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Short communication

Customized design for the ejector to recirculate a humidified hydrogen fuel in a submarine PEMFC

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Abstract

The customized design of an anode recirculation system that uses an ejector based on the humidified hydrogen is proposed for a submarine PEMFC. Generally, the ejector is useful to enhance its system performance and to easily be operated and maintained since it does not require any parasitic power and has very simple structure. However, the existing commercial ejectors do not meet the practical operating requirements of the PEMFC system with the humidified hydrogen recirculation since the included water raises the ejector performance reduction and accompanying operating limits. The subsonic flow ejector designed by the proposed approach has met the desired entrainment ratio through the whole operating range of the target system as well as it allows the additional advantages to improve the system efficiency and simplicity and to overcome the conventional operating limits.

Keywords: PEMFC; Ejector; Subsonic flow; Design; Submarine

1. Introduction

In a polymer electrolyte membrane fuel cell (PEMFC), one of the important issues to improve the efficiency of a fuel cell system is the hydrogen recirculation management. Hydrogen fuel to the anode side of the fuel cells is excessively supplied to reduce the risk of fuel cell starvation and to purge the water droplets that are accumulated on the surface of its flow path. However, releasing the unused hydrogen reduces the efficiency of the system and may have negative environmental impact. To solve this problem, Rodatz et al. suggest the use of an ejector and the used of a pump (or blower) as an anode side recirculates system [1]. In particular, the application of the ejector for the recirculation system of the automotive fuel cell is very useful in terms of its system efficiency, operation, and maintenance since the ejector needs no parasitic power and has very simple mechanical structure.

In case of the ejector for the automotive PEMFC, the performance of the entrainment ratio depends on the operating conditions of the PEMFC system. However, the commercial ejectors cannot meet the requirements of the ejector performance during those operations of the automotive PEMFC. Thus it is necessary to design the ejector customized for the fuel cell system. Many existing research works have been conducted about the ejector design for the refrigeration system, absorption system, and so on [2–5]. Recently, some studies to apply ejector into the fuel cell have been performed [6–8]. However, these approaches have some practical limits to assume the perfect water removal of the recirculated hydrogen. It is difficult to reach the perfect dry of the hydrogen as well as it arises the additional defects such as consumption of power, increase in a system complexity and frequent equipment errors by using an water removal equipment though they theoretically have showed a good performance.

This paper addresses the methodology of design for the ejector with a humidified recirculation hydrogen fuel in a submarine PEMFC. The proposed design approach make the customized ejector with constant throat and mixing tube areas be acceptable in not the whole operating range but the practical operating range. The main goal of the ejector design is to keep its entrainment ratio more than a predefined threshold during the practically acceptable operating range. To achieve the optimally customized ejector, the physical properties of the humidified hydrogen is newly introduced and subsonic ejector flow is applied to prevent a water freezing, a physical wear and a roaring sound which supersonic ejector flow generally raise due

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Nomenclature

A	area (m^2)
C_p	specific heat of gas at constant pressure ($kJ\,kg^{-1}\,K^{-1}$)
C_v	specific heat of gas at constant volume ($kJ\,kg^{-1}\,K^{-1}$)
D	diameter (mm)
f	flow rate (SLPM)
k	tolerance of the ejector exit pressure
M	Mach number
Mw	molecular weight
P	pressure (kPa)
R	gas constant ($kJ\,kg^{-1}\,K^{-1}$)
t	temperature (°C)

Greek symbol

γ	C_p/C_v

Subscripts

e	exit of ejector, condenser
m	flow mixed with the primary and secondary flows
mix	flow mixed with water and gas
P	primary flow
s	suction or secondary flow
sat	satuation
set	set point
sy	suction flow at the location of choking for the secondary flow

to the water in the recirculated hydrogen. And then the ejector manufactured according to the design values is verified by experimental test within the practical operating range. He design values are the diameters of the nozzle throat and mixing tube area.

2. Customized design approach

Fig. 1 shows the architecture of the proposed design procedure for the ejector with a humidified recirculation flow. The proposed approach is based on the two-dimensional and iteratively numerical solving method. Firstly, the ejector design conditions are defined based on the operating conditions of a target fuel cell system. From the given ejector design conditions, the initial pressure, temperature, flow rate of the primary and secondary flows are determined. And then two design values and the ejector exit pressure are iteratively calculated from the determined conditions by gradually updating the primary flow pressure until the calculated exit pressure is approximately equal to its required design. The detail relationships among the design values and the ejector's operating conditions are referred to [9]. The primary flow pressure has to be always more than the ejector exit pressure like Eq. (1). However, primary flow pressure can be less than the ejector exit pressure with the infeasible design values before the optimal solutions are found. Therefore, the optimal design values are also iteratively decided by updating the secondary flow Mach number until the relationship between the primary flow pressure and the ejector exit pressure (Eq. (1)) is acceptable. The detail equations needed to calculate can be also shown at [9]:

$$p_e \le \left(\frac{2}{\gamma_m + 1}\right)^{\gamma_m/(\gamma_m - 1)} p_p \tag{1}$$

Fig. 2 shows the physical properties of the humidified hydrogen. In case of the PEMFC, the recirculated flow includes the water since the water is generated by the electric chemical reactions. The entrainment ratio is generally reduced since the molecular weight of the water is larger than that of the hydrogen. To overcome the problem, it is necessary to increase both the driving force from the primary flow and the suction area of the secondary flow based on the properties of the humidified hydrogen fuel. The water vapor saturation pressure is a strong function of temperature like Eq. (2). The water mass fraction according to the gas is calculated using Eqs. (3) and (4):

$$\log_{10} p_{\mathrm{sat,H_2O}} = -2.1794 + 0.02953 t_{\mathrm{H_2O}} - 0.000091837 t_{\mathrm{H_2O}}^2 + 0.00000014454 t_{\mathrm{H_2O}}^3 \tag{2}$$

$$x = \frac{p_{\mathrm{sat,H_2O}} \mathrm{Mw_{H_2O}} / p_{\mathrm{mix}} \mathrm{Mw_{mix}}}{1 - p_{\mathrm{sat,H_2O}} \mathrm{Mw_{H_2O}} / p_{\mathrm{mix}} \mathrm{Mw_{mix}}} \tag{3}$$

$$\mathrm{Mw_{mix}} = \frac{p_{\mathrm{sat,H_2O}}}{p_{\mathrm{mix}}} \mathrm{Mw_{H_2O}} + \left(1 - \frac{p_{\mathrm{sat,H_2O}}}{p_{\mathrm{mix}}}\right) \mathrm{Mw_{gas}} \tag{4}$$

3. Case study

3.1. Definition of design conditions

In case of the ejector for the automotive PEMFC, the performance of the entrainment ratio depends on the operating conditions of the PEMFC system. The operating conditions of the ejector are directly affected by the ones of the fuel cell system as followings (Fig. 3): (1) the primary flow rate of the ejector follows the various load required by the automotive application; (2) the exit pressure of ejector has to reach 300 kPa as the inlet pressure of the PEMFC stack; (3) the suction pressure in the recirculation flow has to drop into 277 kPa as the inlet pressure decreases throughout the anodic flow field; (4) the temperatures of the primary and secondary flows are varied by the operating temperature of the condenser. The design conditions of ejector from the target submarine PEMFC system are determined as shown in Table 1.

3.2. Results of the customized design

The Mach number represents the speed of a flow as followings: the Mach number 1 is a sonic flow, the Mach number more than 1 is a supersonic flow, and the Mach number less than 1 is a subsonic flow. The secondary flow Mach number is initialized with “1” and the changed amount of the Mach number is

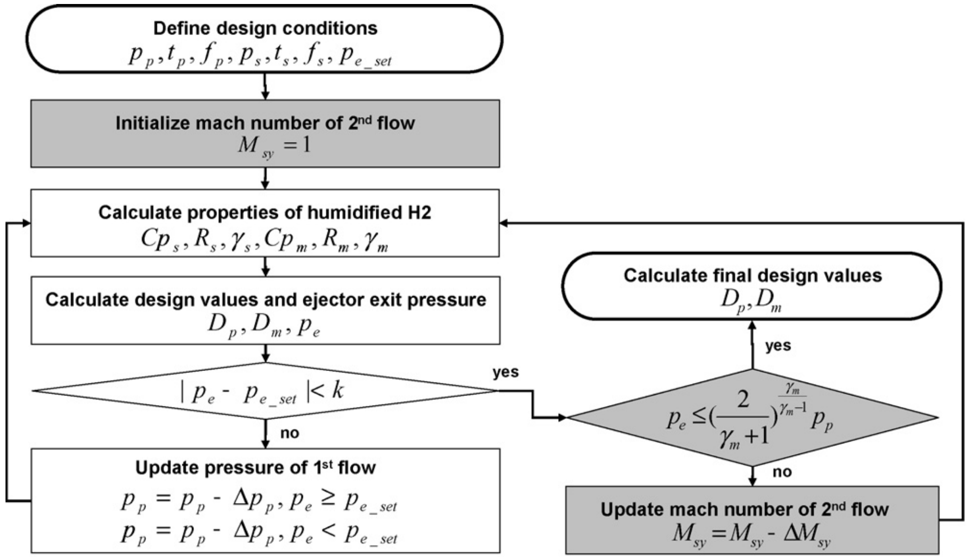

Fig. 1. The architecture of the proposed design procedure.

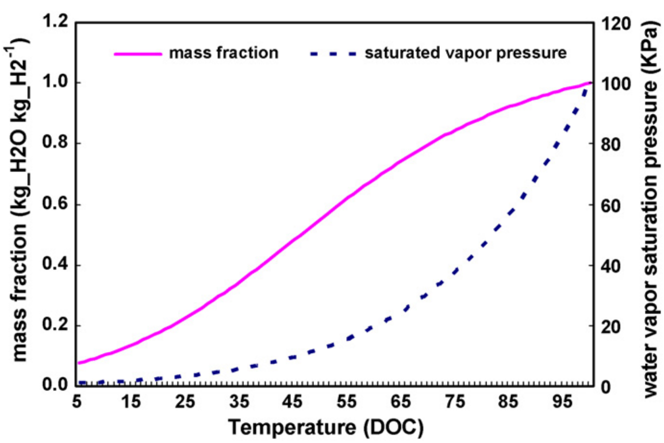

Fig. 2. The physical properties of the humidified hydrogen.

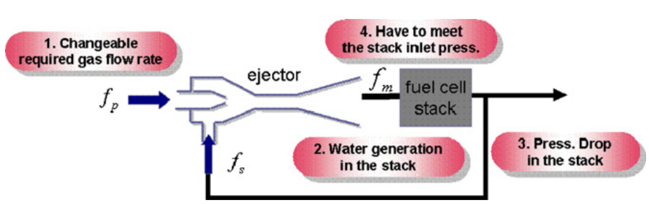

Fig. 3. The ejector design conditions determined from the target PEMFC system.

Table 1
Ejector design conditions

Maximum power (kW)	40
Primary flow	
Pressure (kPa)	–
Temperature (K)	343
Secondary flow	
Pressure (kPa)	277
Temperature (K)	323
Total flow rate (SLM)	600
Ejector exit pressure (bara)	3.00

0.05. The tolerance of the ejector exit pressure is 0.01. The Mach number of the secondary flow depends on the mixing tube area at a given secondary flow rate. Therefore the change of the Mach number causes the change of both the mixing tube area and its ejector exit pressure. And thereby the new primary flow and its new design values are determined to approximate the ejector exit pressure to its desired value. The optimal Mach number satisfying two pressure criteria of the proposed design approach is determined as 0.25 shown in Fig. 4. The conventional ejector design approaches keep the secondary flow to a sonic or supersonic flow, however, in this study, the final secondary flow can be a subsonic flow since the Mach number of the secondary flow is used as the decision variable. Consequently, the subsonic secondary flow decided based on the customized design approach additionally prevent a water freezing, a physical wear and a roaring sound generally arising at the supersonic flow ejector with water. The final designed diameters of nozzle throat and mixing tube are 1.40 and 3.40 mm.

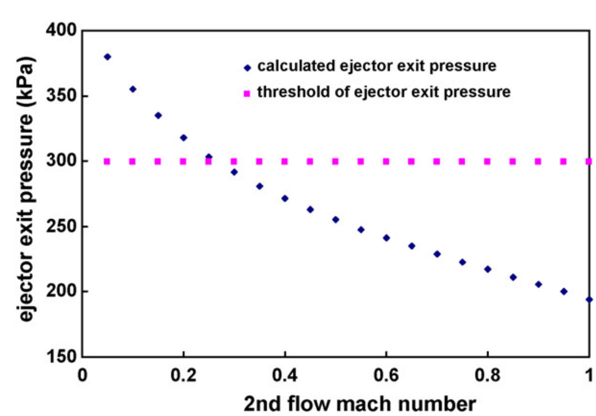

Fig. 4. The results of the customized design: secondary flow Mach number vs. the ejector exit pressure.

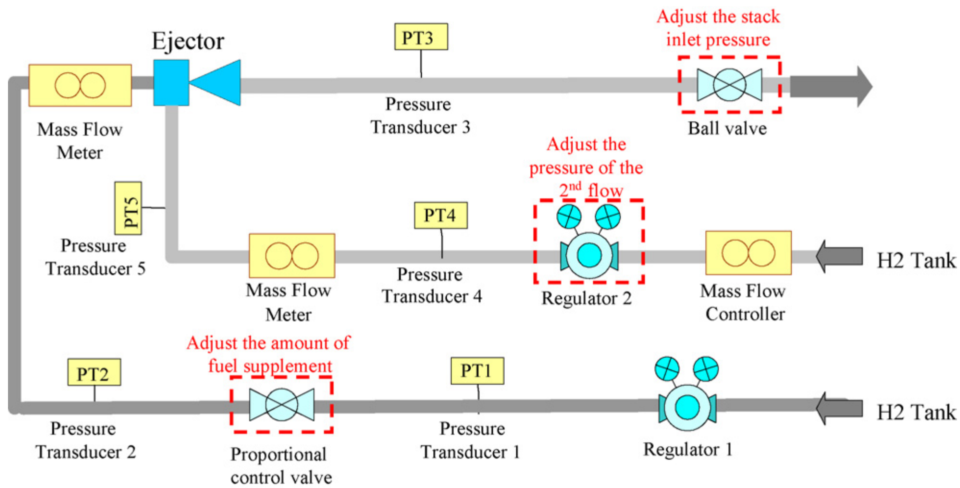

Fig. 5. Outline of the experimental system.

3.3. Design of the experimental system

Generally, experimental verification for the balance of plants (BOPs) like an ejector has still some problems occurred from the real stack since the real stack is very expensive and is likely to be damaged during the critical experiments. To solve the problem, the design of the experimental system focuses to reduce the experimental cost by introducing mock-up stack. Mock-up stack which imitates the main conditions such as changeable supplement of the fuel, pressure drop in channel, and adjustment of the stack inlet pressure is introduced instead of a real stack. Fig. 5 shows the outline of the test equipment. The dotted boxes explained the functional mock-up stack as followings. The pressure and flow rate of the primary flow are adjusted by the pressure regulator 1 and proportional control valve, respectively. The pressure regulator 2 is in charge of decreasing the secondary flow pressure due to the pressure drop of the anodic flow field. The inlet pressure of the stack is regulated by the fuel output through the ball valve. All the measurements and automatic controls are based on the commercial control program, Labview^{TM}.

There are two major methodologies to verify the performance of the manufactured ejector. The one is to adjust the primary flow from maximum to minimum amounts using the proportional control valve to check the acceptable range of the ejector entrainment ratio during the practical range of the power load. The other is to get the pressure drop between the stack inlet pressure and the pressure of the secondary flow using the pressure regulator 2 to investigate the effect of the stack pressure drop on the ejector entrainment ratio.

3.4. Experiments and validation

The operating power of the target submarine PEMFC is required from 10 to 40 kW. Table 2 shows the experimental conditions by changing the power for the submarine PEMFC. The conditions are determined by calculating the required hydrogen flow rate and its theoretical and practical pressure drops according to the various power requirements [10,11]. The theoretical pressure drop means the simply decreasing pressure in the only anodic channel while the practical pressure drop means the totally decreasing pressure including the effects of the condenser, lines, pressure transducer as well as the anodic channel. At each experimental condition, the entrainment ratio for the ejector is investigated.

The ejector performance, entrainment ratio is also changeable according to the changes of operating conditions of the target system. It is impossible that the ejector with constant throat and mixing tube areas keeps its best performance when the operating conditions are changed. In addition, it is no use that the ejector keeps its best performance. It is noted that the practically optimal design keeps its acceptable performance during its overall operating range.

At the PEMFC for the submarine, the fuel utilization has to be more than 75% to improve the efficiency of the PEMFC stack. The fuel utilization 75% of the stack is equal to the entrainment ratio 0.33 of the ejector. The result of the load change experiment is shown in Fig. 6. The experimental range of the entrainment ratio for the ejector designed by the proposed approach is from 0.56 to 1.29 according to the practical pressure drop. Finally the entrainment ratio of the designed ejector is more than 0.33

Table 2
Experimental conditions of the hydrogen flow rate and pressure drop in anodic channel by changing the required power

Power (kW)	Hydrogen flow rate (SLM)	Theoretical pressure drop in anodic channel (kPa)	Practical pressure drop in anodic channel (kPa)
10	72	1.4	5.9
20	143	2.8	11.3
30	214	4.2	15.0
40	286	5.6	23.0

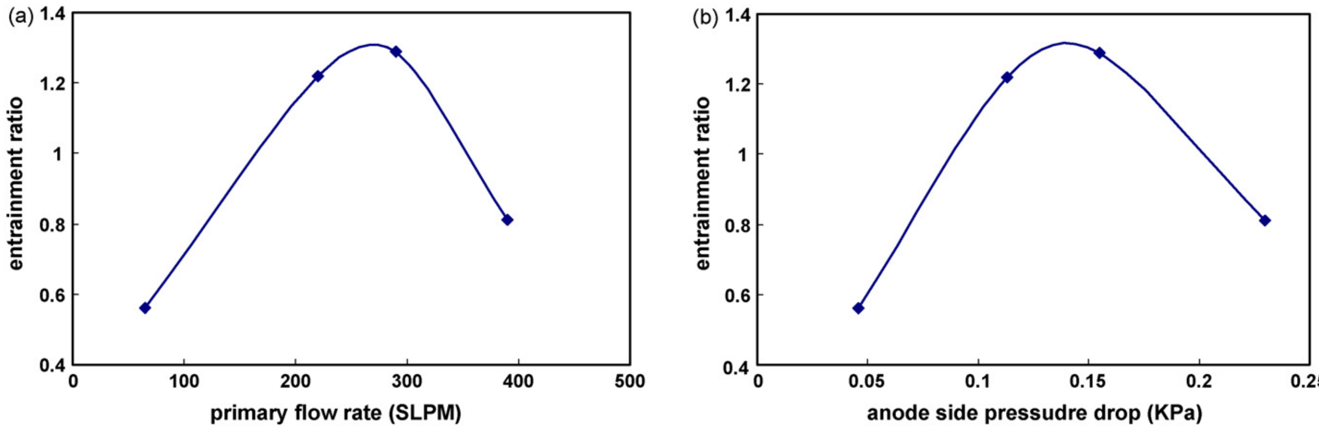

Fig. 6. Entrainment ratio by changing (a) the primary flow rate and (b) the anode side pressure drop.

throughout practical operating range in the anode side and therefore the designed ejector is acceptable.

4. Conclusions

In PEMFC applied to the submarine, the design methodology of the ejector to recirculate the humidified and unused hydrogen is suggested. The real ejector has been designed by the proposed methodology and verified its performance through the whole practically acceptable operations. The designed subsonic flow ejector allows not only the general advantages such as no parasitic power, easy operation and maintenance but also the additional advantages as followings: (1) the system efficiency and simplicity improves by exclude the water removal tool and its power consumption; (2) the conventional problems of a water freezing, a physical wear and a roaring sound are overcome. Recently, PEMFC has been used to many automotive applications such as bus, automobile, motorcycle, etc. The ejectors of the automotive PEMFCs have the same problem arising from water and a supersonic flow except the different capacity and the operating conditions. However, the proposed design approach is not restricted by the ejector capacity and the operating conditions and therefore the proposed methodology can be expected to be applied into those applications.

Acknowledgements

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