Journal of Power Sources 270 (2014) 608–618

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Various supercritical carbon dioxide cycle layouts study for molten carbonate fuel cell application

Seong Jun Bae, Yoonhan Ahn, Jekyoung Lee, Jeong Ik Lee*

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

HIGHLIGHTS

- Various S–CO_2 cycles were compared in terms of application to a MCFC bottoming cycle.
- A novel concept of S–CO_2 cycle is proposed and intensively studied.
- The relationship of the size to the performance is studied for various S–CO_2 cycles.

ARTICLE INFO

Article history:
Received 27 May 2014
Received in revised form
17 July 2014
Accepted 20 July 2014
Available online 30 July 2014

Keywords:
MCFC
S–CO_2 cycle
Hybrid system
PCHE

ABSTRACT

Various supercritical carbon dioxide (S–CO_2) cycles for a power conversion system of a Molten Carbonate Fuel Cell (MCFC) hybrid system are studied in this paper. Re-Compressing Brayton (RCB) cycle, Simple Recuperated Brayton (SRB) cycle and Simple Recuperated Transcritical (SRT) cycle layouts were selected as candidates for this study. In addition, a novel concept of S–CO_2 cycle which combines Brayton cycle and Rankine cycle is proposed and intensively studied with other S–CO_2 layouts. A parametric study is performed to optimize the total system to be compact and to achieve wider operating range. Performances of each S–CO_2 cycle are compared in terms of the thermal efficiency, net electricity of the MCFC hybrid system and approximate total volumes of each S–CO_2 cycle. As a result, performance and total physical size of S–CO_2 cycle can be better understood for MCFC S–CO_2 hybrid system and especially, newly suggested S–CO_2 cycle shows some success.

1. Introduction

The supercritical carbon dioxide (S–CO_2) Brayton cycle is receiving significant attention as a promising future power conversion system due to its high efficiency under moderate operating temperature range (450–750 °C) and compact size [1]. The main reason why these advantages exist is because the S–CO_2 Brayton cycle has lower compressing work than other Brayton cycles due to its high density and low compressibility near the critical point where it is being compressed. Furthermore, CO_2 has less problems with structure material than water does which can be eventually facilitated to reach higher turbine inlet temperature with less material issues than a steam Rankine cycle [1]. Moreover, unlike the steam Rankine cycle, the chemistry control and component cooling systems are relatively simple for the S–CO_2 Brayton cycle, which enables the total system footprint to be greatly reduced.

The high temperature fuel cells such as molten carbonate fuel cells (MCFCs) and solid oxide fuel cells (SOFCs) are being considered as one of the next generation electric power sources because of its eco-friendliness and high efficiency advantages. The high temperature fuel cells can achieve high efficiency due to its high operating temperature and this high operating temperature is followed by high temperature exhaust heat which can be utilized as another heat source for other power conversion systems. Therefore, hybrid systems such as high temperature fuel cells coupled to gas turbine systems have been considered in the previous works [2–4]. Furthermore, since a MCFC operates at temperature range of 600–700 °C, which matches well with the operating temperature range of a S–CO_2 Brayton cycle, the S–CO_2 Brayton cycle was applied to MCFCs as a bottoming cycle to improve the total system performance previously [5,6] in addition to the gas turbine coupling study.

* Corresponding author.
E-mail addresses: seongjunbae@kaist.ac.kr (S.J. Bae), yoonhan.ahn@gmail.com (Y. Ahn), leejaeky85@kaist.ac.kr (J. Lee), jeongiklee@kaist.ac.kr (J.I. Lee).

http://dx.doi.org/10.1016/j.jpowsour.2014.07.121
0378-7753/

It is theoretically demonstrated that the S–CO_2 Brayton cycle can be a more efficient bottoming cycle for the MCFC hybrid system than the air gas turbine system for the same layout with Simple Recuperated Brayton (SRB) cycle [6]. However, various layouts were recently developed for the S–CO_2 cycle but applying these recent layouts to the MCFC system as a bottoming cycle was not extensively investigated. Therefore, in this paper, various S–CO_2 cycles are studied by changing the design conditions such as heat exchanger effectiveness to understand and compare each S–CO_2 cycle performance and size variation under the same boundary condition which represents the MCFC waste heat condition. Along with the SRB cycle, a Simple Recuperated Trans-critical (SRT) cycle, which has an equal number of components with the SRB cycle but having a phase change at heat emission section, is selected for this study. The Re-Compressing Brayton (RCB) cycle layout is also considered, which is widely known as the most efficient S–CO_2 Brayton cycle layout [1]. Additionally, in this study, authors are suggesting a novel concept of S–CO_2 cycle, a cascading cycle of S–CO_2 Brayton cycle with carbon dioxide (CO_2) trans-critical Rankine cycle. This S–CO_2 Brayton and Rankine Cascading (BRC) cycle concept is using the waste heat of the S–CO_2 Brayton cycle as a heat input to the CO_2 Rankine cycle. It was expected that by dividing the thermal power of the heat source into the Brayton cycle and the Rankine cycle of the S–CO_2 BRC cycle appropriately, the net system performance and operating range can be improved.

Preliminary studies of comparing performance of various S–CO_2 cycles will be presented when each cycle is coupled to the MCFC system. Moreover, by sizing the total heat exchanger volume, the relationship of the cycle size to the cycle performance will become apparent as well. The study is conducted by utilizing in-house codes built by KAIST research team.

2. Review of previous studies

Generally, a MCFC is consisted with two porous electrodes and an electrolyte which is located between each electrode, anode and cathode. Fig. 1 shows the basic principle of a MCFC, which is reproduced from Ref. [2]. First, hydrogen rich fuel feeds into the anode side and then it splits into protons and electrons. In case of electrons, they are not permitted to go through the electrolyte, so negatively charged electrons are transported to cathode side via external circuit. This electrical current generates electricity in MCFC. Oxygen from air and carbon dioxide from the anode side are fed to the cathode side while electrons from the anode side are also transported. In this reaction, a carbonate ion is formed and goes through the electrolyte to the anode side. The negatively charged carbonate ions have a chemical reaction with the protons at the anode side; eventually it maintains the charge balance and produces by-products, water and carbon dioxide. The carbon dioxide goes to the cathode as mentioned before and then the water is exhausted with heat, which the waste heat can be utilized as a heat source for other bottoming cycles [2]. This net process is only possible when the electrolyte is operated under sufficiently high temperature range, i.e. above 600 °C [3].

The high temperature fuel cell and gas turbine cycle system can be categorized into two main types, direct and indirect systems. In the case of the direct hybrid system, the air for cathode side is pressurized by compressor and the exhaust gases of the high temperature fuel cell are integrated with an open cycle gas turbine. The indirect hybrid system can be composed with open or closed power conversion cycle. Therefore, the waste heat from the exhaust gas of fuel cell is transferred through a heat exchanger [4]. The concept of such system was studied by various researchers previously [2–6]. In case of the S–CO_2 closed Brayton cycle, the indirect type system is generally utilized due to pressure difference between the fuel cell side and the bottoming cycle side. To investigate the S–CO_2 closed Brayton cycle design, an in-house code, KAIST-CCD, is developed by KAIST research team. The code is based on MATLAB and the fluid property database is from the NIST database.

In this study, the authors referred to the previous study of the MCFC operating condition [6] for the MCFC and S–CO_2 Brayton cycle hybrid system study. Table 1 shows the verification of the in-house code by summarizing the results from both in-house code and Ref. [6]. In Table 1, the reference values are numerical results, which were calculated under the assumed conditions in the previous research. The calculated results from the in-house code show reasonable agreement with the reference value. The same conditions will be assumed in the following analyses.

3. S–CO_2 cycle review

The S–CO_2 Brayton cycle is considered as one of the most attractive candidates of the waste heat recovery system due to its two notable advantages; one is its relatively high thermal efficiency

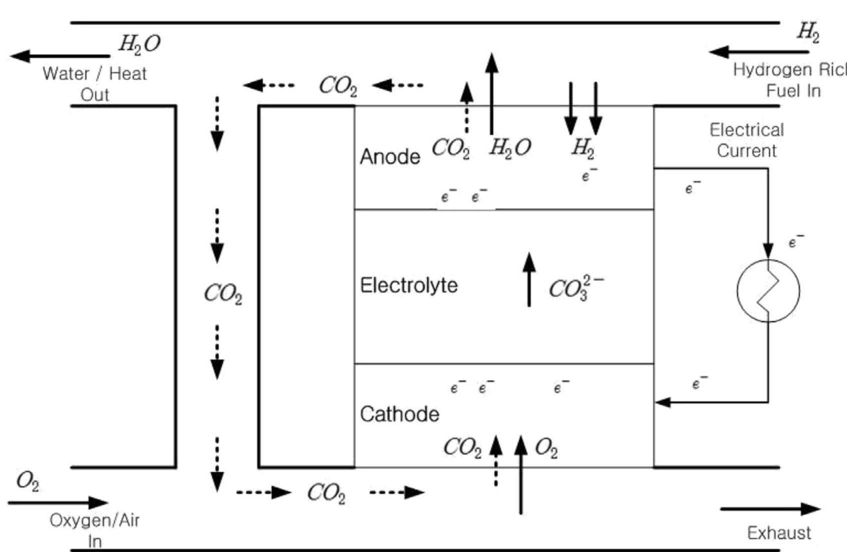

Fig. 1. Basic principle of a MCFC reproduced from Ref. [2].