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Modeling, design and analysis of a stand-alone hybrid power generation system using solar/urine

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ABSTRACT

The urine turned to hydrogen as an energy conversion process is integrated into a stand-alone hybrid (PV/FC/battery) power generation system. The optimization and simulation of a new urine-to-hydrogen processor is evaluated in Aspen Plus environment. In our approach, the PV generator aims to reduce urine consumption and the lithium-ion battery can compensate the power gap due to the fuel processing delay. Based on prescribed patterns of solar irradiation and the daily load demand of a 30-persons classroom, scenario analyses of the hybrid power dispatching and operational feasibility is addressed.

1. Introduction

Many researches often interest in renewable and sustainable power generation techniques such as photovoltaic, wind, and fuel cell powered systems. The power generated by a PV or wind system is highly dependent on weather conditions and locations, but it has significant advantages such as zero carbon emissions and free energy. To overcome the fluctuating nature of solar radiation, a PV system is usually integrated with other power systems. Muselli et al. [1] developed a stand-alone hybrid system which was composed of the PV panels, an electrical generator using fossil fuels, and battery storage, and Elhadidy [2] studied the feasibility of using wind/solar/diesel energy conversion systems to meet the power demand of the specific community in Saudi Arabia, where the gasoline or diesel engine is treated as the backup power generator.

The fuel cell using hydrogen tank could rapidly meet the load demand, e.g. fuel cell vehicles. The guidelines for the hydrogen storage, safer operation and transportation are quite rigorous [3]. The fossil fuel processing unit can effectively produce the high purity of hydrogen [4], but its conversion efficiency, energy consumption, and feedstock are usually criticized. Although the steam reforming is the most widespread process for hydrogen production, but it is not well suited as the stand-alone unit. To explore the possibility of the stand-alone fuel processing unit, the specific energy conversion technique for the wastewater treatment process is an unusual approach.

Most of the municipal wastewater treatment processes are quite complicated and consume a lot of energy. For instance, the urine recovery form wastewater is a typically and significant treatment process [5]. Urine is an alternative source of nitrogen and phosphorus. Urea is the main component of human and livestock urine, as well as a key ingredient of fertilizers. Recently, the technique about urine turned into hydrogen fuel has been progressively developed [6,7]. In other words, the separation of urine not only benefits wastewater treatment, but also it has the potential to turn wastewater treatment from an energy consumer into an energy producer.

Basically, the thermal hydrolysis of urea is the preferred process for converting urea/water solution into a gaseous mixture containing ammonia, carbon dioxide and water vapor, where the optimization and simulation study conducted for continuous process and effect of operation conditions has been addressed [8]. Alagharu et al. [9] showed an ammonia decomposition reactor, which is operated at non-adiabatically and heated electrically, is possible to get over 99.5% conversion of ammonia. The favor operating temperature of ammonia decomposition reactor is close to the operation of the steam methane reforming process, but it offers the simplest approach to produce hydrogen. The temperature for a sufficient catalytic acceleration of ammonia cracking with prescribed catalysts is usually between 700 and 1100 °C [10]. Whatever takes the thermal hydrolysis of urea or ammonia decomposition, the foul

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Nomenclature

a_f	ideality factor
A_{fc}	effective fuel cell area, cm^2
A_s	surface area of the solar panel, m^2
C_{O_2}	oxygen concentration at the cathode/membrane interface, mol/m^3
C_{H_2}	hydrogen concentration at the anode/membrane interface, mol/m^3
C_{dl}	double layer capacitance, F
E	fuel cell potential, V
E_0	reference solar radiation, W/m^2
E_g	gap energy voltage for silicon, eV
E_s	solar radiation, W/m^2
F_{SR}	flow split factor
i	current density, A/cm^2
I_s	terminal current of PV cell, A
F	Faraday constant, C/mol
k_{an}, k_{ca}	flow constant of anode and cathode, mol s atm
l_m	membrane thickness, cm
$\dot{m}_{H_2}$	pure hydrogen molar flowrate, kmol/h
$\dot{m}_{O_2}$	pure oxygen molar flowrate, kmol/h
c_p	specific heat capacity, J K kg
D	diameter of the reactor, m
L	length of the reactor, m
n	the number of electrons in the electrochemical reactions
P_i	partial pressure of i component, atm
P_{BPR}	back pressure, atm
P	cell power, W
p_1	proportional constant, A m^2 W
p_2	correction factor of the photoelectric constant, m^2/W
p_3	correction factor of the photoelectric constant, 1/K
p_4	coefficient for accepter and donor concentration, A/K
T_a	ambient temperature, K
T_0	reference junction temperature, K
T_{NCOT}	normal cell operating temperature, K
T	temperature of unit operation, K
R	universal gas constant, J/mol K
R_s	series resistance, Ω
R_{sh}	parallel resistance, Ω
u	superficial velocity, m/s
V	volume of anode and cathode, m^3
V_{act}	activation overvoltage, V
V_{ohm}	ohmic overvoltage, V
V_s	terminal voltage of PV cell, V

Subscripts

an	anode
ADR	ammonia decomposition
battery	Li-ion cell
ca	cathode
fc	fuel cell
in	at reactor inlet
out	at reactor outlet
UHR	urea hydrolysis
fc	fuel cell

Greek symbols

ΔH_i	heat of reaction i, kJ/mol
λ_{O_2}	oxygen excess ratio

ammonia odor may release to air and its toxicity may induce environmental pollution.

In this article, the urine turned to hydrogen by virtue of the sequential reaction modules for thermal hydrolysis of urea and ammonia decomposition is expected to be a feasible process. This unit not only carry out the wastewater treatment, but also its effluent hydrogen flow is fed into the fuel cell system to generate electricity. In view of the cost-effective wastewater treatment and viable power source, the urine-powered fuel cell system in place of the hydrogen fuel cell system is presented. In fact, the daily supply of human urine from a 4-persons family is very limit, so it is predictable that the hydrogen produced is too little to meet the daily power demand. In our approach, first the hybrid power generation framework is used to reduce the urine consumption of urine-powered fuel cell system, and second the specific pattern for daily power demand of a 30-persons classroom is specified. The PEM fuel cell, the photovoltaic (PV) generator and the battery are denoted as the power supplies in the hybrid power system. The hydrogen directly supplied by a so-called urine-to-hydrogen processor should face the fuel processing delay. In our design, the Li-ion battery and auxiliary power supplies (DC/DC converter, DC/AC inverter and DC bus) are employed to compensate the instant power gap. Through scenario analyses, the operational feasibility with regard to power dispatching and reduction of urine consumption is successfully investigated by the simulation.

2. Urine-powered fuel cell system

The modeling, design and simulation of a urine-powered fuel cell system, which consists of a urine-to-hydrogen processor and a PEMFC, is addressed as follows.

2.1. Urine-to-hydrogen processor

Regarding the fuel processing of urine to hydrogen, the urea hydrolysis reaction is the first step, which consists of two sequential reactions:

$$NH_2CONH_2 + H_2O \xrightarrow{-Heat} NH_2COONH_4, \quad \Delta H_1 = -15.5\ kJ/mol \tag{1}$$

$$NH_2COONH_4 \xrightarrow{+Heat} 2NH_3 + CO_2, \quad \Delta H_2 = 177\ kJ/mol \tag{2}$$

The reaction (1) shows that urea hydrolyzes to form ammonium carbamate with mildly exothermic. The reaction (2) carry out the production of carbon dioxide and ammonia with strongly endothermic. Notably, excess water promotes the hydrolysis reaction, and the external heat supply dominates the ammonia yield.

Referring urea hydrolysis kinetics [11], the first-order kinetic model is determined by experimental tests in a semi-batch reactor without using any catalyst at atmospheric pressure taking different concentration of urea solution from 7 wt% to 40 wt% [11]

$$r_{UHR} = 3.9 \times 10^6 \exp\left(-\frac{59{,}850}{RT_{UHR}}\right) C_{urea} \tag{3}$$

where T_{UHR} is the urea hydrolysis temperature and C_{urea} is the concentration of urea.

The second step is to carry out the ammonia decomposition reaction, where the reaction of ammonia over Ni/Al_2O_3 catalyst decomposes to hydrogen and nitrogen shown by

$$2NH_3 \xrightarrow{+Heat} N_2 + 3H_2, \quad \Delta H_3 = 44.22\ kJ/mol \tag{4}$$

Referring ammonia decomposition kinetics [12], the high ammonia conversion with conditions of high operating temperatures is required for fuel cell applications. The first-order kinetic model by