Opening Optimization and Diameter Matching for Back Pressure Valve in a High Pressure PEMFC System

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Abstract—**In air supply sub-system, the stack pressure influence the stack efficiency as well as air compressor power consumption. In order to improve system global efficiency, the optimization of system efficiency based on the two inputs manipulation variables such as opening position of back pressure valve(BPV) and air compressor command voltage were investigated at a series of given system net power. Meanwhile, for a given fuel cell system, the BPV with the different diameters were adopted to match the system, and the simulations show that the BPV with the diameter of 30mm is good for the system with the purpose of the control accuracy.**

Keywords-PEMFC; efficiency optimizatin; back pressure valve

I. INTRODUCTION

Polymer exchange membrane fuel cell (PEMFC) is an electrical-chemical devise which directly convert the energy of a chemical reaction between hydrogen and oxygen into electrical energy [1]. In recent years PEMFCs by virtue of its credible energy density as well as zero polluting emissions, have been considered as one of the most attractive candidates to replace the conventional power sources [2, 3]. As been researched, high pressure PEMFC system is more effective than the low one [4]. However, high pressure needs more electricity power due to the air compressor diminishes the fuel cell stack output net power and may decrease the system inefficiency. In PEMFC system, although other auxiliary devices such as BPV, water pump, fan and so on also consume the power, the total power consumption are small compared to the air compressor, and the power difference between the different optimization is also small. Thus, in this paper, the power consumption by other auxiliary devices is neglected. Therefore, air compressor efficiency and stack efficiency need to be traded off to find a global optimal efficiency by both regulating the opening position of back pressure valve (BPV) and the driving voltage of the air compressor.

With a given power, the cathode pressure is determined by input and output flow rate, which also determine the compressor power consumption. Ref.[5] analyses the relation among the fuel cell consumption, pressure and flow rate at the different opening of BPV and find that the less the opening, the more the influence on system pressure and air mass flow. In [6], a research is made on the advantages by using a regulating valve for the cathode outlet flow and the compressor motor voltage as manipulated variables in a fuel cell system. Thirumalai D et al [7] investigate two fuel cell stack operation modes, one of which the speed of compressor is constant, the other is varied with the electric load on the fuel cell stack. Moreover, in [8] tuning the rotation speed of compressor and the opening of electrical throttle, which as system BPV, regulate the pressure of air system and thus diminish the consumption of auxiliary system. Chen F et al [9] find the optimal opening at specific work condition to promote the system efficiency, however, the details of BPV diameter matching is ignored. Furthermore, in [10] a set of optimization of air management is proposed, and a Constrained Optimization By Linear Approximation (COBLA) algorithm is implemented to solve the optimal speed of the compressor and the optimal throttle opening. From aforementioned research, tuning the opening of BPV precisely could attenuate the compressor consumption and promote PEMFC system efficiency.

The paper aims to find an optimal opening angle as well as matching diameter of BPV at different work condition to promote the system efficiency and decrease the control accuracy of the opening position for the BPV.

II. OPTIMIZATION OF BACK PRESSURE VALVE

A. *Configuration of Back Pressure Valve*

Back pressure valve (BPV), an electrical throttle, mounted after the outlet of the stack cathode to regulate the inlet air pressure of the stack (back pressure), consists of drive motor, reduction-gear set, resetting spring, throttle and position sensor (see Figure I). In this paper the model of fuel cell is adopt by [11], in which the area of the cross-section of the back pressure nozzle is a constant. Therefore, the model of BPV is re-modeling as follows. The mass flowrate of the BPV is proportional to the diameter square [12]. Therefore, for a 50mm-diameter BPV, the mass flowrate m_{bpv} (g/s) can be expressed as follows (details see the demo example of stateflow: Modeling a Fault-Tolerant Fuel Control System, Matlab 2016a)].

$$m_{bpv}=\begin{cases}\left(\dfrac{D}{D_0}\right)^2 f(\theta)*2\sqrt{\dfrac{p_{amb}}{p_{an}}-\left(\dfrac{p_{amb}}{p_{an}}\right)^2} & \dfrac{p_{amb}}{p_{an}}\geq 0.5\\ \left(\dfrac{D}{D_0}\right)^2 f(\theta) & \dfrac{p_{amb}}{p_{an}}<0.5\end{cases} \tag{1}$$

where $f(\theta)=2.821-0.05231\theta+0.10299\theta^2-0.00063\theta^3$, D is the diameter of the BPV(mm), $D_0=50mm$ the constant, θ the opening position (degree), p_{amb} the ambient pressure (pa), p_{an} the anode pressure(pa).

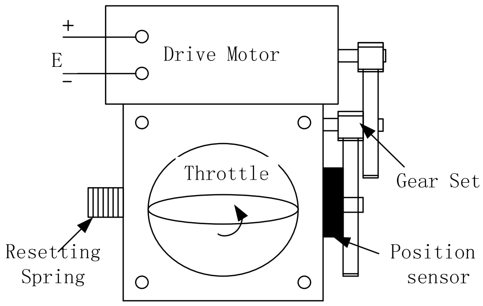

FIGURE I. BACK PRESSURE VALVE SCHEMATIC DIAGRAM

B. Efficiency Calculation

In practical application, auxiliary devices consume excessive power, which generated in stack by electrical-chemical reaction. Considering the reaction efficiency in the stack, system efficiency could be calculated as:

$$\eta_{sys}=\frac{V(\mathrm{i})}{n\times E_{OC}}\cdot\frac{P_{net}}{V(i)\times i}\times 100\% \tag{2}$$

where η_{sys} denotes fuel cell system efficiency, $V(\mathrm{i})$ the output voltage of the stack(V), i stack current(A), system gross power $P{=}V(i)\times i$, E_{OC} open circuit voltage of fuel cell with low heat value($\Delta H=286(\mathrm{kJ/mol})$ (V), n the number of cells($n{=}381$ in our system), P_{net} net system output power (W), $P_{net}{=}P-P_{aux}$. Equation (2) is equivalent to following from:

$$\eta_{sys}=\frac{1}{i}\cdot\frac{P_{net}}{n\times E_{OC}}\cdot 100\% \tag{3}$$

where $E_{OC}{=}1.229$. From the (3) , we can see that the system efficiency η_{sys} is inversely proportional to the stack current i with the given net system output power.

In high pressure PEMFC system, compressor consume the most of the auxiliary consumption power, so we only take the compressor consumption into the consideration [6]:

$$P_{net}=P-P_{ac} \tag{4}$$

where P_{ac} is the power of air compressor (W).

Considering the chemical reaction on the anode, $H_2\rightarrow 2H+2e^-$, the hydrogen consumption can be expressed as follow:

$$m_{H_2}{=}k\cdot i \tag{5}$$

where m_{H_2} represents hydrogen consumption (kg/s), k is a constant defined by:

$$k=\frac{n}{2F}M_{H_2} \tag{6}$$

where $F{=}96486$ is the Faraday constant (C/mol), $M_{H_2}{=}0.002$ is the mole mass of the hydrogen (kg/mol). $n{=}381$ the total numbers of the fuel cells, and thus $k=3.9488\text{e-}6$.

C. Optimization and Analysis of Opening for Back Pressure Valve

The difference cross-sectional area of nozzle mounted in the cathode exhausted port leads to the difference system efficiency. Using an electrical throttle as BPV replaces a nozzle, and variable cross-sectional area could be obtained by regulating BPV opening. In precondition of sufficient air(regulate the stoichiometric number λ), with reference to (2), optimal system efficiency can be considered to find the minimum current under a given net power or find the maximum system net power under a given stack current. From the viewpoint of physic, the former method should be selected in this work to implement the optimization. Computing the optimal global efficiency with the constrained condition is a typical multi-dimension constrained optimization problem. Referring to [13], simplify optimization problem into a mathematic model:

$$\begin{aligned}&\min.\ J=i(\theta,V_{cp})\\ &s.t.\ \begin{cases}1.5-\lambda_{O_2}\leq 0\\ P_{net}=c\\ V_{cp}\in[V_{cp\_\min},V_{cp\_\max}],\theta\in[\theta_{\min},\theta_{\max}]\end{cases}\end{aligned} \tag{7}$$

where θ is the BPV opening position, V_{cp} the voltage added to the air compressor, λ_{O_2} the oxygen excess ratio, c the constant, V_{cp_min}, V_{cp_max} the minimum and maximum voltage of the air compressor, θ_{min} , θ_{max} the minimum and the maximum opening position of the BPV, c is the constant. In the optimization problem (6), the cost function $i(\theta, V_{cp})$ is to be minimized and the optimization variable are θ, V_{cp} respectively.

In order to find out the suitable variable θ, V_{cp} for a given BPV with the diameter 40mm, and set the net power from 15kW to 50kW. The simulation results are shown in Table.1. The hydrogen consumption of the per kilowatt is defined as following with the unit of g/(kW*s).

$$w_{H_2} = \frac{m_{H_2}}{P_{net}} \times 10^{-6} \tag{8}$$

TABLE I. OPTIMAL RESULT UNDER 40MM DIAMETER

P_{net} (kW)	I(A)	U(V)	θ (°)	η_{sys} (%)	m_{H_2} [g/(kW*s)]
15	59.42	89.87	29.93	53.91%	1.5643E-02
20	82.96	99.87	29.90	51.49%	1.6380E-02
25	107.64	120.23	28.01	49.60%	1.7002E-02
30	132.58	152.23	27.72	48.32%	1.7451E-02
35	159.78	163.21	29.73	46.78%	1.8027E-02
40	188.84	183.97	31.86	45.24%	1.8642E-02
45	221.85	199.24	34.84	43.32%	1.9468E-02
50	262.80	210.89	36.84	40.63%	2.0755E-02

D. Matching and Analysis of the Diameter for Back Pressure Valve

In real application, for the BPV, the mass flowrate is approximate linear characteristic when the opening positon is about range from 15°~ 60°[14]. In a 60kW PEMFC system, with 40mm diameter BPV, the optimal openings stay in a low and narrow range (30°~37°) as shown in Table II, which requires high control accuracy of the opening position. In order to find out a proper BPV, of which the opening position can cover the interval [15°, 60°] as large as possible, but not exceed. Therefore, the different BPV with the diameters as 25mm, 30mm, 35mm, 40mm are simulated, and the their openings are listed as Table I-Table IV.

TABLE II. OPTIMAL RESULT UNDER 35MM DIAMETER

P_{net} (kW)	I(A)	U(V)	θ (°)	η_{sys} (%)	m_{H_2} [g/(kW*s)]
15	59.47	101.18	33.64	53.87%	1.5656E-02
20	82.98	97.54	26.80	51.47%	1.6384E-02
25	107.46	137.61	31.19	49.68%	1.6974E-02
30	132.59	150.75	32.64	48.32%	1.7452E-02
35	159.78	163.25	34.77	46.78%	1.8027E-02
40	188.85	183.76	37.60	45.23%	1.8643E-02
45	221.85	199.11	40.84	43.32%	1.9468E-02
50	261.54	214.16	35.28	40.83%	2.0655E-02

TABLE III. OPTIMAL RESULT UNDER 30MM DIAMETER

P_{net} (kW)	I(A)	U(V)	θ (°)	η_{sys} (%)	m_{H_2} [g/(kW*s)]
15	59.07	80.05	43.91	54.23%	1.5550E-02
20	82.97	100.66	40.78	51.48%	1.6382E-02
25	107.62	129.37	36.23	49.61%	1.6999E-02
30	132.57	152.84	38.77	48.33%	1.7450E-02
35	159.78	159.51	43.49	46.78%	1.8027E-02
40	188.9	184.10	45.89	45.22%	1.8648E-02
45	221.84	199.04	49.46	43.32%	1.9467E-02
50	262.67	214.46	53.10	40.65%	2.0745E-02

TABLE IV. OPTIMAL RESULT UNDER 25MM DIAMETER

P_{net} (kW)	I(A)	U(V)	θ (°)	η_{sys} (%)	m_{H_2} [g/(kW*s)]
15	58.90	69.95	90.00	54.39%	1.5506E-02
20	82.90	95.61	55.84	51.52%	1.6368E-02
25	107.44	137.35	47.00	49.69%	1.6970E-02
30	132.57	152.96	48.76	48.33%	1.7450E-02
35	159.87	161.60	51.07	46.75%	1.8037E-02
40	188.85	182.92	56.74	45.23%	1.8643E-02
45	221.86	199.25	63.57	43.32%	1.9468E-02
50	262.69	213.12	68.40	40.65%	2.0746E-02

From Table I-Table IV, with the same net power, stack currents are almost the same under the different diameter of BPV, which is keeping with reality. And we also find the global efficiency is decreases with net power increase. However, in reality, the efficiency should increases firstly and then decreases as net power increase. The peak efficiency, locating at around 10 presents of rating power of system, is 5-6kW approximately which out of the range we implement the simulation.

With the purpose of making the problem clearer, the opening position with the different net power and BPV are shown in Figure II, from which, we can see that the optimal opening increase as diameter decrease for a given net power. The maximum optimal opening is up to 90°when the diameter is 20mm. The working opening position is range from 36° to 53°, which is largely cover the interval [15°, 60°], therefore the BPV with the diameter around 30 mm is advised to be used in this fuel cell systems.

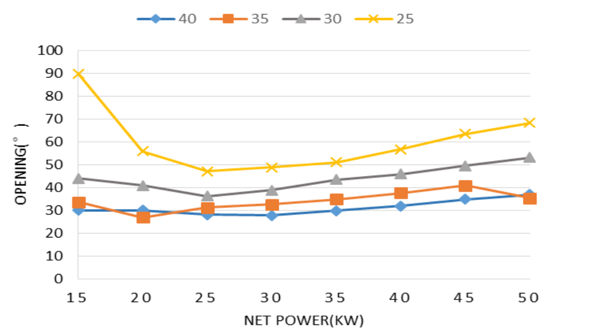

FIGURE II. OPTIMAL OPENING UNDER THE DIAMETER FROM 25-40MM

III. CONCLUSION

A. *System Efficiency Optimization*

Firstly, we find that the system efficiency is inversely proportional to the stack current for a given system net power. Then, in order to improve the PEMFC system efficiency, for a given net power, a constrained nonlinear optimization scheme is proposed to find out the optimal working point. The optimization simulation results show that the opening position varies for the different net power requirements.

B. *Back Pressure Valve Diameter Matching and Analysis*

Alter the diameter of BPV from 20mm to 40mm with the step of 5 mm, and repeat opening optimization process. The results are shown in Table I-Table IV, and the map of optimal opening position versus net power in difference BPV diameter are shown in Figure II. The conclusion is that the BPV with the diameter around 30mm is advised to be applied in the 60kW PEMFC system.

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