be compact and suitable system for reducing the total system size significantly while keeping the passive safety features. Helium and carbon dioxide (CO_2) are strong candidates as a coolant for the gas-cooled nuclear system. Helium Brayton cycle is commonly known that it can obtain very simple system arrangement with direct cycle and high thermal efficiency under high outlet temperature range due to its advantages such as less interaction with structure material, chemical stability and so on. However, supercritical carbon dioxide (S-CO_2) Brayton cycle can be more suitable power conversion cycle with HTGR. The S-CO_2 Brayton cycle has advantages over the helium Brayton cycle because it can achieve higher thermal efficiency at similar or even lower turbine inlet temperature (T.I.T) and can be more compact than a helium cycle.

Both Brayton cycles can be a suitable power conversion system for a small modular gas-cooled reactor. Thus, for this study, preliminary design works of helium and the CO_2 Brayton cycles for a $5MW_{th}$ small modular gas-cooled reactor were carried out and evaluated while considering turbomachinery efficiency variation. Considering the size of a small modular nuclear system, the cycle configurations should be simple and compact. So, a simple recuperated Brayton cycle was chosen as candidate of the cycle layout for this study.

2. Cycle Analysis

Thermal power, T.I.T, minimum temperature, cooling system, maximum pressure, turbomachinery efficiency, recuperator effectiveness and generator efficiency used in this study are assumed as shown in Table I.

An optimum turbine pressure ratio which makes both Brayton cycle to achieve high efficiency should be first obtained. Figs.1 and 2 show the results of the optimum pressure ratio study while turbomachinery efficiency is varying for each Brayton cycle case. The reason why turbomachinery efficiency was varied is because the turbine and compressor efficiencies in such a small scale power system with helium and CO2 are not certain, while the cycle efficiency significantly affected by these efficiencies. As the turbine efficiency increase from 64% to 100% by 6% increment, the compressor efficiency will also increase from 40% to 100% by 10% increment. This is typical case, since it is well known fact that compressor efficiency is usually lower than the turbine efficiency in real engineering practice.

Table I: Basic parameters for each Brayton cycle.

Coolant	He		CO_2	
Thermal Power (MWt)	5		5	
T.I.T (℃)	800	650	650	
Minimum temperature (℃)	40		40	
Cooling system	Air		Air	
Maximum Pressure (MPa)	7		15	20
Turbine Efficiency (%)	76~100		64~100	
Compressor Efficiency (%)	60~100		40~100	
Recuperator Effectiveness (%)	95		95	
Generator efficiency (%)	98		98	

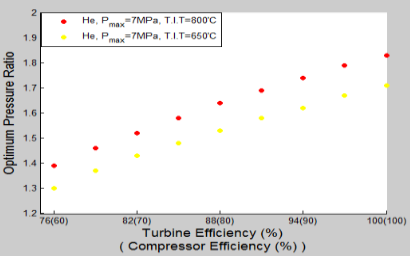

Fig.1 The optimum pressure ratio according to the turbomachinery efficiency for the helium recuperated cycle.

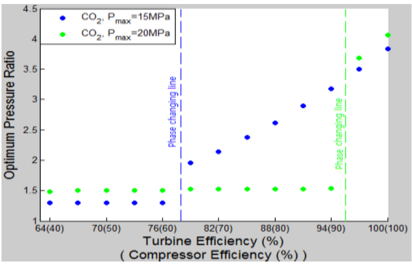

Fig.2 The optimum pressure ratio according to the turbomachinery efficiency for the CO_2 recuperated cycle.

The optimum pressure ratios of the helium Brayton cycles are gradually increasing, but those of the CO_2 Brayton cycles have sudden changes due to the CO_2 phase change. There is each peak of pressure ratio which makes the CO_2 Brayton cycle to achieve high thermal efficiency in accordance with the CO_2 phase, subcritical or supercritical. As shown in Fig.2, the CO_2 Brayton cycle with 15MPa maximum pressure has the phase changing line between 76(60) and 82(70)% turbomachinery efficiency and the 20MPa maximum pressure case has that between 94(90) and 100(100)% turbomachinery efficiency, respectively. The reason is because in this study we set the maximum pressure at constant and varied the pressure ratio, which results in change in compressor inlet pressure. As the pressure ratio increases the compressor inlet pressure decreases and when the compressor inlet pressure falls below the critical pressure (~7.38MPa) the cycle shifts from super-critical Bryaton cycle to trans-critical cycle. The left side of the phase changing line is supercritical case and the right side of the line is subcritical case.

Using the obtained optimum pressure ratio, each cycle performance calculation was performed by using an in house code. Fig.3, 4 show respectively the thermal efficiency and net electricity according to the varying turbomachinery efficiency.

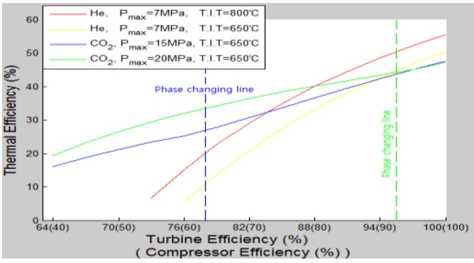

Fig.3 The thermal efficiency vs. turbomachinery efficiency of each case.

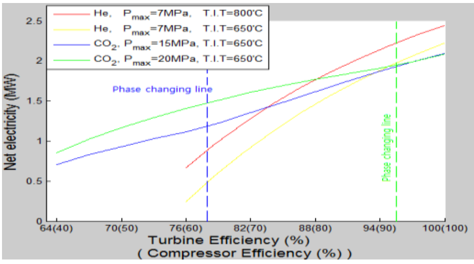

Fig.4 The net electricity vs. turbomachinery efficiency of each case.

3. Heat Exchanger Design

The heat exchanger design was carried out by using the calculation of cycle performance. For this study, the cooling type is air cooling system, the material of the heat exchanger is AISI 303 and Printed Circuit Heat Exchanger (PCHE) type is considered as the heat exchanger design condition

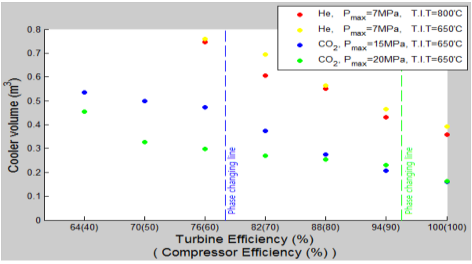

Fig.4 The cooler volume according to the turbomachinery efficiency of each case.

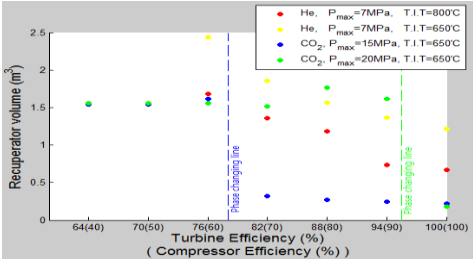

Fig.5 The recuperator volume according to the turbomachinery efficiency of each case.

Fig.5, 6 show the cooler and the recuperator volume according to the each cycle performance calculation which is calculated for different turbomachinery efficiency, respectively.

4. Summaries and Further Works

In this study, the comparison between the helium cycle and the CO_2 cycle was performed from the viewpoint of the cycle performance and heat exchanger volume for a small modular gas-cooled reactor application.

As shown in Figs.3 and 4, the cycle performances of the CO_2 cycle are higher than those of the helium cycle at similar T.I.T and turbomachinery efficiency except for the cases of very high turbomachinery efficiency, which is almost impossible to achieve in a small scale system such as in this case. And the variation in the performance of the helium cycle is more heavily dependent on the turbomachinery efficiency than that of the CO_2 cycle.

The cooler volumes of the CO_2 cycle are smaller than those of the helium cycle, but the recuperator volume is hard to compare between helium and CO_2 cycles because there are sudden changes in the recuperator volume between the supercritical CO_2 case and the subcritical CO_2 case. But, only considering the subcritical case of CO_2 cycle, the recuperator volumes of the CO_2 cycle are smaller than those of the helium cycle, too.

Further studies about the recuperator, the cycle performance with changing the minimum temperature, pressure ratio and the turbomachinery design should be carried out in the future progressively.

ACKNOWLEDGEMENT

This research was supported by the National Research Foundation of Korea (NRF) and Innovation project of Korea Atomic Energy Research Institute (KAERI).

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[1] S.J. Bae, Comparison between Helium Cycle and Supercritical CO_2 Cycle for MMR & AMR, KNS, May, 2013