Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 24-25, 2013

Feasibility Study of Mixture Gas Coolant Based HTGR Concept using Conventional Gas Turbine Power Conversion Systems

Serin Shin[1], Min-Young Park[1], Eung Soo Kim[1*], Sung Joong Kim[2], Jeong Ik Lee[3]
[1]*Department of Nuclear Engineering, Seoul National University, 559 Gwanak-ro, Gwanak-gu, Seoul, South Korea*
[*]*Corresponding author: kes7741@snu.ac.kr*
[2]*Department of Nuclear Engineering, Hanyang University, Seoul 133-791, Korea*
[3]*Department of Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology, 373-1, Guseong-dong, Yuseong-gu, Daejeon 305-701, Republic of Korea*

1. Introduction

A Very High Temperature Reactor (VHTR) is one of the most promising Gen-IV reactor concepts due to its inherent safety, high efficiency, and various possibilities of high temperature application [1]**.** Nevertheless, there are still some technical issues for the near-term commercialization (i.e. high temperature materials, closed gas Brayton cycle, low power density, etc.) This paper proposes a couple of new ideas to tackle those issues and evaluates their feasibility. The details are presented in the following sections.

2. Main Ideas and Characteristics of Mixture Gas-Coolant Based HTGR

This paper proposes a mixture gas-based primary coolant and conventional combined gas turbine systems for high temperature gas cooled reactors (HTGRs). The main ideas and characteristics are summarized below:

- **Helium Gas Mixture Based Primary Coolant**: The proposed system utilizes helium gas mixture as a primary coolant to enhance cooling performance in the core [2]. The improved cooling capability can eventually reduce reactor core size with increased power density or reduce circulation power with improved overall system efficiency.
- **Low Core Outlet Temperature**: The proposed system is designed to be operated at 750°C in the core outlet, avoiding high temperature material issues [3]. The core outlet temperature can be increased along with new materials development.
- **Conventional Combined Gas Turbine System with Auxiliary Natural Gas Combustor**: The proposed system utilizes conventional combined air gas turbine cycle with high efficiency (~45%), which is commercially proven. Because system efficiency is significantly dependent on turbine inlet temperature, an auxiliary natural gas combustor (NGC) is proposed to raise the temperature from 750°C. Therefore, in the proposed system, the heat at the low and medium temperature range (~750 °C) is supplied by a nuclear reactor and the heat at the high temperature (750 °C ~900 °C) by a natural gas combustor.
- **High Temperature Waste Heat Utilization**: The proposed system effectively utilizes high temperature waste heat (~150°C) from the gas turbine. With state-of-the-art desalination systems such as Multi-Effect Distillation (MED) and Forward Osmosis (FO), the waste heat can be recovered up to 80% [4].

3. Feasibility Study on the Proposed Concepts

In order to evaluate the proposed ideas and concepts above, feasibility study have been carried out based on analytical and computation methods. The notable results are summarized below:

3.1 Enhancement of Cooling Performance using Helium Gas Mixture as Primary Coolant

In order to measure cooling performance of the helium mixture, simple analyses based on convective heat transfer and pressure drop were conducted using Engineering Equation Solver (EES). A total of five different gas mixtures (He-CO_2, He-Ar, He-Ne, He-Kr, He-Xe) were taken into account for their various concentrations. The followings are the results:

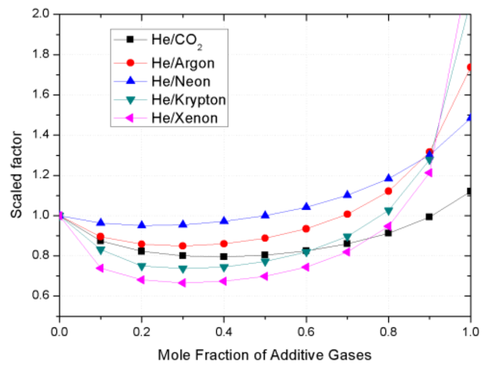

Figure 1. Comparisons of relative core scale for fixed pressure drop.

- Helium gas mixture can significantly improve convective cooling performance. For fixed core size, circulation power can be reduced by a factor of 8 (for CO_2), and for fixed pressure drop, the core volume, by 40% (for Ar) (Figure 1).
- Considering the various aspects including cooling performance, chemical stability, radioactivity, price, etc., He-Argon (7:3) and He-CO_2 (6:4) mixtures are evaluated to be the best candidates with the optimum concentrations in the parentheses.

3.2 Conventional Open Gas Turbine with Auxiliary Natural Gas Combustor

Thermodynamic analyses for more than 10 potential systems have been conducted using UNISIM software. In this study, (1) electricity generation efficiency, (2) nuclear energy usage ratio, and (3) total energy utilization efficiency have been evaluated and three systems have been finally proposed as summarized in Table I. The basic assumptions include (1) reactor power: 250MWt, (2) core inlet/outlet temperature: 440ºC/750ºC, (3) primary pressure: 7MPa, (4) turbine inlet temperature: max.1050ºC, (5) compressor/gas turbine efficiency: 85%/90%, and (6) heat exchanger effectiveness: max. 95%.

Table I. System Configurations.

	System A	System B	System C
Primary Coolant	Helium Mixture		
PCU Type	Gas Turbine/ Rankine Combined Cycle	Gas Turbine/ KALINA Combined Cycle	Gas Turbine Regenerate with Reheat /Intercooling
Efficiency	44 %	45%	40 %
Nuclear Energy Ratio	53 %	37%	70%
Total Heat Utilization	44%	45%	90%

- **System A** has high efficiency but relatively low nuclear energy usage ratio and low energy utilization.
- **System B** has the highest efficiency among the three systems with KALINA cycle [5]. However, it also has relatively low nuclear energy ratio and heat utilization.
- **System C** has the lowest but still high efficiency. It also has high nuclear ratio and very high heat utilization from high temperature waste heat (Figure 2).

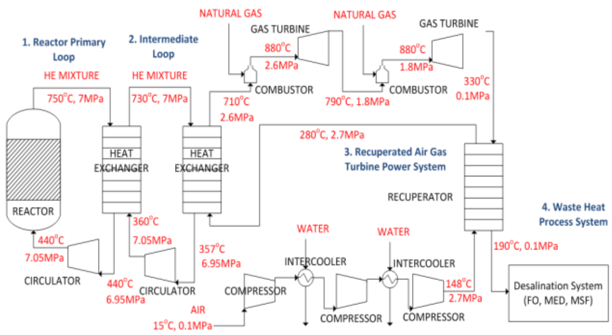

Figure 2. Configuration of System C.

This study also investigated effects of core outlet and turbine inlet temperature. The results are shown in Figure 3 and a summary is given below:

- For fixed turbine inlet temperature, nuclear energy ratio is linearly increased with core outlet temperature.
- For fixed core outlet temperature, efficiency increases with turbine inlet temperature by 1% per 50 ºC.
- Efficiency is not sensitive to core outlet temperature.

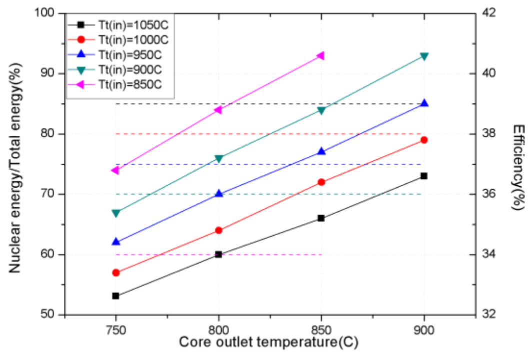

Figure 3. Efficiency and nuclear energy ratio (System C). (symbol: nuclear energy ratio, non-symbol: efficiency)

4. Summary

This study has proposed a HTGR concept which utilizes helium gas mixture and conventional combined gas turbine systems with an auxiliary natural gas combustor. Simple analytical estimation showed that helium based gas mixture can effectively reduce circulation power or reduce core volume with higher power density. He-Ar (7:3) and He-CO_2 (6:4) are considered as the best candidates. Using conventional combined gas turbine with an auxiliary natural gas combustor, the system efficiency can be maintained high despite of reduced core outlet temperature. System efficiency can be achieved more than 40% with 70% of nuclear energy usage ratio. With MED or FO desalination systems, total energy utilization efficiency can be increased up to 80%.

5. Acknowledgement

This work was supported by National R&D Program through the National Research Foundation of Korea(NRF) grant funded by MSIP; Ministry of Science ICT & Future Planning (No. 0620-20130023)."

REFERENCES

[1] M. P. LaBar, A. S. Shenoy, W. A. Simon, and E. M. Campbell, Status of the GT-MHR for Electricity Production, World Nuclear Association Annual Symposium, Sep.3-5, 2003, London, UK.
[2] El-Genk, M.S., Tournier, J.M., Noble gas, binary mixtures for gas-cooled reactor power plant, Nuclear Engineering and Design, Vol. 238, pp. 1353-1372.
[3] Penfield, S., Rittenhouse, P., Evaluation of Materials Issues in the PBMR and GT-MHR, Technical Report 1007505, EPRI, Palo Alto, CA, November 2002.
[4] Park, M.Y., Park. G.C., and Kim, E.S., Forward osmosis water desalination using advanced reactor waste heat, ICAPP 2013, Jeju, South Korea, 2013.
[5] Henry, A., MLCAK, P.E., An Introduction to the KALINA Cycle, Proceedings of the International Joint Power Generation Conference, 1996.