Journal of Power Sources 299 (2015) 544–556

Contents lists available at ScienceDirect

Journal of Power Sources

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

Thermodynamic analysis of Direct Urea Solid Oxide Fuel Cell in combined heat and power applications

F. Abraham*, I. Dincer

University of Ontario Institute of Technology, 2000 Simcoe Street North, Oshawa, Ontario L1H 7K4, Canada

HIGHLIGHTS

- We present thermodynamic analysis of urea-fed SOFC integrated with a gas turbine.
- Urea fuel mitigates health and safety risks associated with hydrogen and ammonia.
- Water-gas shift reaction imposes detrimental effects on the SOFC anode of SOFC-H.
- The SOFC-O based system offers better performance than that with the SOFC-H.

ARTICLE INFO

Article history:
Received 24 May 2015
Received in revised form 27 July 2015
Accepted 12 August 2015
Available online xxx

Keywords:
Solid oxide fuel cell
Energy
Exergy
Efficiency
Gas turbine
Urea

ABSTRACT

This paper presents a comprehensive steady state modelling and thermodynamic analysis of Direct Urea Solid Oxide Fuel Cell integrated with Gas Turbine power cycle (DU-SOFC/GT). The use of urea as direct fuel mitigates public health and safety risks associated with the use of hydrogen and ammonia. The integration scheme in this study covers both oxygen ion-conducting solid oxide fuel cells (SOFC-O) and hydrogen proton-conducting solid oxide fuel cells (SOFC-H). Parametric case studies are carried out to investigate the effects of design and operating parameters on the overall performance of the system. The results reveal that the fuel cell exhibited the highest level of exergy destruction among other system components. Furthermore, the SOFC-O based system offers better overall performance than that with the SOFC-H option mainly due to the detrimental reverse water-gas shift reaction at the SOFC anode as well as the unique configuration of the system.

1. Introduction

Fuel cells offer a unique combination of values and benefits that make them ideal candidates for stationary power generation and public transportation applications. Qualities like high efficiency, versatility and proven reliability continue to reinforce the prominent position of fuel cells among other energy conversion technologies. This is clearly demonstrated through the rapid growth of the global market share of the solid oxide fuel cell (SOFC) from $303 million in 2008 to just over $906 million in 2013. It is also expected that this figure will reach about $1.3 billion by 2018 [1]. The growth opportunity may be further expanded by overcoming key technology barriers and challenges such as cost of materials and effective fuel storage.

We previously examined the viability of using ammonia as a hydrogen carrier and fuel in a direct ammonia solid oxide fuel cell integrated with a gas turbine bottoming cycle. Although the study concluded that ammonia is a suitable fuel for SOFC applications, drawbacks including public health and safety concerns are hindering its adoption and use in the mass market [2]. In order to mitigate these risks and challenges, several other methods have been investigated in effort to develop safe ammonia storage compounds which are predominantly based on ammonium salts and complex borohydrides [3].

Alternatively, urea is also considered an excellent candidate for the safe storage of ammonia and hydrogen. It is a non-toxic chemical that can be found in natural systems as well as mammal waste (urine). Pure urea is formed as white, odourless prills or granules when artificially synthesized. Owing to its stable nature, it

* Corresponding author.
E-mail addresses: fadi.abraham@uoit.ca (F. Abraham), ibrahim.dincer@uoit.ca (I. Dincer).

http://dx.doi.org/10.1016/j.jpowsour.2015.08.048
0378-7753/

can be easily and safely handled, transported and stored at room temperature.

Lan et al. [4] reported, for the first time, the development and operation of a working direct urea fuel cell. The experimental fuel cells employed anion-exchange resin – polyvinyl alcohol membrane and inexpensive catalysts such as nickel and manganese dioxide. The team conducted a series of experimental tests using different concentrations of aqueous urea (1.0 M, 3.0 M and 5.0 M) as fuel and moist air as oxidant. Regardless of the combination of electrolyte and catalyst materials, the alkaline fuel cell exhibited the highest current and power densities at the lowest urea concentration. They attributed this observation to slow urea hydrolysis and diffusion at the anode among other reasons. Despite the successful demonstration of a direct urea fuel cell, further work is required to improve and optimize its operating performance.

Xu et al. [5] developed nickel-cobalt bimetallic anode catalyst for use in direct urea fuel cells. Anion exchange membrane (AMI-7001, AMFOR Inc.) was used as an electrolyte. Testing was conducted to determine the effects of various parameters and conditions on the overall performance of the urea fuel cell. It was found that the best cobalt to nickel ratio was 10% with a maximum power density of 1.57 $mWcm^{-2}$ when 0.33 M urea is used as fuel and oxygen as oxidant at operating temperature of 60 °C.

The principal objective of this study is to examine the energetic and exergetic performance of a direct urea SOFC integrated with gas turbine power cycle. The core differences between the current system and the ammonia fuelled system as investigated earlier lie in the type of fuel used and the methods with which it is stored, processed and supplied to the fuel cell and downstream gas turbine. As it will be shown later, the on-demand use of urea dictates unique storage solution to prevent freezing of aqueous urea in cold conditions and requires robust control strategy to inhibit the potential formation of carbon (coking) in the system. In order to facilitate this objective of the current work, the operation of the integrated system is described in details. Then, cell-level electrochemical analysis and component-based thermodynamic formulation of the system are furnished. Finally, parametric studies are carried out to investigate the effects of design and off-design variables on the overall performance of the system.

2. System description

The DU-SOFC can be integrated with a gas turbine bottoming cycle in a CHP system. In the system arrangement depicted in Fig. 1, pressurized water is mixed with solid urea in predetermined proportions and fed into HXM as required. By virtue of component design, it is assumed that a complete thermohydrolysis of urea solution into ammonia and carbon dioxide is attained within the HXM. The ammonia is heated and further dissociated into hydrogen and nitrogen as it enters the fuel cell stack.

Two types of urea-fed SOFC are considered in this work, namely the oxygen-conducting solid oxide fuel cell (SOFC-O) and the hydrogen proton-conducting counterpart (SOFC-H). The operation of SOFC-O is assumed to take an indirect path to the oxidation of the fuel by thermally decomposing the ammonia to extract the hydrogen which will then be directly oxidized in the fuel cell. On the cathode side, oxygen, from the air, is transported through the cathode layer to the cathode-electrolyte interface where it is reduced to oxygen ion. The oxygen ions are then transported through the electrolyte to electrochemically react with hydrogen at

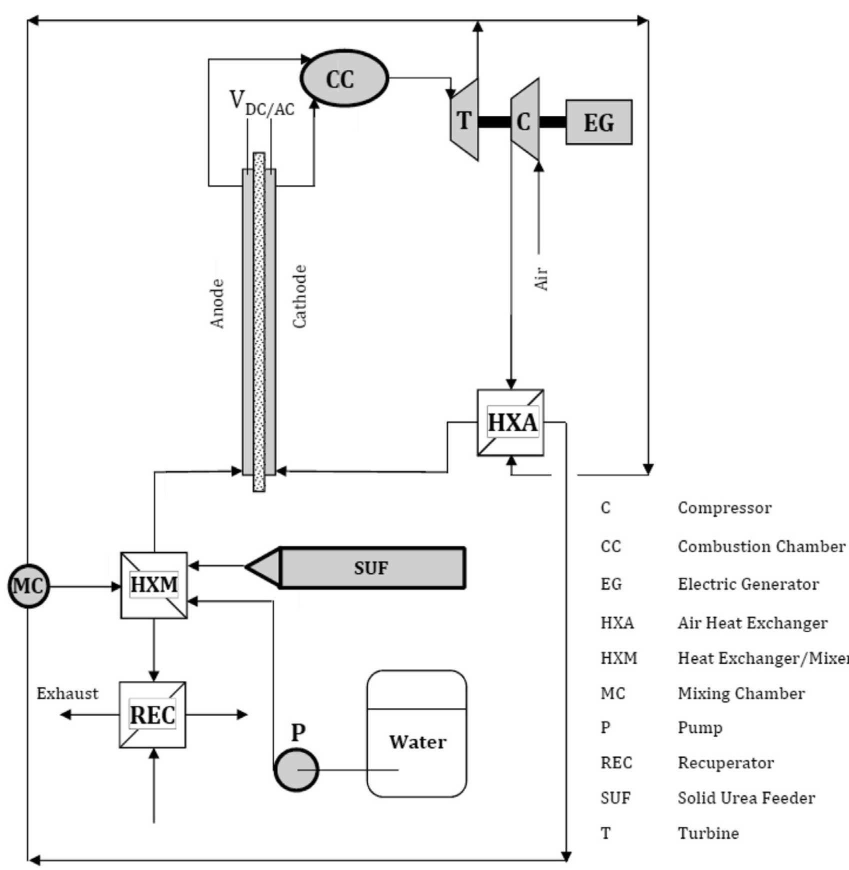

Fig. 1. Schematic representation of integrated DU-SOFC/GT system.