



The thermodynamic and cost-benefit-analysis of miniaturized lead-cooled fast reactor with supercritical CO₂ power cycle in the commercial market



Ming-Jia Li^{a,b,*}, Yan-Jun Jie^a, Han-Hui Zhu^a, Guo-Jia Qi^a, Meng-Jie Li^a

^a Key Laboratory of Thermo-Fluid Science and Engineering of Ministry of Education, School of Energy & Power Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, China

^b Department of Earth and Environmental Engineering, Columbia University, New York, NY 10027, USA

ARTICLE INFO

Keywords:

Miniaturized system
Lead-cooled fast reactor
Reheating recompression S-CO₂ Brayton cycle
Thermodynamic analysis
Investment analysis
Commercial market

ABSTRACT

The lead is considered as a more attractive material of coolant than lead/bismuth because of higher availability, lower price and fast neutron spectrum in recent years. In this paper, the thermodynamic analysis and cost-benefit-analysis of miniaturized lead-cooled fast reactor (LFR) composing different power cycles have been investigated to examine the optimization result of the miniaturized system in the commercial market. The study proposes a design of such the miniaturized LFR system for a first step implementation of the technology. First, the typical cycles include the reheating recompression supercritical CO₂ Brayton cycle (hereinafter referred to as S-CO₂ cycle), the traditional steam Rankine cycle and the helium (He) Brayton cycle. Second, main parameters of thermodynamic analysis and economic analysis are based on the National Standards of Chinese Industry and the realistic financial and cost estimating assumptions in China. Third, the reheating recompression S-CO₂ Brayton cycle is the optimal option to the LFR. The main results demonstrate that the thermal efficiency of the reheating recompression S-CO₂ Brayton cycle is 43.72%. The efficiency of the LFR generation system comprising reheating recompression S-CO₂ Brayton cycle is 41.53%. Both of them are greater than the efficiencies of steam Rankine cycle (38.62%, 36.69%) and He cycle (37%, 35.41%). Finally, the electricity production costs (EPC) of LFR generation system is obtained as \$0.0536/(kW·h), which is lower than the average electricity price in China (\$0.0632/kW·h). The payback period of the investment is 31.4 years while the lifespan is 40 years. The profit of company undertaking the LFR generation system is \$6.3 million. Therefore, it can be found that the reheating recompression S-CO₂ Brayton cycle is the primary choice of the LFR system, and its profit for commercialization of the system is beneficial.

1. Introduction

With the increasing energy shortage, environmental pollution and greenhouse effect, high efficiency and clean energy attracted more attention in the world. Nuclear energy has become one of the major solvable choices. The sodium cooled fast reactor has been developed profoundly. The lead-cooled fast reactor (LFR) is the IV generation advanced nuclear energy system. The lead is considered as a more attractive material of coolant than lead/bismuth because of higher availability, lower price and fast neutron spectrum. It works with the high-temperature operation, and it is cooled by molten lead or lead–bismuth eutectic (LBE) which is chemically inert liquids with good thermodynamic properties. Moreover, the physical characteristics of the LFR have significant advantages, such as small core volume, high service temperature, large coolant density and long refueling cycle.

As an important development prospect of advanced nuclear energy, the LFR has multiple applications include the fission nuclear energy system, fusion nuclear energy systems and subcritical hybrid nuclear energy systems. The commercialization of miniaturized LFR system has become one of frontier topics. The traditional steam Rankine cycle is mainly adopted in the present commercialized reactors. Although the technology is mature, the shortcomings are obvious including low conversion efficiency and high volume/power ratio etc. It is necessary to adopt a compact high-efficiency power cycle to encourage the wide commercialization of miniaturized LFR system. The supercritical CO₂ Brayton cycle (hereinafter referred to as S-CO₂ cycle) has been largely studied for nuclear applications. Kim et al. (2012) analyzed the comparison of S-CO₂ power cycle and CO₂ cycle and concluded that the S-CO₂ cycle is more proper for harvesting energy from low-grade heat sources that neat which the low-temperature heat sink is accessible.

* Corresponding author. Key Laboratory of Thermo-Fluid Science and Engineering of Ministry of Education, School of Energy & Power Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, China.

E-mail address: mjli1990@mail.xjtu.edu.cn (M.-J. Li).

<https://doi.org/10.1016/j.pnucene.2017.11.015>

Received 3 August 2017; Received in revised form 1 November 2017; Accepted 24 November 2017

Available online 22 December 2017

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Sarkar (2015) investigated the performance analysis and optimization result of S-CO₂ power cycle comprising with different working fluids, component design and prototypes. Kim et al. (2016) compared nine S-CO₂ bottoming power cycles to a topping cycle equipping in the gas turbine. They found out that S-CO₂ power cycle has higher pressure, higher temperature and higher mass flow rate than other systems. Ahn et al. (2015) and Angelino (1968a) conducted a comparison of various S-CO₂ layouts that present cycle performance. They presented that the efficiency of recompression S-CO₂ is better than others. Li et al. (2017) further presented a detailed comprehensive study to investigate the recent development trends of the S-CO₂ power cycle and the different applications of the S-CO₂ power cycle in various energy industries. Kato et al. investigated the cycles' application of Liquid Metal cooled Fast Reactors (LMFRs) by testing three CO₂ direct cycles. They concluded that CO₂ power cycle is expected to be a potential option to the LMFRs because of high safety, low costs and feasible maintenance (Kato et al., 2001). Similar studies and numerical analysis are adopted in the Sodium cooled Fast Reactors (SFRs) (Moiseyev and Sienicki, 2007; Cha et al., 2009; Jeong et al., 2011; Floyd et al., 2013). Wang et al. (2017) studied the effect of various operating and design parameters with different cycle layouts. The Sandia National Laboratory built a carbon dioxide experimental loop to analyze the S-CO₂ power cycle (Wright et al., 2010). (Akbari and Mahmoudi, 2014) investigated a combined recompression cycle integrating with S-CO₂ power cycle and organic Rankine cycle (ORC) cycle from the respects of exergy. They concluded that the exergy efficiency of cycle can be improved by up to 11.7%.

From the above studies, it can be concluded that majority of studies focused on the S-CO₂ cycle merely concerning thermodynamics, exergy, cycle performance, only few of them combined the S-CO₂ cycle with fast reactors. A comprehensive thermodynamic study and cost-benefit analysis on the miniaturized LFR system comprising S-CO₂ power cycle and the feasibility of its commercial operation, to our knowledge, has not yet been performed. According to the wide application of miniaturized LFR system, a right decision from the economic perspective needs a detailed thermodynamic investigation as well as the cost-benefit analysis. The study proposes a design of such the miniaturized LFR system for a first step implementation of the technology.

In the study, the thermodynamic analysis and cost-benefit-analysis of the application of S-CO₂ cycles are adopted to the LFR with 10MWe liquid lead (Pb) coolant for the commercial miniaturized application. The capacity of 10MWe is selected because it is the medium proper size for the wide application in commercial market. For the convenience, the flowchart of thought of the paper is clearly presented in Fig. 1. The remaining section of the paper is organized as follows. Section 2 presents the advantage and layout of reheating recompression S-CO₂ Brayton cycle. In section 3, the thermodynamic model of the LFR power generation system composing the reheating recompression S-CO₂ cycle is established. The optimized thermodynamic performance of the system is calculated in detail. Comparison of the thermal efficiency of reheating recompression S-CO₂ cycle, that of traditional steam Rankine cycle and that of helium (He) Brayton cycle are further investigated. To verify whether the conversion efficiency of S-CO₂ cycles can be greater than 40%. In section 4, investment economic analysis of the LFR power generation system is demonstrated. The economic model of the system is analyzed to obtain the optimized electricity costs primarily. The investment analysis is further adopted to verify whether the LFR using the reheating recompression S-CO₂ Brayton cycle is beneficial for the commercialization.

2. The advantage and layout of recompression S-CO₂ Brayton cycle

There are various layouts of S-CO₂ Brayton cycle, the single-recompression cycle is the earliest layout (Sulzer, 1950), and the corresponding *T-s* diagram is as shown in Fig. 2. Although waste heat can be recovered at turbine outlet with high-temperature and low-pressure,

the improvement of efficiency is limited by the “pinch point problem” because the heat capacity of both sides with regenerator is seriously unbalanced in the S-CO₂ power cycle. In order to solve this problem, Feher (1968) primarily proposed a recompression S-CO₂ Brayton cycle. Angelino (1968b) extensively developed a regeneration process for the improvement of cycle efficiency based on the modification of S-CO₂ Brayton cycle. Hejzlar et al. (2006) and Ishiyama et al. (2008) compared the indirect S-CO₂ recompression cycle with helium and water cycle, respectively. The results demonstrate the efficiency of cycles is attractive. Moreover, a recompression S-CO₂ Brayton cycle demonstration was designed by the Sandia National Laboratory with the capacity of 1 MWth (Dostal et al., 2004a). Sarkar (2009) presented an exergetic analysis and optimization analysis of the S-CO₂ recompression cycle to investigate the influence of operating parameters on the optimum pressure ratio and exergetic efficiency. The result demonstrated that the effect of parameters is important to the recuperators. Sarkar and Bhattacharyya (2009) optimized the thermal efficiency of the S-CO₂ recompression cycle with reheating. It concluded that the improvement of thermal efficiency is depended on the rise of maximum cycle temperature and the decrease in minimum cycle temperature. Bae et al. (2014) compared the thermal performance of S-CO₂ recompression cycle and S-CO₂ simple cycle when they are equipped with the 300 MW LFR system, respectively. They presented that the efficiency of S-CO₂ recompression cycle is higher than 40% constantly. The efficiency of S-CO₂ simple cycle is obviously affected by the change of highest pressure. In a summary, many studies presented that recompression S-CO₂ Brayton cycle has high efficiency and the cycle structure is relatively simple and compact. It is one of the promising S-CO₂ cycle layouts.

The advantage of recompression S-CO₂ Brayton cycle is prominent. The cycle reduces the thermal tolerance of low-temperature recuperator (LTR) by reducing the mass flow of the high-pressure side through splitting flow. It can eliminate the “pinch point problem”. The main compressor power consumption can be further reduced, and the efficiency of recuperator has been significantly improved. In the paper, the reheating recompression S-CO₂ Brayton cycle is adopted to compose with the LFR. The schematic diagram is as shown in Fig. 3. To compare with the simple-reheat cycle, an additional compressor has been adopted. The recuperator is divided into the high-temperature recuperator (HTR) and the LTR for improving the efficiency of heat utility. The main components of reheating recompression S-CO₂ Brayton cycle include the LFR, intermediate heater, and intermediate reheater, high-pressure turbine, low-pressure turbine, and re-compressor, main compressor, HTR, LTR and cooler.

3. Thermodynamic analysis of LFR system

In the section, a thermodynamic model of the LFR power generation system comprising reheating recompression S-CO₂ Brayton cycle has been established. Moreover, the benchmarking qualified level of different system efficiencies comprising with different layouts has been set as 40%. The optimized thermodynamic performance has been analyzed based on the design parameters of SFR to calculate the conversion efficiency of the system. Furthermore, traditional steam Rankine cycle and that of He Brayton cycle are applied to the LFR, and the corresponding efficiencies of thermodynamic models are investigated to make the comparison.

3.1. Thermodynamic analysis of LFR composing the reheating recompression S-CO₂ Brayton cycle

3.1.1. Thermodynamic model

In this part, there are assumptions as follows. First, all processes in the system are steady state. Second, the pressure loss and heat loss of pipe are ignored. Third, the kinetic energy and potential energy of fluid are not considered in each component. Fourth, the heat exchange

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