Journal of Power Sources 195 (2010) 4811–4815

Contents lists available at ScienceDirect

Journal of Power Sources

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

Short communication

Mass minimization of a discrete regenerative fuel cell (RFC) system for on-board energy storage

Li Xiaojin*, Xiao Yu, Shao Zhigang**, Yi Baolian

Fuel cell R&D Center, Dalian Institute of Chemical Physics, Chinese Academy of Sciences, Dalian 116023, China

ARTICLE INFO

Article history:
Received 2 February 2010
Accepted 15 February 2010
Available online 21 February 2010

Keywords:
Regenerative fuel cell system
On-board energy storage
Mass minimization
Current density

ABSTRACT

RFC combined with solar photovoltaic (PV) array is the advanced technologic solution for on-board energy storage, e.g. land, sky, stratosphere and aerospace applications, due to its potential of achieving high specific energy. This paper focuses on mass modeling and calculation for a RFC system consisting of discrete electrochemical cell stacks (fuel cell and electrolyzer), together with fuel storage, a PV array, and a radiator. A nonlinear constrained optimization procedure is used to minimize the entire system mass, as well as to study the effect of operating conditions (e.g. current densities of fuel cell and electrolyzer) on the system mass. According to the state-of-the-art specific power of both electrochemical stacks, an energy storage system has been designed for the conditions of stratosphere applications and a rated power output of 12 kW. The calculation results show that the optimization of the current density of both stacks is of importance in designing the light weight on-board energy system.

1. Introduction

RFC combined with solar photovoltaic (PV) array is the advanced technologic solution for on-board energy storage, e.g. land, sky, stratosphere and aerospace applications, due to its potential of achieving high specific energy. Currently, high altitude platforms operating in the stratosphere have been becoming a new research hotspot in the field of telecommunication, atmospheric monitoring and cosmos observation [1]. For sky, stratosphere and outer space missions, launch mass is critical for the flight altitude and the energy storage system takes a high ratio of the over launch mass. Due to the low specific energy, the existing battery technology for energy storage restricts the flight altitude and is limited in sky, stratospheric and space applications. Regenerative fuel cell system has the potential of achieving much higher specific energy densities (0.4–1.0 kWh kg^{-1}) than any of the advanced battery systems [2]. Therefore, RFC combined with solar PV is the advanced technologic solution for the energy storage operating in sky, stratosphere and aerospace.

RFC is an energy storage unit similar to rechargeable batteries, with hydrogen and oxygen as a storage medium. The advantage of RFC is it separates the power and energy components of the system. The RFC can be classified two kinds: the unitized and the discrete. For unitized RFC, the electrolyzer and fuel cell functions can be integrated into a single unit. However, there exists difficulty in designing the bi-functional electrode for unitized RFC. The discrete RFC can achieve somewhat higher roundtrip efficiency, because both the fuel cell and the electrolyzer can be optimized separately. A discrete RFC system consists of solar photovoltaic array to supply primary energy, discrete electrolyzer and fuel cell subsystems, radiator to reject waste heat, fuel storage and power management subsystem, etc. Currently, researches on the RFC system are mainly on the electrochemical performance [3–6], few works [2,7–9] have concentrated on the RFC system mass for on-board energy storage and made comparisons with battery systems. Hauff and Bolwin [8] have carried out the mass optimization for the on-board energy storage for a geosynchronous earth orbit (GEO) mission. Barbir et al. [9] have compared the RFC to an advance battery system in terms of total system mass for aerospace applications. Appleby [2] and Bolwin [7] have compared H_2/O_2 RFC systems with the Ni/H_2 battery for unmanned space missions ranging from low earth orbit (LEO) to GEO. Knaupp and Mundschau [1] made an assessment and a predesign of solar-hydrogen technology for long-term energy supply at high altitude. As far as we know, no work has been reported on mass minimization on the solar-hydrogen system for operation in the stratosphere.

For a RFC system, the total mass is dependent not only on the masses of the electrochemical stacks, but also on the mass of the fuel storage, as well as PV array and the radiator. Minimization of the stack weight of both fuel cell and electrolyzer leads to high current densities operating. However, light-weighting of fuel storage, radiator and PV array needs operating electrochemical stacks with low current densities. Therefore, the variation of the operating

* Corresponding author. Tel.: +86 411 84379051; fax: +86 411 84379185.
** Corresponding author. Tel.: +86 411 84379153; fax: +86 411 84379185.
E-mail addresses: xjli@dicp.ac.cn (X. Li), zhgshao@dicp.ac.cn (Z. Shao).

0378-7753/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.jpowsour.2010.02.045

Nomenclature

A	total elelctrode area of stack (cm^2)
E^0	open-circuit potential (V)
E_f	theoretical energy density of H_2 (kWh kg^{-1})
f	energy efficiency of fuel cell
f_v	voltage efficiency of fuel cell
i	cell operating current density (A cm^{-2})
M	mass of RFC system (kg)
m	mass of key components (kg)
P_{fc}	rated power output of PEM fuel cell (kW)
P_{el}	power input of electrolyzer (kW)
t_{fc}	period of nighttime (fuel cell working) (h)
t_{el}	period of daytime (elctrolyzer working) (h)
Q_{rad}	capacity of radiator in rejecting waste heat (kW)
u	average cell operating voltage (V)
W_{fc}	electrical power density of fuel cell (W cm^{-2})

Greek letters

β	mass consumption ratio of O_2 to H_2 for H_2/O_2 fuel cell
γ	mass ratio of container to oxygen
δ	mass ratio of container to hydrogen
ρ_{fc}	specific mass of PEM fuel cell (kg cm^{-2})
ρ_{el}	specific mass of PEM electrolyzer (kg cm^{-2})
ρ_{rad}	specific mass of the radiator (kg kW^{-1})
ρ_{array}	specific mass of the photovoltaic array (kg kW^{-1})

Subscripts

fc	fuel cell
el	electrolyzer

current densities has a great influence on the mass of the RFC system, and there exists a compromise in determining the operating point of the current densities of fuel cell and electrolyzer for the minimization of the RFC system mass. This paper will focus on discrete RFC system for the conditions of stratosphere applications, aiming to optimize the operating current densities for designing the light weight RFC system, as well as to identify the influence of the design parameters on the mass of the on-board storage power system.

2. Mass modeling of the RFC system

An RFC system consists of a fuel cell stack, an electrolyzer stack, fuel storage, a photovoltaic array as the primary energy supply, a radiator to reject the waste heat and the auxiliary system. During sunlight period, a photovoltaic array supplies electrical power to an electrolyzer fed by water to produce hydrogen and oxygen. The product gases are stored in tanks for fuel cell use. During nighttime, a proton exchange membrane fuel cell delivers necessary electrical energy to drive the electrical motor of the propulsion subsystem. A block diagram of a regenerative fuel cell (RFC) system for on-board energy storage is shown in Fig. 1. The mass of the RFC system is the sum of these components in Eq. (1)

$$M_s = m_{fc} + m_{el} + m_{storage} + m_{rad} + m_{array} + m_{aux} \quad (1)$$

where M_s is the mass of the RFC system, m_{fc} the mass of fuel cell stack, m_{el} the mass of electrolyzer stack, $m_{storage}$ the mass of fuel storage, m_{rad} the mass of radiator, m_{array} the mass of photovoltaic array, and m_{aux} the mass of auxiliary system including fuel cell auxiliary subsystem, electrolysis auxiliary subsystem, control subsystem and power conditioning. The mass of the auxiliary system is mainly related to the rated power, depending on the process designing and the operating characteristics. In general, the auxiliary system mass maintains constant to a certain scope of rated power, namely, it increases in step with the increase of rated power.

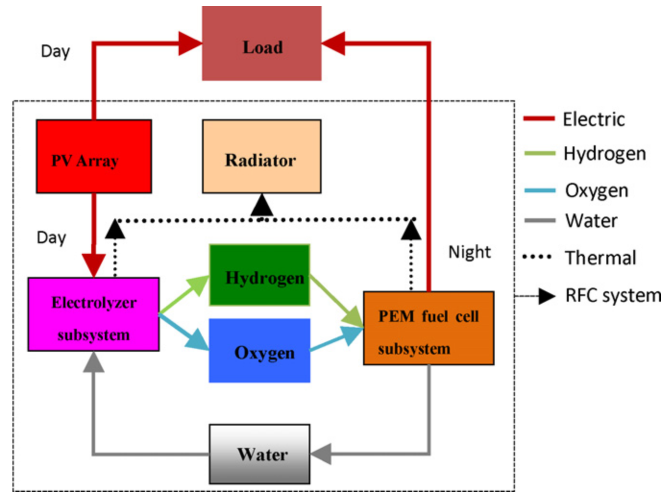

Fig. 1. Block diagram of a regenerative fuel cell (RFC) system for on-board energy storage.

Except the auxiliary system, the masses of other components are determined by the fundamental parameters (e.g. rated power, operating current density). Performing the mass optimization of the entire RFC system, the masses of these components are required to be modeled in terms of these fundamental parameters. The assumptions and simplifications adopted in the present model for the minimization problem are as following:

(1) Constant power output of fuel cell during nighttime.
(2) Constant power input of electrolyzer by PV array during daytime.
(3) Neglecting the parasitic power loss of RFC system.

2.1. Mass modeling of fuel cell stack

Performance of the fuel cell is determined by its polarization curve. In general, the fuel cell performance is correlated to its operating conditions, especially the current density. In depth analysis, the fuel cell performance mainly depends on two aspects. One is its polarization curve under the operating conditions (e.g. reactant gas pressure, working temperature), which characterize the electrochemical performance of fuel cell. The other is process designing and seal structure (e.g. the material of bipolar plates and end plates), which characterize the process level of fuel cell stack.

Usually, fuel cell operating point is selected on the ohmic polarization region. In this region, the voltage falls slowly and the ohmic loss due to the electrolyte resistance of the electrodes, and the resistance to the flow of ions in the electrolyte, is simply proportional to the current. Therefore, in this region, the cell voltage can be described by linear function as Eq. (2)

$$u_{fc} = a - b i_{fc} \quad (2)$$

where u_{fc} is the average voltage of the fuel cell stack; a is the extrapolated intercept at $i_{fc} = 0$; b is the electrical resistance corresponding to 1 cm^2 of the cell, called the area-specific resistance, $\Omega\,cm^2$; i_{fc} is the current density, A cm^{-2}.

According to Eq. (2), the electrical power density, W_{fc}, is easily calculated from the well-known formula

$$W_{fc} = i_{fc} u_{fc} = (a - b i_{fc}) i_{fc} \quad (3)$$

The mass of fuel cell stack can be formulated as Eq. (4)

$$m_{fc} = A_{fc}\rho_{fc} = \frac{P_{fc}\rho_{fc}}{W_{fc}} = \frac{P_{fc}\rho_{fc}}{(a - bi_{fc})i_{fc}} \tag{4}$$

where A_{fc} is the entire electrode surface of the fuel cell stack, P_{fc} the rated power output of RFC system, ρ_{fc} is the specific mass of the fuel cell stack, kg cm^{-2}.

2.2. Mass modeling of eletrolyzer stack

The solid polymer electrolysis is most interesting due to the possible combination with a fuel cell in one single unit. Assuming mass balance of the RFC system during a round trip, we have the following formulation according to the Faraday law

$$A_{el}i_{el}t_{el} = A_{fc}i_{fc}t_{fc} \tag{5}$$

where i_{el} and A_{el} denote the operating current density and the entire elelctrode surface of electrolyzer stack; t_{el} and t_{fc} denote the period of the daytime and nighttime for land, sky and stratosphere applications, or the period of the sunshine and eclipse phase for aerospace application. For land, sky and stratosphere applications, the period of daytime and nighttime varies with seasons and latitude. For aerospace applications, the period of the sunshine and eclipse phase differs depending on the radii of earth orbit [8]. According to Eq. (5), the entire electrode surface of electrolyzer can be related to that of fuel cell.

$$A_{el} = A_{fc}\frac{i_{fc}}{i_{el}}\frac{t_{fc}}{t_{el}} \tag{6}$$

Thereby, the mass of electrolyzer stack can be formulated as Eq. (6)

$$m_{el} = A_{el}\rho_{el} = A_{fc}\frac{i_{fc}}{i_{el}}\frac{t_{fc}}{t_{el}}\rho_{el} = \frac{P_{fc}}{W_{fc}}\frac{i_{fc}}{i_{el}}\frac{t_{fc}}{t_{el}}\rho_{el} = \frac{P_{fc}\rho_{el}}{(a - bi_{fc})i_{el}}\frac{t_{fc}}{t_{el}} \tag{7}$$

where ρ_{el} is the specific mass of the electrolyzer stack, kg cm^{-2}.

2.3. Mass modeling of fuel storage

The mass of fuel, oxidant and the container also takes a great portion of the RFC system. The mass of fuel depends on the energy efficiency of fuel cell, which can be formulated as Eq. (8)

$$f = f_T f_i f_v \tag{8}$$

where f_T is thermodynamic efficiency of the H_2/O_2 electrochemical reaction, equaling to $\Delta G^\circ/\Delta H^\circ = 0.83$; f_i is the current efficiency, usually approaching 100%; f_v the voltage efficiency, depending on the polarization curve and the working current density of fuel cell. f_v can be formulated as Eq. (9)

$$f_v = \frac{u_{fc}}{E^0} = \frac{a - bi_{fc}}{E^0} \tag{9}$$

where E^0 is the open-circuit potential. It can be seen from Eq. (9) that the lower the operating current density, the higher efficiency of the fuel usage, and the less fuel required for the same energy output.

To an RFC system, the required energy output equals to $P_{fc} \times t_{fc}$, and the mass of reactant gases and the container can be formulated as Eq. (10).

$$m_{storage} = \frac{P_{fc}t_{fc}}{E_f f}(1+\beta+\delta+\gamma\beta) = \frac{P_{fc}t_{fc}}{E_f}\frac{E^0}{0.83(a - bi)}(1+\beta+\delta+\gamma\beta) \tag{10}$$

where E_f is the theoretical energy density of fuel, β the mass ratio of oxidant to fuel, δ the mass ratio of container to hydrogen, γ the mass ratio of container to oxygen.

2.4. Mass modeling of radiator

For the RFC system, the overall efficiency is only 50–60%, its waste heat can be used as a useful source of vehicle heating during both charging and discharging. Hauff and Bolwin [8] gave the details of the amount of thermal energy that could be recycled into the process. In this paper, a simplification was adopted that all the waste heat is rejected by the radiator. For the radiator, the capacity is related to the waste heat production rate of the fuel cell reduced by the amount of thermal energy [8]. The waste heat production rate is formulated to the efficiency of the fuel cell:

$$Q_{rad} = P_{fc}\left(\frac{1}{f_v} - 1\right) \tag{11}$$

The fuel cell efficiency follows directly from its polarization curve and the operating current density. Therefore, the mass of radiator can be expressed by Eq. (12)

$$m_{rad} = \rho_{rad}Q_{rad} = \rho_{rad}P_{fc}\left(\frac{E^0}{a - bi_{fc}} - 1\right) \tag{12}$$

where ρ_{rad} is the specific mass of radiator, kg kW^{-1}, which is mainly dependent on the heat transfer coefficient. Since there is no convection in stratosphere and aerospace, the specific mass of radiator in those two regions is much higher than that in land and sky.

2.5. Mass modeling of the photovoltaic array

The required power produced by PV array includes the rated power and the power demand of the electrolyzer. In this paper, only the mass of PV array contributed to the RFC system is concerned. Therefore, the required primary power by PV array for the power input of electrolyzer, can be deduced from Faraday law. For the fuel cell and electrolyzer, according to the well-known formula, we have

$$A_{fc}i_{fc} = \frac{P_{fc}}{u_{fc}} \tag{13}$$

$$A_{el}i_{el} = \frac{P_{el}}{u_{el}} \tag{14}$$

where u_{el} and P_{el} denote the cell voltage and the consumption power of electrolyzer. According to Eqs. (13) and (14), the consumption power of electrolyzer, P_{el}, can be described in Eq. (15)

$$P_{el} = P_{fc}\frac{u_{el}}{u_{fc}}\frac{t_{fc}}{t_{el}} \tag{15}$$

From Eq. (15), the power input of the electrolyzer is determined by the efficiency and the operating periods of electrolyzer and fuel cell. Similar to fuel cell, the electrolyzer operating point is also selected in the ohmic region, which can also be described by linear function as Eq. (16)

$$u_{el} = a' + b'i_{el} \tag{16}$$

where a' is the extrapolated intercept at $i_{el} = 0$, b' is the area-specific resistance of electrolyzer cell. So, the power input of electrolyzer can be easily described in Eq. (17)

$$P_{el} = P_{fc}\frac{a' + b'i_{el}}{a - bi_{fc}}\frac{t_{fc}}{t_{el}} \tag{17}$$

The mass of the photovoltaic array can be expressed by Eq. (18)

$$m_{array} = \rho_{array}P_{el} = \rho_{array}P_{fc}\frac{a' + b'i_{el}}{a - bi_{fc}}\frac{t_{fc}}{t_{el}} \tag{18}$$

where ρ_{array} is the specific mass of the photovoltaic array, kg kW^{-1}.

2.6. Mass modeling of RFC system

According to the mathematical modeling above, it can be seen that the masses of the components are expressed in the function of current densities of both the electrolyzer and the fuel cell. Since the mass of auxiliary system is independent of the operating current density, it is not in the consideration for optimization. According to Eq. (1), the system mass for minimization, can be described in Eq. (19)

$$fun = m_{fc} + m_{el} + m_{storage} + m_{rad} + m_{array}$$

$$= P_{fc}\left[\frac{\rho_{fc}}{(a-bi_{fc})i_{fc}} + \frac{\rho_{el}}{(a-bi_{fc})i_{el}}\frac{t_{fc}}{t_{el}} + \frac{t_{fc}}{E_f}\frac{E^0}{0.83(a-bi_{fc})}1+\beta+\sigma+\gamma\beta + \rho_{array}\frac{a'+b'i_{el}}{a-bi_{fc}}\frac{t_{fc}}{t_{el}} + \rho_{rad}\left(\frac{E^0}{a-bi_{fc}}-1\right)\right] \quad (19)$$

Eq. (19) is the objective function in terms of current densities of the electrochemical stacks for optimization. Thus, the system mass optimization problem in this work can be defined as

Minimize $fun(i_{el}, i_{fc})$

$$\text{Subject to}: \begin{cases} 0.1 \le i_{fc} \le 0.9\,\text{A cm}^{-2} \\ 0.2 \le i_{el} \le 1.1\,\text{A cm}^{-2} \end{cases}$$

The bounds for the two design parameters are selected according to lower and upper limits of ohmic region.

2.7. Optimization procedures

The minimization problem formulated above is solved using the MATLAB optimization toolbox [11], including functions for linear programming, quadratic programming, nonlinear optimization, nonlinear least squares, solving systems of nonlinear equations, multi-objective optimization, and binary integer programming. The problem under consideration in the present work belongs to the constrained nonlinear minimization problems, which can be solved using the *fmincon* function in MATLAB as the following syntax:

$$fmincon(fun, x0, lb, ub) \quad (21)$$

where *fun* denotes the scalar objective function of variable x, $x0$ is initial estimate, *lb* and *ub* are lower and upper bounds of the design parameters. The MATLAB *fmincon* function implements the Sequential Quadratic Programming (SQP) method to find a minimum of constrained nonlinear multivariable function, starting at an initial estimate.

In addition, it is possible to get the 3D graph by using MATLAB function MESHGRID, to find the trend of target object and the optimal parameters.

3. Results and discussion

The RFC system mass is related to the operating current densities of fuel cell and electrolyzer. High current densities are beneficial for reduction of the stack weight of both fuel cell and electrolyzer; however, it will increase the weight of the storage, the radiator and the PV. So the mass minimization problem under consideration in this paper is to determine the optimal operating point regarding the current densities of fuel cell and electrolyzer. This paper will focus on the designing of an energy storage system for the conditions of the stratosphere application and a rated power output of 12 kW. For stratosphere, the periods of daytime and nighttime vary with seasons and latitude. In this paper, the daytime and nighttime are set to t_{el} = 10 h and t_{fc} = 14 h.

In the objective function, the characteristic parameters of the electrolyzer and fuel cell, including a, b, a', b', ρ_{fc} and ρ_{el}, can be calculated according to the state-of-the-art electrochemical stacks at DICP. The fuel cell stack weighs 25 kg, composing of 130 cells with an active area of 276 cm^2. Thus, the specific mass of fuel cell stack is $\rho_{fc} = 0.7 \times 10^{-3}$ kg cm^{-2}. Fig. 2 gives the performance curve of the fuel cell stack, and the cell voltage expression for the ohmic region by linear curve fitting. The electrolyzer stack developed by DICP composes of 130 cells with an active area of 166 cm^2, weighing 30 kg. Thus, the specific mass of the electrolyzer stack is $\rho_{el} = 1.39 \times 10^{-3}$ kg cm^{-2}. Fig. 3 gives the performance curve of the electrolyzer stack, as well as the cell voltage expression for the ohmic region by linear curve fitting.

Main emphasis regarding gas tank developments was put in the past on the automobile applications. In this paper, composite tanks of carbon fiber reinforced aluminum are used for on-board fuel storage, having a specific mass of 9 wt% in storing hydrogen, 144 wt% in storing oxygen, i.e., $\delta = 11$, $\gamma = 0.6875$ correspondingly. Other characteristic parameters for PV array and radiator [10], together with the mentioned parameters above, are listed in Table 1.

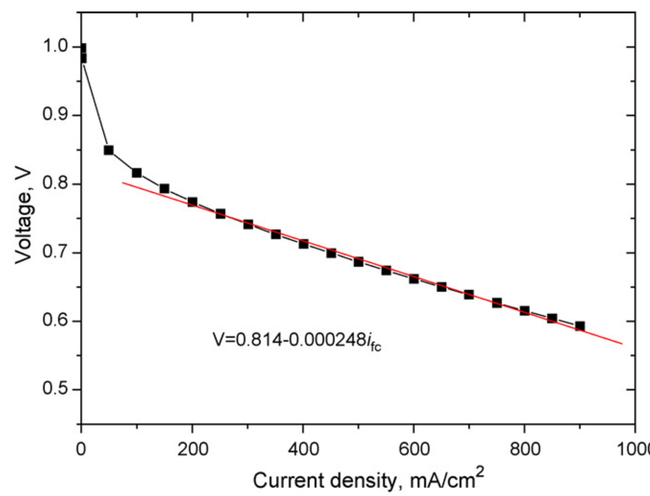

Fig. 2. Fuel cell polarization curve and the fitted linear voltage expression in the ohmic region.

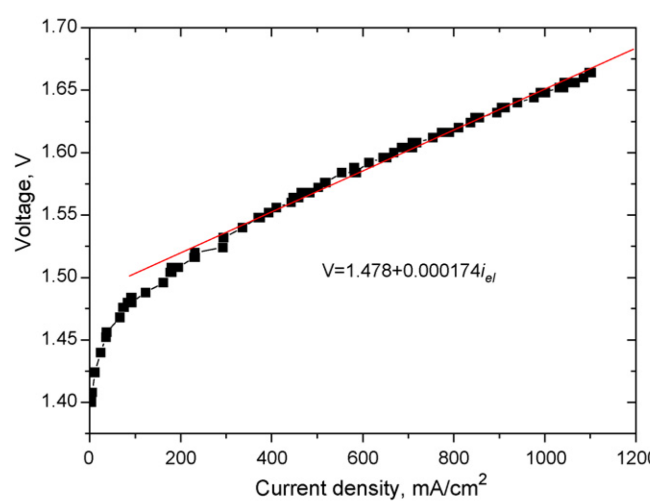

Fig. 3. Electrolyzer cell polarization curve and the fitted linear expression in the ohmic region.

Table 1
Characteristic parameters of RFC components.

Symbol	Value	Description
a	0.814 V	Extrapolated intercept of linear voltage expression for fuel cell at $i_{fc} = 0$
b	$0.248 \times 10^{-3}\ \Omega\,cm^2$	Area-specific resistance of fuel cell
a'	1.478 V	Extrapolated intercept of linear voltage expression for electrolyzer at $i_{el} = 0$
b'	$0.174 \times 10^{-3}\ \Omega\,cm^2$	Area-specific resistance of electrolyzer
E_f	40 kWh kg^{-1}	Theoretical energy density of H_2
P_{fc}	12 kW	Power output of PEM fuel cell
t_{fc}	14 h	Period of nighttime (fuel cell working)
t_{el}	10 h	Period of daytime (electrolyzer working)
ρ_{fc}	0.7×10^{-3} kg cm^{-2}	Specific mass of PEM fuel cell
ρ_{el}	1.39×10^{-3} kg cm^{-2}	Specific mass of PEM electrolyzer
ρ_{rad}	24.26 kg kW^{-1}	Specific mass of the radiator
ρ_{array}	10.0 kg kW^{-1}	Specific mass of the photovoltaic array
β	8	Mass consumption ratio of O_2 to H_2 for H_2/O_2 fuel cell
δ	11	Mass ratio of container to hydrogen
γ	0.6875	Mass ratio of container to oxygen

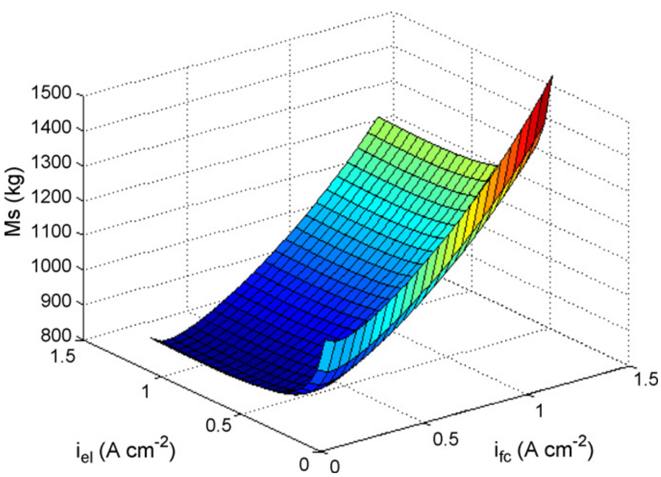

Fig. 4. System mass of a discrete RFC system operating in stratosphere vs. the operating current densities of fuel cell and electrolyzer.

Using MESHGRID function in MATLAB, the calculation results are presented in 3D graph, shown in Fig. 4. In this calculation, the current density has been varied between 0.1 and 0.9 A cm^{-2} for fuel cell, between 0.2 and 1.1 A cm^{-2} for elctrolyzer. From the 3D graph, it is clearly seen that the operating current densities of both fuel cell and electrolyzer have a great effect on the system mass. This is different from the trends of RFC system for GEO applications. For GEO missions, a slight dependency of the system mass was seen on the operating point of the electrolyzer [8], due to a low ratio of the periods of the eclipse to sunshine phase, which result in a low power input of electrolyzer to ensure the power supply during the eclipse phase.

From the 3D diagram, the system mass was varied considerably across the ohmic region of the operating current densities of both stacks, showing a high potential of mass reduction. Using the *fmincon* function in MATLAB, a distinct minimum of system mass of 830.8 kg was found at the optimal current densities of ($i_{fc} = 0.1738$ A cm^{-2}, $i_{el} = 0.8938$ A cm^{-2}) in the ohmic region of both electrochemical stacks. From the calculation, the minimum of system mass composed of $m_{fc} = 62.7$ kg, $m_{el} = 33.9$ kg, $m_{array} = 356.0$ kg, $m_{rad} = 173.0$ kg, $m_{storage} = 205.2$ kg. Based on the optimal current density and the rated power, the total electrode area of fuel cell was calculated according to Eq. (4), having $A_{fc} = 89.6 \times 10^3$ cm^2. Therefore, a 325-cell fuel cell stack with single-cell active area of 276 cm^2 was designed for optimal operation. According to Eq. (6), the total electrode area of electrolyzer stack for optimal operation is $A_{el} = 24.4 \times 10^3$ cm^2, consisting of 147 cells with single-cell active area of 166 cm^2.

Therefore, the specifications of both electrochemical stacks have been designed according to their optimal current densities. From the 3D graph in Fig. 4, it was shown that the optimal design of both fuel cell and electrolyzer stacks can effectively reduce the system mass.

4. Conclusions

In this paper, the masses of key components (e.g. fuel cell stack, electrolyzer stack, radiator, photovoltaic array, storage) were correlated to the operating current densities of both fuel cell and electrolyzer and the RFC system mass was modeled. System mass minimization was made for the stratosphere missions by a nonlinear constrained optimization procedure using the MATLAB optimization toolbox, and the optimal operating current density was obtained for both fuel cell and electrolyzer. The calculation results show that the optimization of the current densities of both stacks is of importance in designing the light weight on-board energy storage system. It is also found that the operating current densities of both stacks have a great effect on the system mass for stratosphere applications, which is different from the trends for GEO applications.

Acknowledgements

This work was financially supported by the National High Technology Research and Development Program of China (863 Program No. 2007AA05Z131) and the National Natural Science Foundation of China (No. 20206030).

References

[1] W. Knaupp, E. Mundschau, Aerosp. Sci. Technol. 8 (2004) 245–254.
[2] A.J. Appleby, J. Power Sources 22 (1988) 377–385.
[3] P. Millet, Electrochem. Acta 36 (1991) 263–267.
[4] K. Onda, T. Murakami, T. Hikosaka, M. Kobayashi, R. Notu, K. Ito, J. Electrochem. Soc. 149 (2002) A1069–A1078.
[5] K.W. Harrison, E. Hernandez-Pacheco, M. Mann, H. Salehfar, J. Fuel Cell Sci. Technol. 3 (2006) 220–223.
[6] A.B. Goldberge, L.I. Kheifets, A.G. Vaganov, S.G. Ogryz'ko-zhulovskaya, A.V. Shabalin, J. Appl. Electrochem. 22 (1992) 1147–1154.
[7] K. Bolwin, J. Power Sources 40 (1992) 307–321.
[8] S. Hauff, K. Bolwin, J. Power Sources 38 (1992) 303–315.
[9] F. Barbir, T. Molter, L. Dalton, Int. J. Hydrogen Energy 30 (2005) 351–357.
[10] DLR, Solar Dynamic Energy Supply Systems, BMFT Contract 8603/8, 1987.
[11] MATLAB, The Language of Technical Computing, sixth ed., The MathWorks Inc., Natick, MA, 2000.