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Application of solid oxide fuel cell for flare gas recovery as a new approach; a case study for Asalouyeh gas processing plant, Iran

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ABSTRACT

Flare gas emission is one of the main sources of environmental pollution and global warming. Implementations of some no flaring methods have a great impact in reducing the pollutants emission. Using solid oxide fuel cell (SOFC) system is a new approach which is proposed in this study. In this work, an electrochemical model is developed for a steady-state, planar SOFC by considering the direct internal methane steam reforming. In this new configuration, there is no pre-reforming and the sweetened flare gas is fed to SOFC directly. Also a part of required steam is supplied by recycling the anode outlet gas. The present model is validated with experimental and modeling data taken from the literature. Application of SOFC technology for flare gas recovery of Asalouyeh gas processing plant not only generates about 1200 MW electrical energy, but also it decreases the equivalent mass of greenhouse gas emission from 1700 kg/s to 68 kg/s. Economical evaluations show that the total capital investment of this method is significantly lower than other no gas flaring approaches. For parametric investigation, the effects of some related parameters such as temperature, recirculation, fuel utilization and air ratios are studied. The results show that increasing the operating temperature of SOFC enhances the cell voltage and maximum power density. Decreasing the recirculation ratio from 0.6 to 0.2 increases the electrical efficiency of the cell. Although at lower current densities, changing the recirculation ratio has no significant effect, it is observed that at average current density equals to 1.5 A/cm^2, increasing the recirculation ratio from 0.2 to 0.6 decreases the power density from 0.51 W/cm^2 to 0.48 W/cm^2. Also increasing the fuel utilization ratio improves the cell performance.

1. Introduction

Environmental pollution and global warming due to high emission of greenhouse gases are the most worldwide challenging issues in this century. Recent investigations of satellite data indicate that more than 139 billion m^3 of gas are flared annually (Elvidge et al., 2009). This amount of flaring gas releases approximately 281 million tones of CO_2 to atmosphere yearly (Johnson and Coderre, 2011, 2012). Therefore, avoid of burning gases in flares is an effective approach to control the greenhouse gases level. Rahimpour et al. proposed three methods for recovery of flare gas instead of conventional gas burning in Farashband Gas Processing plant and Asalouyeh Gas Processing plant (Rahimpour et al., 2012; Rahimpour and Jokar, 2012). These methods include: 1) Gas-to-Liquid (GTL) production, 2) electricity generation with a gas turbine and 3) compression and injection into refinery pipelines.

Use of flare gases as a feed of fuel cell can be considered as a new approach to recovery of flare gas. Fuel cells are power-generation systems that convert directly the chemical energy of fuel to electricity. Among the various types of fuel cells, solid oxide fuel cell (SOFC) is more efficient (Petruzzi et al., 2003). SOFC is a kind of fuel cell contains two porous electrodes, which are separated by a nonporous oxide ion-conducting ceramic electrolyte. SOFC operates at temperatures about 600–1000 °C and uses hydrogen containing gas mixture as a feed and the oxygen of air as an oxidant (Stambouli and Traversa, 2002). The high operation temperature leads flexibility of using various fuel types such as methane, methanol, ethanol, biogas and etc. (Yuan and Sunden, 2005). When hydrocarbon (C_nH_m) is used as a feed, the hydrocarbon-reforming reaction to produce hydrogen can be described as

$$C_nH_m + nH_2O \rightarrow (n + 0.5m)H_2 + nCO \quad (1)$$

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The produced heat in a SOFC can provide the required heat for the endothermic steam reforming reaction. When internal steam reforming reaction occurs in a SOFC, 40–70% of generated heat in the cell is used by this reaction, so less excess air is needed for cooling the cell (Nakagawa et al., 2001; Lee et al., 1990). Another advantage of the internal steam reforming configuration is providing a part of necessary steam for reforming reaction via electrochemical reaction product. Furthermore, due to continuing consumption of hydrogen in the reaction, the equilibrium conditions of the steam reforming and water gas-shift reactions shift to the right side and as a result, it leads to methane conversion enhancement. Therefore by using an appropriate catalyst in the anode side, not only there is no need to the external reformer, but also it leads to simplify the overall system design and finally the cost of these power systems will decrease substantially (Kang et al., 2009).

In SOFC, Ni/Zr ceramic–metallic (cermet) anodes have appropriate catalytic properties for power generation and also it can be used as a suitable catalyst for the steam reforming and shift reactions (Dicks, 1998; Clarke et al., 1997; Xu and Froment, 1989; Georges et al., 2006). One of the main problems of the internal steam reforming is carbon deposition on the Ni-based anode which leads to catalyst deactivation and reduces the cell performance and lifetime. To prevent this problem, the high steam/carbon (S/C) ratio is used, but it is an unattractive action because dilution of fuel by steam leads to lowering the electrical efficiency (Ahmed and Foger, 2000). The minimum amount of S/C ratio to prevent carbon formation on anode, while methane is used as a fuel, is about 1.5 (Sasaki et al., 2004). Since the anode outlet gas contains high percentage of steam, the required water for steam reforming reaction can be supplied by recycling the anode outlet gas (Lee et al., 2011).

Natural gas and flare gas which contain mainly methane, i.e. 80–95%, is the most interesting fuel for SOFC. Kinetic models for internal steam reforming of methane over Ni/Zr catalyst were proposed by many researchers (Lee et al., 1990; Achenbach and Riensche, 1994; Belyaev et al., 1995; Ahmed and Foger, 2000; Dicks et al., 2000). Due to high concentration of methane in the flare gas, it is supposed that just methane steam reforming occurs in the SOFC.

2. Objective

Iran holds the world's second largest natural gas reserves. Asalouyeh gas processing plant is the biggest refinery in the south of Iran. It has been designed for the gas refining of South-Pars gas field. South-Pars was initially identified in 1988 and estimated to contain 3.4×10^{12} standard m^3 of natural gas or even more (Javanmardi et al., 2006). The South-Pars gas region contains five refineries in 10 phases (Davoudi et al., 2013). Natural gas from the South-Pars field is transported to Asalouyeh gas processing plant by pipelines where liquid hydrocarbons are separated. Since this refinery emits enormous quantities of gas to the atmosphere, it is necessary to prevent its emission for environmental protection. Thus in this study, application of SOFC as a novel method for flare gas recovery of Asalouyeh gas processing plant is suggested. The first step in this process is removal of hydrogen sulfide from the flare gas and sweetening the feed of SOFC. In this work, the electrochemical performance of SOFC is evaluated by an equilibrium model. In this method the composition of species in the cell is calculated while direct internal reforming reaction takes place in the SOFC. The impact of anode outlet gas which is important especially for supplying steam for initiating the chemical reactions and preventing carbon deposition is investigated. After that, the kinetic of internal steam reforming is investigated using the rates of reactions. The effect of inlet temperature on the species concentration and cell temperature is studied. For calculating the numbers of required cell and also the generated power of the stack, an electrochemical model is developed. Finally, for more investigation, environmental and economical considerations by this approach are studied. The composition and conditions of the flare gas are reported in Table 1 (Asalouyeh Gas Processing Data from South-Pars Gas Company, 2010).

3. SOFC model description

Several publications focus on the modeling of SOFC. Such models investigate the performance of SOFC for different geometries (planar, tubular or monolithic), for different flow configurations (cross-, co-, or counter-current flow), based on dimensions, in steady-state or dynamic and considering or ignoring the internal reforming reaction (Ferguson et al., 1996; Iwata et al., 2000; Aguiar et al., 2002). In this work, a model is developed for a steady-state, planar SOFC by considering the internal methane steam reforming. It is assumed that the sweetened flare gas and water with S/C ratio equals to 2, is directly fed to SOFC without any pre-reforming. It is supposed that the feed behaves like an ideal gas. Due to high operating temperature of the SOFC, the rate of H_2 oxidation is 2–3 times more than CO oxidation (Li and Chyu, 2005). So it is assumed that only H_2 participates in the electrochemical reaction (Hofmann et al., 2009).

Since the generated voltage by a single SOFC is quite small, to provide a useful voltage, a complete SOFC system is made up several repeating cells in a module connected in series or parallel and assembled to compose a stack (Aguiar et al., 2004). To simplify the model, one unit cell is considered and then the results are developed for the whole stack. Here, the unit cell is located in the center of the stack to prevent heat interaction with environment. This cell is shown in Fig. 1 and its properties are summarized in Table 2. It is divided into four parts: the interconnect plates that are placed above and below the cell, the electrochemical section that is composed positive–electrolyte–negative (PEN), air and fuel channels.

Fig. 2 shows a schematic diagram of a unit cell which is modeled here. The sweetened flare gas (f_1) and a percentage of the anode outlet gas (f_2) are sent to the fuel channel as a feed of SOFC. The steam reforming of methane (Eq. (2)), water gas-shift reaction (Eq. (3)) and electrochemical reaction (Eq. (4)) occur simultaneously

Table 1
Specifications of Asalouyeh refinery flare gas, before and after sweetening process.

Specifications		Value
Temperature (°C)		34.19
Pressure (kPa)		305
Molar flow (kg mol/h)		17,760
Mass flow (kg/h)		337,600
Flare gas composition (mol %)		
	Before sweetening process	After sweetening process
Methane	0.852	0.873
Ethane	0.054	0.056
Propane	0.020	0.020
i-Butane	0.003	0.004
n-Butane	0.006	0.006
i-Pentane	0.002	0.002
n-Pentane	0.002	0.002
N_2	0.035	0.036
CO_2	0.020	0.000
H_2O	0.001	0.001
H_2S	0.005	0.000