Fuel 196 (2017) 352–361

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Numerical modeling of an indirect internal CO_2 reforming solid oxide fuel cell energy system fed by biogas

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HIGHLIGHTS

- CO_2 reforming of biogas internal to solid oxide fuel cell.
- Numerical modeling of an SOFC energy system with partial anode exhaust gas recirculation.
- Carbon dioxide as reforming promoter.
- Carbon deposition monitoring through carbon dioxide.

ARTICLE INFO

Article history:
Received 24 March 2016
Received in revised form 27 January 2017
Accepted 31 January 2017
Available online 10 February 2017

Keywords:
SOFC
Biogas
Modeling
Clean energy

ABSTRACT

High-temperature Solid Oxide Fuel Cells have a flexible fuel supply and high energy performance. When fed with biofuels, such as biogas, they provide an attractive, ecofriendly and efficient energy system.

The Internal Reforming that uses the high temperature of the same fuel cell makes them suitable to biogas, whose carbon dioxide content can be exploited.

The fuel cell is characterized by an Internal CO_2 Dry Reforming that converts the CH_4 in the biogas into an H_2 rich stream, owing to the role of CO_2, acting as reforming promoter.

The paper presents the formalization and the implementation in Matlab of a steady state-zero dimensional numerical model which describes the various processes of a global self-sustained Indirect Internal CO_2 Reforming Solid Oxide Fuel Cell System fed by biogas. In addition to the energy core of the system with reforming and electrochemical section, the plant scheme considers the preheating of fresh gases, partial recirculation of the fuel cell exhausted gases and combustion of the expelled ones.

The model aims at assessing energy performance and at monitoring carbon deposition.

1. Introduction

The world's growing energy needs and environmental issues, arising from the fulfillment of energy demand, entail the search for innovative solutions to produce clean energy [1–3]. A valuable contribution can be made by exploiting residual organic resources, when treated in anaerobic digestion processes and converted to biogas [4,5].

The said biogas, mainly composed of methane and carbon dioxide, has all the characteristics to be an excellent fuel, given its renewable nature and its residual origin and its quality. Therefore, biogas can provide an energy efficient and environmentally friendly system [6].

Much more efficiency and compatibility can be achieved when biogas is fed to high temperature fuel cells [7,8], valid for the energy processing of biogas.

They are suitable for hydrocarbon fuelling, rather than the usual hydrogen, because they can sustain a hydrogen conversion process, internal to their architecture. The high temperature of the same fuel cell is exploited making it self-sustaining, thus the system can be considered Internal Reforming [9,10].

Among high-temperature systems, the Solid Oxide Fuel Cell (SOFC) has the best quality in terms of flexibility in fuel supply and high energy performance, and therefore it is energetically more advantageous and attractive [11–16].

Moreover, the high operating temperature opens the interesting prospect of actively using CO_2 since it participates in the thermochemical processes, in spite of having to implement the usual abatement and sequestration processes.

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http://dx.doi.org/10.1016/j.fuel.2017.01.123

In this work, the CO_2 Dry reforming process is therefore taken into account for converting biogas to hydrogen, which also usefully converts CO_2 [17–21].

In any case, attention must be paid to carbon deposition causing performance degradation because of the consequent obstruction/deactivation of the electrocatalytic sites [22–24].

Indeed, this issue should be closely monitored when feeding biogas, owing to the build-up of carbon from CO_2.

As can be noticed from the scientific literature, a significant and increasing shift to biogas-fueled SOFC systems has occurred in the last few years. Several researchers are involved in studying, both experimentally and numerically, SOFC systems fed by biogas.

Lanzini et al. assessed and experimentally observed SOFC responses in the laboratory under simulated biogas feeding [25,26]. Goula et al. investigated the performance of an SOFC with particular reference to the electrocatalytic activity of the anodic material [27]. Bonura et al. directed attention to the preparation of Ni-Cu catalysts with the aim of designing an efficient system for the reforming phase, searching for high resistance to carbon formation in the SOFC when fed with biogas [28]. Girona et al. similarly evaluated and measured the electrochemical performance of a typical SOFC with particular reference to carbon deposition [29]. Santarelli et al. [30] focused attention on the heterogeneous reactions taking place in a tubular anode-supported solid oxide fuel cell (SOFC) when the designated fuel is biogas from anaerobic digestion directly feeding the fuel cell, outlining that a direct biogas utilization in an anode-supported SOFC is able to provide good performance. Chiodo et al. [31] conducted a wide experimental research investigation on SOFC device supplied by a fuel gas mixture produced with different biogas reforming processes (steam reforming, autothermal reforming and partial oxidation) to assess the favourite conversation process to couple to a mono-cell, tested experimentally. Dunst et al. [32] investigated on different catalytic materials for biogas reforming, in particular to evaluate the stave off of the carbon activity.

As for numerical activities, various models of solid oxide fuel cells fed with biogas can be found in the literature. Dokmaingam et al. investigated the main performance parameters as a function of the size of an SOFC [33]. In [34] the authors use a CFD model in COMSOL Multiphysics to describe the performance of an intermediate temperature SOFC. In [35,36] the authors also have adopted CFD codes for predicting the performance of Steam Reforming SOFC fed with biogas derived from anaerobic digestion of different organic fractions. In [37] a model for predicting cooking was developed, in [38] the authors studied the thermodynamic performance of a steam reforming SOFC fed with biogas. Mehr et al. [39] studied different configurations of biogas fed solid oxide fuel cells thermoeconomically, focusing on the influence of anode and/or cathode gas recycling in order to assess the most viable way to operate the system.

An examination of the literature denotes that the study of such applications is mainly carried out through an experimental approach on laboratory prototypes.

Therefore, the present work presents itself as a numerical tool of support since it reports a numerical model developed inhouse in order to detect and predict SOFC performance when fed by biogas. It investigates the electrical and thermal energy performance of a complete system based on Indirect Internal CO_2 Dry Reforming SOFC (IIDRSOFC), fed by biogas. The SOFC system considers the thermal preparation of the incoming gases, which are preheated by the exhaust stream. Partial recirculation of the anode exhaust gas and the mixing of the former with the fresh incoming ones is also taken into account to bring the temperature of the stream close to that of the fuel cell, thus also supporting thermally the subsequent reforming process. Moreover, a combustor is considered for the extraction of the residual thermal energy from the output gases, which contain fuel traces.

The article presents the formalization of a steady state-zero dimensional numerical model which describes the processes, and then the implementation of the same in a Matlab computing environment.

Particular attention is devoted to the monitoring of carbon deposition and to the adjustment of the parameters that allow the operation of the system in safe conditions.

2. Indirect internal dry reforming solid oxide fuel cell system

The crux of the Indirect Internal Reforming Solid Oxide Fuel Cell system is the fuel transformation process to the hydrogen-rich stream. It actively involves carbon dioxide, complementary to methane in the biogas, which assumes the significant role of reforming agent.

The functional scheme of the IIDRSOFC plant is presented in Fig. 1(a).

Fuel and air compressors are used to move the gas while a water pump and evaporator are contemplated for the presence of fluxing steam. A pre-heater (HC) of the input gaseous flows is used to recover the waste heat of the exhaust gas (lines G-H and M-N) and raise the temperature of the fresh ones (A-C and L-B). A mixer (MIX) of the input CH_4 and CO_2 with the recycled stream, previously processed by the SOFC, (lines C-F-D) is employed to further raise the fresh gases temperature. The gases are then sent to the thermo-electrochemical section. They are firstly processed by the CO_2 indirect internal reforming generator (R) for the production of a gas stream rich in hydrogen. Subsequently, the hydrogen stream is converted into electrical and thermal energy in the fuel cell stack (ec), as shown in Fig. 1(b). The thermo-electrochemical processes produce a depleted and a warm gas stream (line E) which is in part, as already mentioned, recirculated (XR) to support the reforming, while the remainder is discharged (1-XR). The expelled anode (1-XR) and cathode gases, being at SOFC temperature, are used for thermal energy recovery in the heat exchanger. The exhaust flows as they contain unreacted fuel gases, will be burnt to provide further useful heat. A combustor, fed with the anode (line N) and cathode (line H) exhaust gases, and if necessary with supplementary external air (line O), is therefore considered as shown in Fig. 1 to produce thermal energy by exploiting the exhaust gas (line I).

3. IIDRSOFC system modeling

A zero dimensional and steady state numerical simulation model is implemented to provide an overall assessment of the main parameters of the SOFC, in normal regime conditions, considering the transition phases typical of the start-up operations, shut down and change of the working point is ended up. The cell parameters to be monitored are the mass and energy flows circulating in the various plant stations.

The numerical simulation model, whose block diagram is shown in Fig. 2, allows to analyze the behavior of the IIDRSOFC system powered by biogas. Through the definition of the management and control parameters of the various processes (pressure, temperature, carbon dioxide-carbon ratio, ratio, fuel utilization factor, oxidant utilization factor, recirculation factor of the anode exhaust gas) and of the composition of the feeding biogas, system's responses are evaluated in terms of energy performance and in terms of safe operation conditions (free from carbon deposits).