공학석사학위논문

고분자 전해질 막 연료전지 항공기 추진시스템에서의 터보 컴프레서 이용 적합성 연구

Feasibility study of turbo-compressor application in polymer electrolyte membrane fuel cell powered aircraft propulsion system

2023 년 8 월

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지도교수 송 한 호

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Abstract

Feasibility study of turbo-compressor application in polymer electrolyte membrane fuel cell powered aircraft propulsion system

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With growing concern of environmental pollution and depletion of fossil fuels, industries are searching for greener power sources. For this reason, there's a lot of research on eco-friendly energy use in the aircraft field. Using hydrogen and electricity is the most representative way to use eco-friendly power source.

Fuel cell is an energy converter which uses hydrogen and oxygen to generate electricity, and recently, it is one of the technologies that are getting attention in aircraft industry. To minimize the adverse effects of changes in atmospheric pressure due to transitions of altitude on the operation of the fuel cell stack, using turbo-compressor is one of the approaches to increase system efficiency compared to conventional systems. When the fuel cell operated at pressurized system, compressor uses power generated from turbine, so it reduces the amount of consumed power from motor.

In this study, a polymer electrolyte membrane fuel cell system is considered as a propulsion system for urban air mobilities (UAMs). At first, conventional compressor system and turbo-compressor system designed for fuel cell aircraft propulsion using GT-Suite program are introduced, and parametric study is conducted by changing the parameters of the two systems in air supply line. After that, the applicability of using a turbo-compressor in a specific mission profile for UAM propulsion is presented through a system modeling analysis. By proposing the useful sections to use turbo-compressor in UAM mission profile, it discusses the aspect to consider in practical applications.

Key Words : Aircraft propulsion system, turbo-compressor, polymer electrolyte membrane fuel cell, system efficiency, compressor, turbine

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Chapter 1. Introduction

1.1. Study Background

Amount of greenhouse gas emissions is increasing every year, and among many energy sectors, transportation is responsible for 14% of the greenhouse gas emissions in the world [1]. Policies and regulations related with greenhouse gases are emerging in response, and industries trying to find alternative fuels and power sources due to greenhouse gas emission regulations. Aircraft, included in transportation, contributes a significant amount of greenhouse gas emissions, because it uses kerosene as fuel and produces emissions such as carbon dioxide, carbon monoxide, nitrogen oxide, which are superintended under environmental policies [2].

Using electric energy is one of the practical ways to make zero greenhouse gas emissions in transportation, and hydrogen is also the promising technology. To use hydrogen, industries attempt to use fuel cell as a power converter.

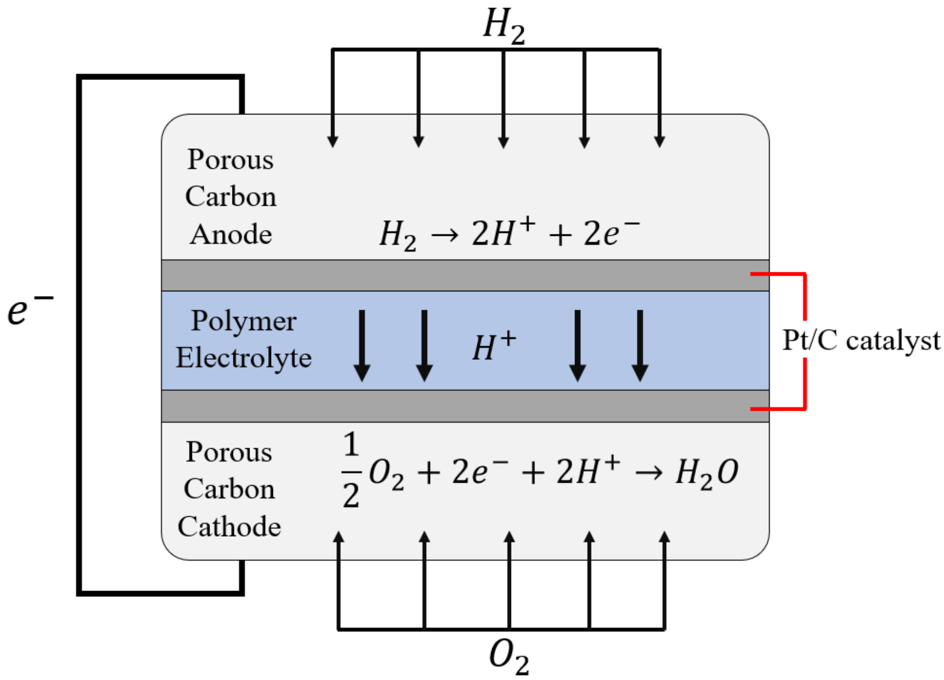


Figure 1.1 Schematics of polymer electrolyte membrane fuel cell (PEMFC).

Polymer electrolyte membrane fuel cell (PEMFC) is an electrochemical energy converter which changes chemical energy of hydrogen and oxygen into electricity [3]. Figure 1.1 shows the schematic of PEMFC. It uses hydrogen and oxygen as fuel, and produce electricity, water, and heat. When hydrogen enters in fuel cell, it contacts with platinum (Pt) catalysts and decomposes into electron and proton. Then the electron leaves the fuel cell while proton moves across membrane and arrives at the cathode. At the cathode, proton, oxygen, and electron from the outer circuit combined as water and escape the fuel cells. Since PEMFC use polymer as an electrolyte, operation temperature range is 25~80℃ because of material suitable operating temperature of membrane, which is relatively low compared to other fuel cell types. Also, PEMFC afford the high-energy densities and fast start-up times which requires for automotive applications.

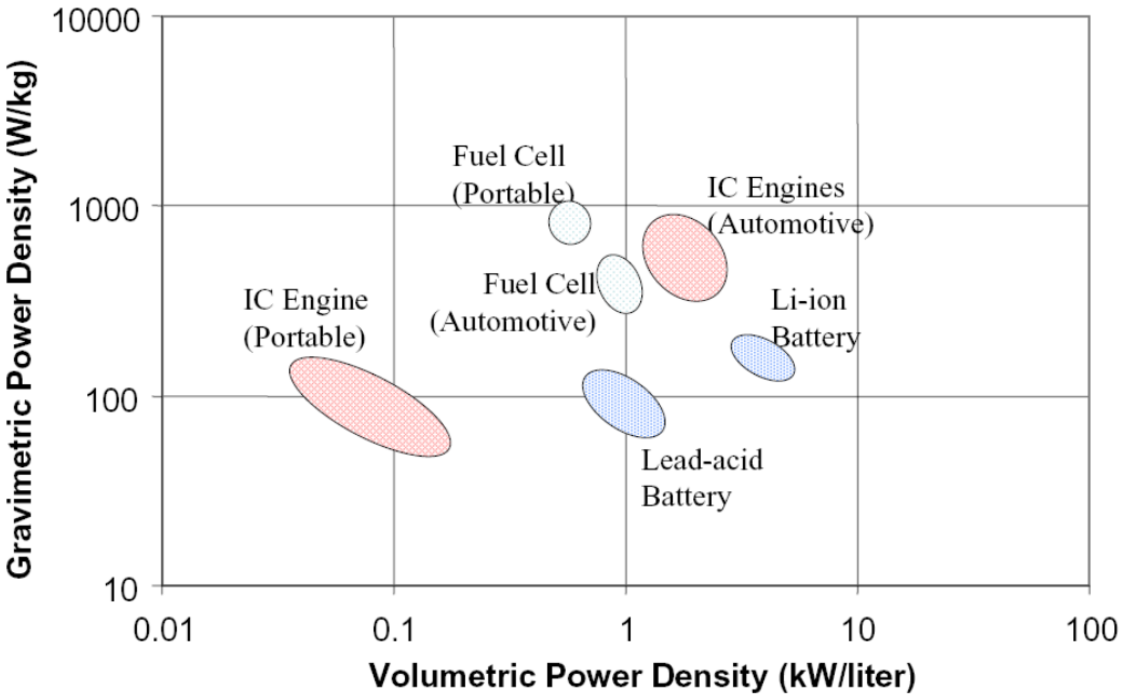


Figure 1.2 Gravimetric power density and volumetric density of engines, batteries, and fuel cells [4].

For aircraft application, weight is a crucial designing sector, as it has a huge impact on the power requirement of an airplane to take off. Figure 1.2 shows that fuel cell gravimetric power density is higher than Li-ion battery, that is, fuel cell is lighter than battery for the same energy [4]. For this reason, it is expected that applying fuel cell application is more critical in not only vehicle but also aircraft industry.

While there is a commercially available fuel cell powered vehicle, NEXO from Hyundai motors company, however, commercialized fuel cell powered aircraft does not exist.

1.2. Previous research

For PEMFC application, the design of stack fundamentally affects fuel cell performance. There had been studies of flow channel design, from serpentine, parallel, interdigitated flow channels to leaf-inspired, tapered, side branch channels [5]. It not only reviews the various designs of flow field but also compared the performance of each flow field design between serpentine flow channels. Arato et al., analyze the effect of diffusion in porous layer close to electrodes [6], and informed about the process of designing serpentine and interdigitated flow channels in simulation using non-dimensional numbers, such as Peclet number and Sherwood number. It also revealed the pressure loss, velocity distribution with flow channel designs [7]. For proper humidification, Aslam et al., conducted experiments with visualizing PEM fuel cell stack and observed distribution of water and temperature by changing mass flow rate of air [8]. For automotive industry, Yu et al., provides information on the importance of air compressor system in automotive fuel cell systems, introducing various air system components such as scroll compressors, screw compressors, turbo-compressors, and roots compressors, as well as the components of air supply systems being considered by automotive companies [9]. Sery et al., stated the compressor and 12 V accessories were the most energy consuming balance-of-plant (BOP) in a fuel cell vehicle system, and provides the configuration diagram of NEXO. It also showed the system efficiency, fuel consumption rate, stack power, battery power, vehicle speed, and power consumption of fans, heaters, and pumps in driving cycles are obtained through tests, and an overall evaluation of the fuel cell vehicle system is made [10]. In aircraft, T. Horde et al., adverted about degradation of fuel cell performance with the effects of low temperature and pressure at high altitude [11], and S. Campanari et al., studied about the phenomena occurring at turbine from the turbo-compressor fuel cell aircraft propulsion system [12]. Schroter et al., also introduced about how maximum pressure ratio and fuel cell stack performance changes as the aircraft operates at low ambient pressure [13]. It stated that decreasing ambient pressure and pressure loss occurred at compressor results in reducing maximum pressure. Abu Kasim et al., discusses a model of a liquid hydrogen fuel cell powered turbocharged system on a Cessna 208 caravan aircraft and the challenges that may arise in real-world use, such as failure to provide air, hydrogen to the system, or subsystem of air [14]. T. Bradley et al., presented energy flows by component based on operating conditions for about 500W fuel cell battery hybrid powered aircraft system [15]. Though fuel cell application in aircraft seems important, still, there is a lack of analysis for the phenomenon of using fuel cell propulsion system in aircraft. The most important point to consider for the use of turbo-compressor in fuel cell aircraft propulsion system is about the degree of improvement in system efficiency, and there has been a lack of comparison between conventional fuel cell system and other system, for example, stack power generation and compressor power consumption.

1.3. Consideration for fuel cell aircraft propulsion system

Unlike fuel cell systems in vehicle, aircrafts operate at high altitude. At high altitude, ambient air temperature and pressure are comparatively lower than ambient condition (Table 1.1). Furthermore, for aircraft, outside air conditions entering the fuel cell changes with altitude, which has a significant impact on fuel cell performance [11], therefore, using compressor is unavoidable, and to maintain the appropriate pressure at the fuel cell, compressor should do more compression when altitude increases in order that the power requirement for compressor raises when the pressure of outside air is low. According to the study by author's group, 28.6 % of the power produced by fuel cell used to utilize the compressor at the worst case. In that case, compressor can be act as the crucial parasite component that should be considered while designing. To overcome this problem, other fuel cell propulsion system should be designed.

Table 1.1 Temperature and pressure of air with altitude

Altitude [m]	Temperature [° C] (K)	Pressure [Pa]
0	15 (288.15)	101,325
600	11.1 (284.25)	94,322
1,200	7.2 (280.35)	87,716
1,800	3.3 (276.45)	81,489
2,400	-0.6 (272.55)	75,626
3,000	-4.5 (268.65)	70,109
3,600	-8.4 (264.75)	64,922

1.4. Purpose of research

Since the use of compressor is unavoidable in fuel cell aircraft propulsion system and significant amount of power generated from fuel cell is consumed from compressor motor, designed model in this paper introduced turbo-compressor in fuel cell system. Since the traditional system uses electric-motor-driven compressor in the aircraft propulsion system, the air from fuel cell outlet is still hot and pressurized. It is anticipated that this condition can be utilized in turbine and generate work. If the compressor and turbine are linked in the same shaft, the power generated from turbine may compensate part of the power required for air compressing. Moreover, as the external pressure decreases with high altitude, the pressure difference between pressurized fuel cell outlet air and outside air becomes large, which makes turbine generates more power. This design had been already introduced from previous research [3, 12], however, as revealed in chapter 1.2., the degree of system efficiency improvement in aircraft fuel cell propulsion had not been studied, which can seriously impact on fuel storage amount, which related to aircraft propulsion system weight and propulsion power requirement.

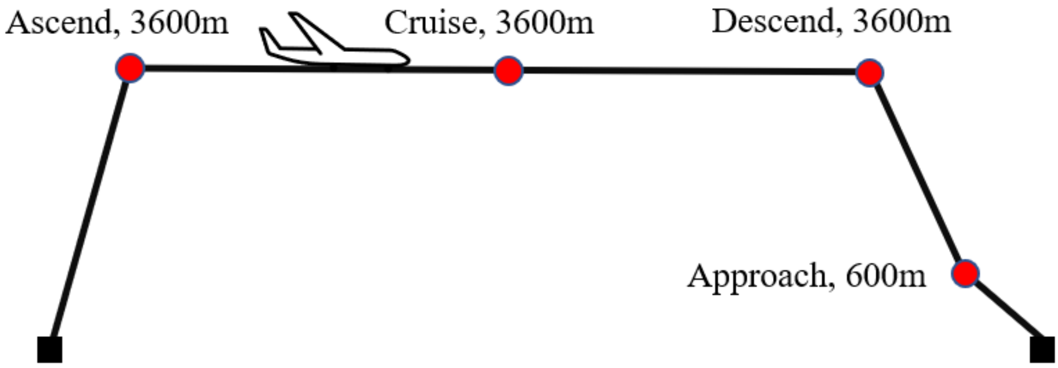
By designing turbo-compressor in fuel cell system and compared with conventional compressor system for aircraft propulsion, this study figured out feasible sections and applicability of using turbo-compressor during a mission profile with degree of system efficiency improvement compared to conventional compressor fuel cell aircraft propulsion system. It is expected that this research can provide practical aspects of using turbo-compressors in fuel cell propulsion in aircraft application.

Chapter 2. Model set up

To analyze the feasibility, aircraft and its mission profile had been chosen, and fuel cell aircraft propulsion system was designed using GT-Suite. It is a program that allows to model the components which make up a system in detail and reproduce the interactions between elements.

2.1. Aircraft, mission profile, and required power for propulsion

For modeling, mission profile for use in KC-100 aircraft was selected. KC-100 is a light aircraft which has 4 passenger seats, max level speed of 210 kts, and has 240 kW engine. Maximum altitude of KC-100 is 7,652 m [16]. Mission profile consists of 4 sections, ascend, cruise, descend, and approach.



		Ascend	Cruise	Descend	Approach
Time	[min]	9	30	32	3
Altitude	[m]	0→3657.6	3657.6	3657.6 → 609.6	609.6→0
Propulsion power	[kW]	230~250	120	40	19

Figure 2.1 Mission profile of KC-100 and requirements for each section.

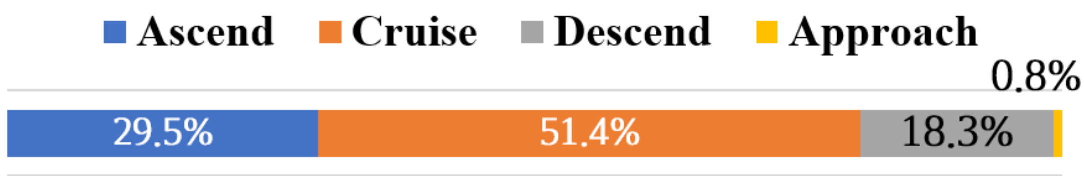


Figure 2.2 Energy usage rate in total mission profile

Figure 2.1 shows altitude, required power for propulsion, and flight time in KC-100 mission profile. Maximum power request section occurred at ascend section because the aircraft must increase altitude by resisting gravity, and cruise section had the longest time duration. It is expected that mission profile from Figure 2.1 can represent the common UAM flight pathway. In the viewpoint of energy, ascend has portion of 29.5% in total mission profile, 51.4% at cruise, 18.3% at descend, 0.8% at approach (Figure 2.2). Nearly 80% of energies through mission profile are consumed at ascend and cruise section.

2.2. System modeling using GT-Suite

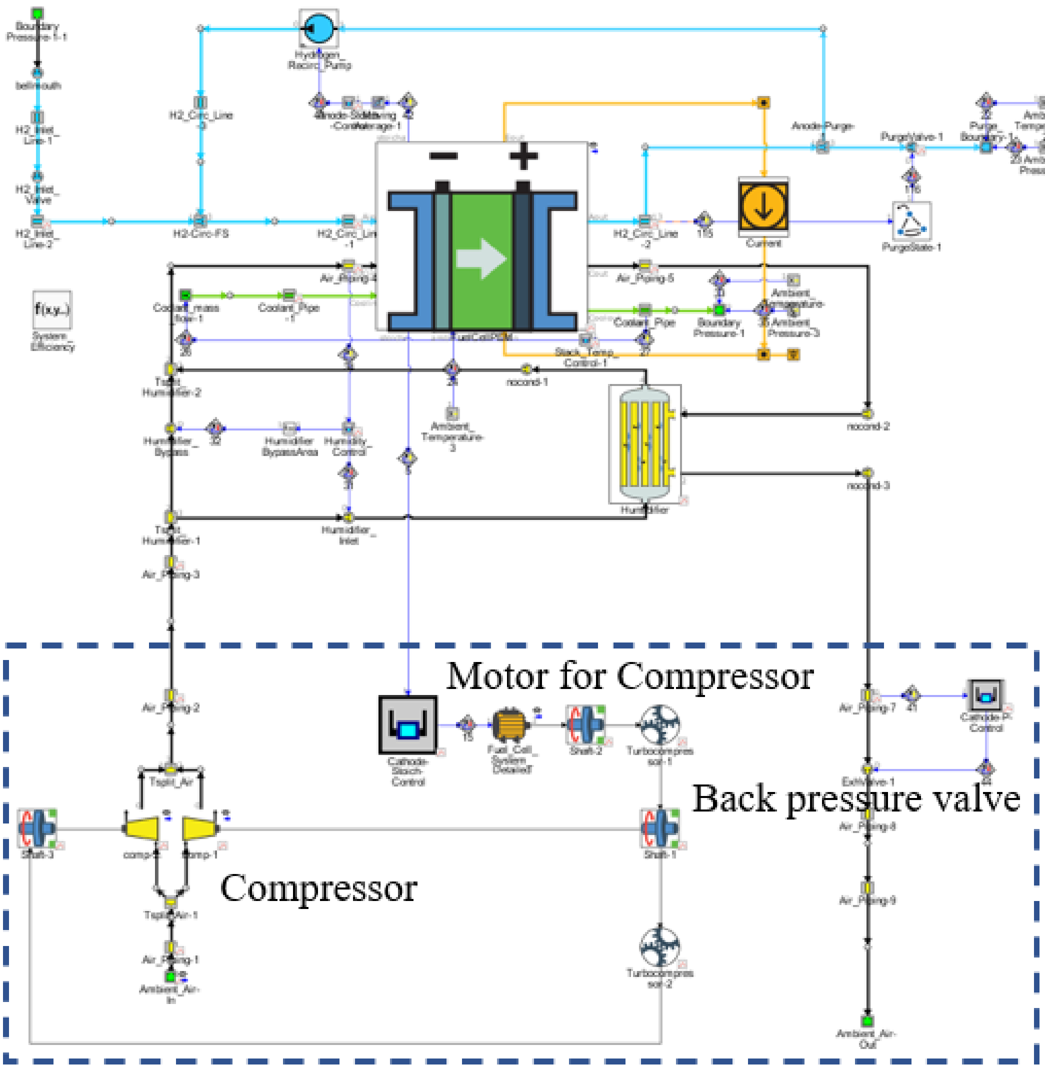


Figure 2.3 Fuel cell aircraft propulsion system model with conventional compressor.

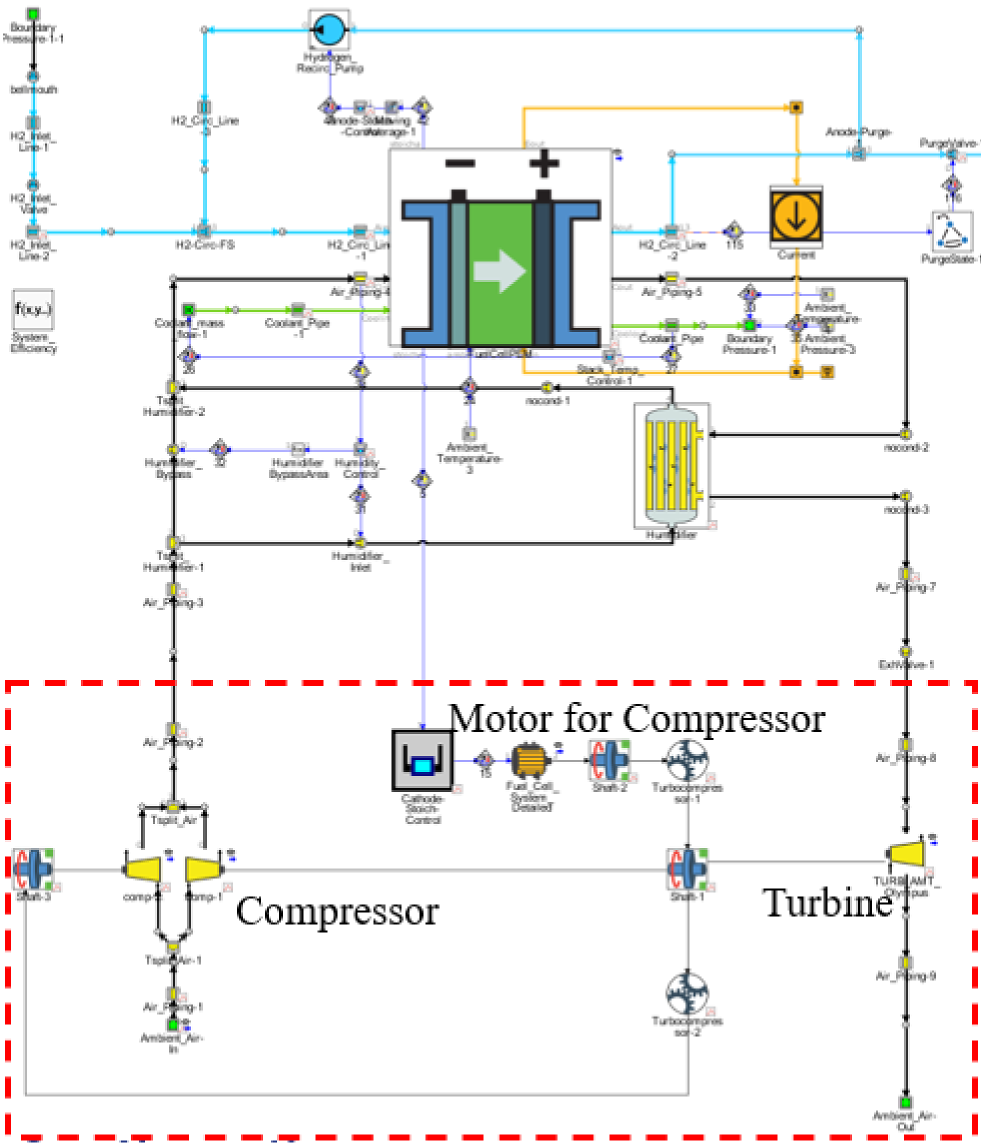


Figure 2.4 Fuel cell aircraft propulsion system model with turbo-compressor.

Figure 2.3 and Figure 2.4 show the fuel cell system models with conventional compressor, and turbo-compressor, respectively, which were designed for analysis. Emphasized as blue and red dash line in Figure 2.3 and Figure 2.4, the difference between conventional compressor system and turbo-compressor system is the existence of turbine and back pressure valve before the air exits the system. For conventional system (Figure 2.3), there is a back pressure valve, which can maintain the pressure inside the fuel cell by controlling the back pressure of the fuel cell outlet. For turbo-compressor system (Figure 2.4), in contrast, there is a turbine instead of back pressure valve. Shaft was used to connect the turbine with compressor to offset the power consumption of compressor by the power generated from turbine.

To design fuel cell stack, reference current density was selected as 1 A/cm^2 [3]. Since the maximum power system had to generate was about 250 kW, 360 A was selected for proper maximum current by considering the practical size of the wire diameter in American wire gauge (AWG) [17]. Under these conditions, active area of fuel cell was calculated as 360 cm^2.

Height and width of flow channel were 1 mm, 1mm for anode and cathode, while 2 mm, 2mm were used for coolant. Materials and thickness of components in fuel cell was used default values of GT-Suite example models. Thickness of membrane was 117 μm, 300 μm for gas diffusion layer (GDL). Porosity and tortuosity of GDL were 0.76, and 1.6 respectively. Average voltage of common fuel cell having 1 A/cm^2 was about 0.6V [3]. Number of stacks was calculated as 1150 to generate 250 kW of power from fuel cell stacks. Using this information, V-I and P-I curve of designed fuel cell stack can be plotted at Figure 2.5.

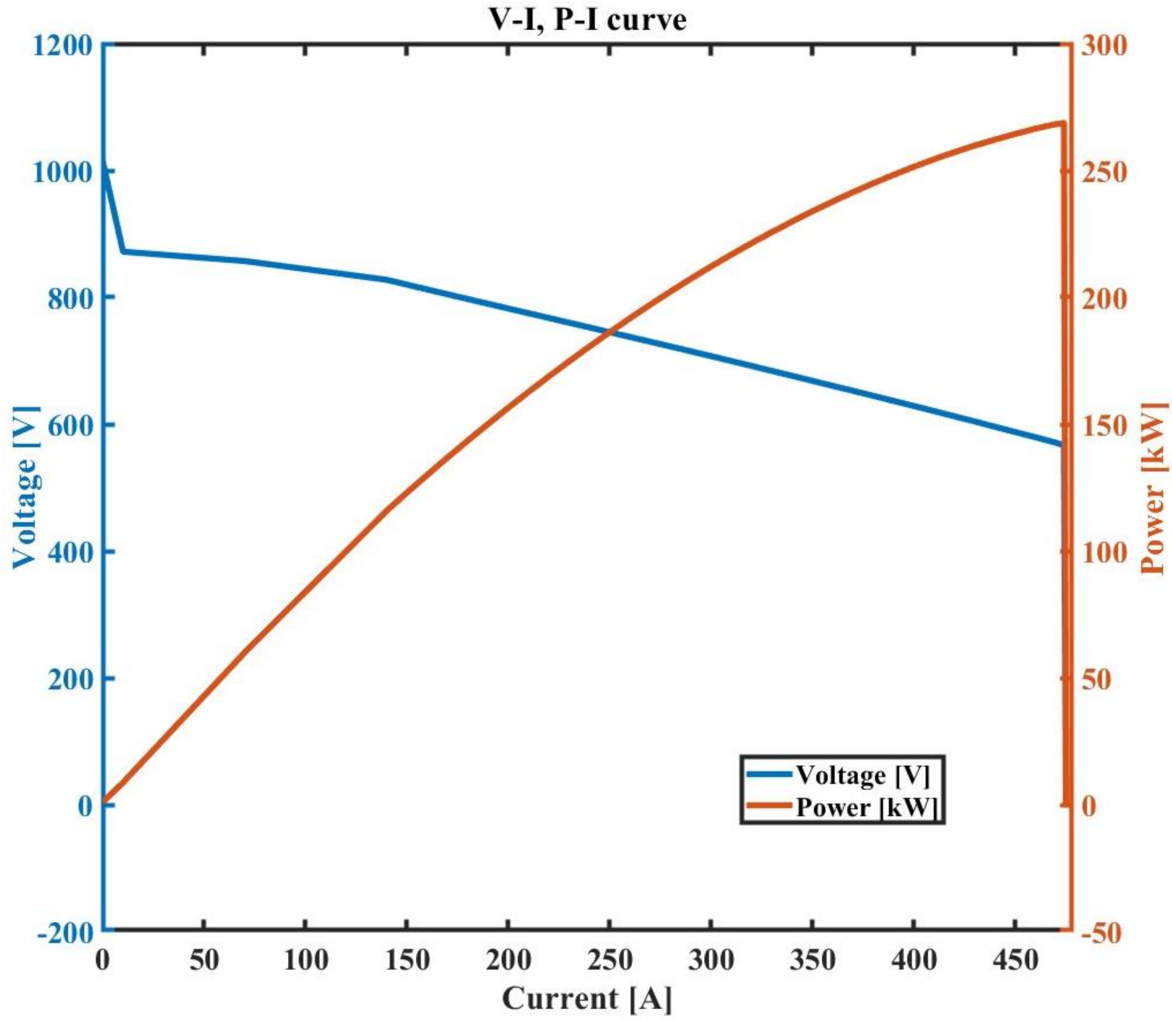


Figure 2.5 P-I, V-I curve of designed fuel cell

Fuel cell system is composed of hydrogen supply line, air supply line, and coolant line. For hydrogen supply line, there is a hydrogen recirculation pump since there can be some hydrogens left after it enters through fuel cell. To control the stoichiometric ratio of anode, PID controller controls the volumetric rate of pump. Some of nitrogen and water may be followed by hydrogen while hydrogen gets out of the fuel cell, so that the fraction of hydrogen for recirculation may be reduced. To maintain the hydrogen fraction, there is a valve for purging when hydrogen fraction goes under 0.3. Inlet conditions of pressure and temperature of hydrogen is 200kPa and 40° C, respectively.

For oxygen supply line, two compressors were used to provide proper pressure with large amount of oxygen, especially for ascend section. Compressor used for simulation is EK40C-2429 from Rotrex [18]. Olympus series turbine produced from AMT Netherlands was used as turbine for turbo-compressor design [19]. For turbo-compressor, there is also a turbine sharing shaft with compressors connected with gears, which referenced from GT-Suite example, and for conventional compressor model, there is a back pressure valve which controls the pressure out of the fuel cell by controlling degree of valve open rate. Since the gears have 1:1 gear ratio, it transfers the power and same rotational speed from turbine. In conventional compressor system, motor is the only source of power to make compressor work, but in turbo-compressor system, turbine also provides the power required by the compressor.

Simple model of motor for compressor in simulation was used, where torque coefficient is 0.014 N-m/A, equivalent resistance is 0.375 ohm. Operation voltage range of motor is 0~400 V. Applied voltage of motor changes with control as stoichiometric ratio of cathode differs.

Proper humidification is an essential condition to generate power in PEMFC, because protons generated from anode passes through membrane with water. Too much water in the fuel cell interferes the chemical reactions of producing electrons, while too little water makes proton difficult to move to cathode, as a result, reducing the performance of the fuel cell. Therefore, with the intention that fuel cell have proper humidity under management, there is a humidifier and humidity controller to make inlet air wet. After inlet air from fuel cell passes through the compressor, water from the fuel cell outlet air transfers water to the compressed fuel cell inlet air by humidifier. It controls inlet air to have 80% relative humidity by opening and closing the valve in front of the humidifier inlet. For humidifier, inner diameter of shell and tube were 350 mm, and 1.5 mm, respectively.

System boundary condition of air depends on altitude, so the temperature and pressure of air outside condition is listed in Table 1.1. Outlet air relative humidity changes from 70% to 40% as altitude increases [20].

For coolant line, EGL5050 which refers 50% water, and 50% ethylene glycol were selected. It is intended to control the stack temperature. It senses the temperature of the coolant from fuel cell outlet and controls the amount of coolant mass flow rate. The stack inlet temperature of coolant fixed as 26.5 ℃.

Lastly, there is the circuit which electrons produced from fuel cell can be used. In practice, it should be joined with inverter to provide power to the propeller motor.

In this study, steady-state, and the highest altitude for each section were considered, because fuel cell is highly vulnerable to low pressure (as it mentioned from chapter 1.3.), so it can be the worst conditions for each section of mission profile. When the pressure inside of fuel cell drops, exchange current density at fuel cell drops (Equation 2.1), which increases the fuel cell activation voltage loss (Equation 2.2).

$$i_0 = i_0^{ref} \, a_c \, L_c \left(\frac{P_{react}}{P_{react}^{ref}}\right)^{\gamma} \exp\left[-\frac{E_{act}}{R\,T}\left(1-\frac{T}{T_{ref}}\right)\right]$$

Equation 2.1 Exchange current density

$$V_{act} = A \, \ln\left(\frac{i}{i_0}\right)$$

Equation 2.2 Activation voltage loss

Here, i_0^{ref}, P_r^{ref}, T_{ref} stand for the reference exchange current density, pressure, and temperature, respectively (‘r’ represents reactants). γ is pressure dependency coefficient, and a_c is the catalyst-specific area. L_c is catalyst loading, which are fixed while designing. $a_c L_c$ is referred as electrode roughness, meaning the surface area of catalyst area $[cm^2]$, and E_{act} is the activation energy [3].

2.3. System efficiency

After modeling, results were compared with system efficiency. Since the fuel cell system inputs are hydrogen, oxygen and outputs are electrical power, the system efficiency was defined as below (Equation 3). Here, $\boldsymbol{P_{fuel}}$ is the enthalpy of total fuel, $\boldsymbol{P_{fuel\,cell}}$ is the power generated from fuel cell, and $\boldsymbol{P_{motor}}$ is the consumed power from motor used by compressor.

$$\boldsymbol{\eta_{system} = \frac{P_{fuel\,cell} - P_{motor}}{P_{fuel}}}$$

Equation 2.3. System efficiency

When fuel cell generates power, some portion of power is consumed from motor connected with compressor. Though there is a recirculation pump in the model, it is considered that the power consumption in the pump can be negligible given that flow rate of hydrogen is small compared to air mass flow rate.

Chapter 3. Results

The system efficiency difference between conventional compressor system and turbo-compressor system had been analyzed using the model described in Chapter 2. To compare the system efficiency between two propulsion system, it was necessary to select a condition where the variables in both models were almost identical. Therefore, before selecting a group of comparison, parametric study of two models had been conducted.

3.1. Parametric study in conventional compressor fuel cell propulsion system

For conventional compressor system, there were two parameters for system, back pressure, and cathode stoichiometric ratio.

3.1.1. Stoichiometric ratio change

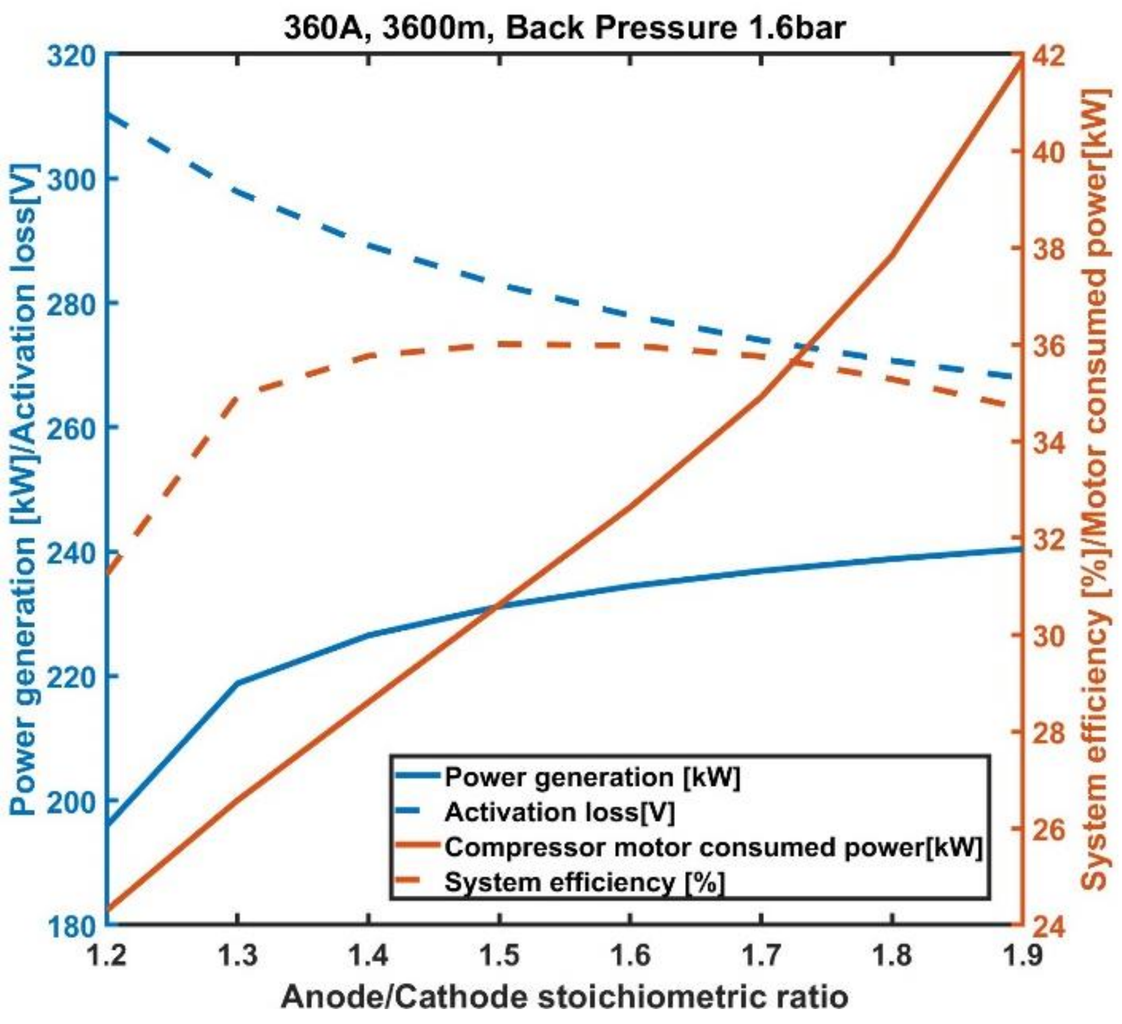


Figure 3.1 System efficiency difference due to stoichiometric ratio change.

$$Air\ usage = \frac{28.97 \times 10^{-3} \times P_e}{0.21 \times 4 \times V_c \times F} \times \lambda_C = 2.37 \times 10^{-7} \times \lambda_C \times \frac{P_e}{V_c}\ kg \cdot s^{-1}$$

$$H_2\ usage = \frac{2.02 \times 10^{-3} \times P_e}{02 \times V_c \times F} \times \lambda_A = 1.05 \times 10^{-8} \times \lambda_A \times \frac{P_e}{V_c}\ kg \cdot s^{-1}$$

Equation 3.1 Air usage and hydrogen usage

$$a = \frac{P_w}{P_{sat}}$$

$$\lambda = 0.043 + 17.81a - 39.85\,a^2 + 36a^3$$

$$\sigma(T_{cell}) = \exp\left[1268\left(\frac{1}{303} - \frac{1}{273 + T_{cell}}\right)\right]\sigma_{30}$$

$$\sigma_{30} = 0.005139\ \lambda - 0.00326 \text{ for } \lambda > 1$$

$$\boldsymbol{V_{ohm}} = \int_0^{t_m} \frac{\boldsymbol{dz}}{\boldsymbol{\sigma(\lambda)}}$$

Equation 3.2 Ohmic loss

Figure 3.1 shows the effect of stoichiometric ratio to system efficiency and fuel cell power generation in conventional fuel cell system. Fuel cell generated power increases when stoichiometric ratio grows. It was because the concentration of oxygen entering the fuel cell increases by increasing mass flow rate, and it induce the pressure of the fuel cell increased. Equation 3.1 represents the amount of air and hydrogen usage related with stoichiometric ratio [21]. Here, P_e is the total power of the fuel cell stack, and V_c is the voltage of cell. F is a faraday number, which is 96,485 C per 1 mole of electrons. λ_C, λ_A are stoichiometric ratio of cathode and anode, respectively. As shown in Equation 2.1, and Equation 2.2, pressure increment results in reducing activation loss and rises the fuel cell performance. Also, as mass flow rate increases, reaction in the fuel cell occurs more active, so the amount of water production increases. It increases water content, water conductivity, therefore decreases ohmic loss. Equation 3.2 is the related equations of ohmic loss. Here, P_w is a partial pressure of water, while P_{sat} is saturated vapor pressure. 'a' is water conductivity, λ is membrane water content, σ is membrane conductivity (σ_{30} represents membrane conductivity at 30 ℃), and V_{ohm} is ohmic loss [22].

Reduction of activation loss and ohmic loss were major reasons of increasing fuel cell performance. However, the motor consumed power for compressor increases as the stoichiometric ratio increases. Thus, the system efficiency of fuel cell propulsion decreases as the stoichiometric ratio increases.

3.1.2. Back pressure change

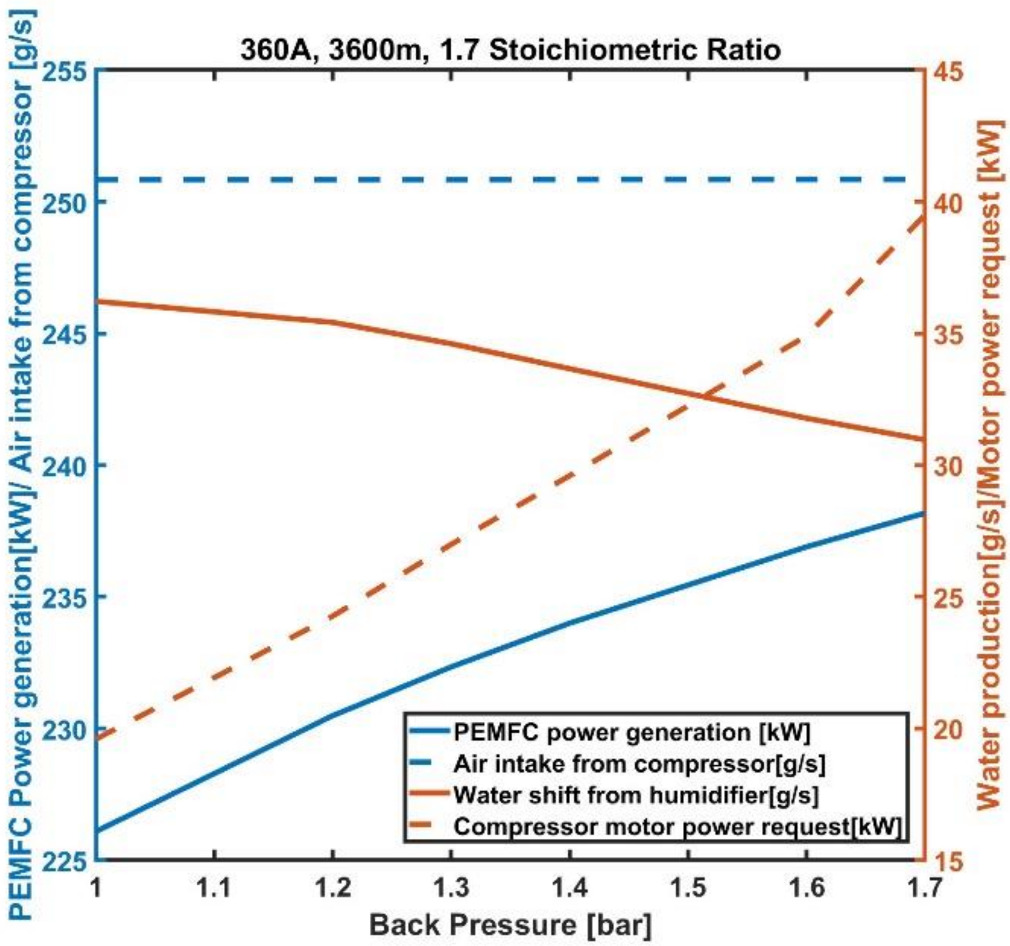


Figure 3.2 Fuel cell power generation information and water transfer rate in conventional compressor system at constant stoichiometric ratio

Figure 3.2 shows the performance of fuel cell with back pressure change. Since the stoichiometric ratio is fixed, air intake from compressor is constant. When back pressure increases, pressure at the inlet of fuel cell should be high to overcome the pressure loss occurred inside of the fuel cell flow channel. It induces the same effect with increasing stoichiometric ratio, that is, it makes the compressor to do more compression. Finally, it increases the fuel cell performance, but decrease the system efficiency because compressor requirement power increases (Figure 3.3).

Amount of air shift from humidifier reduces as the back pressure increases, because as the temperature and pressure of the air after the compressor increases while the mass flow rate of air does not change, which reduce the amount of gas saturation. It made inlet air maintain 80% of humidity with comparatively small amount of water.

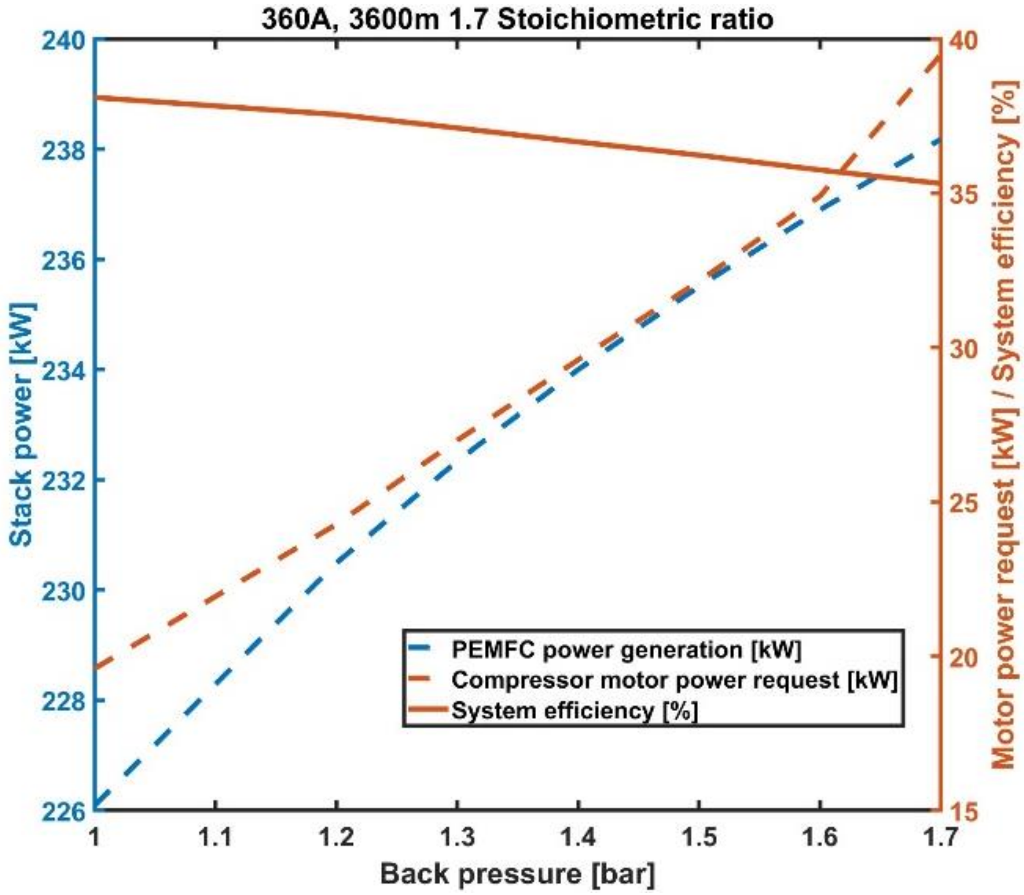


Figure 3.3 Compressor motor power consumption and system efficiency at constant stoichiometric ratio

3.2. Parametric study in turbo-compressor fuel cell propulsion system

While there were two parameters for conventional compressor system, only cathode stoichiometric ratio acts as a parameter in turbo-compressor system.

3.2.1. Stoichiometric ratio change

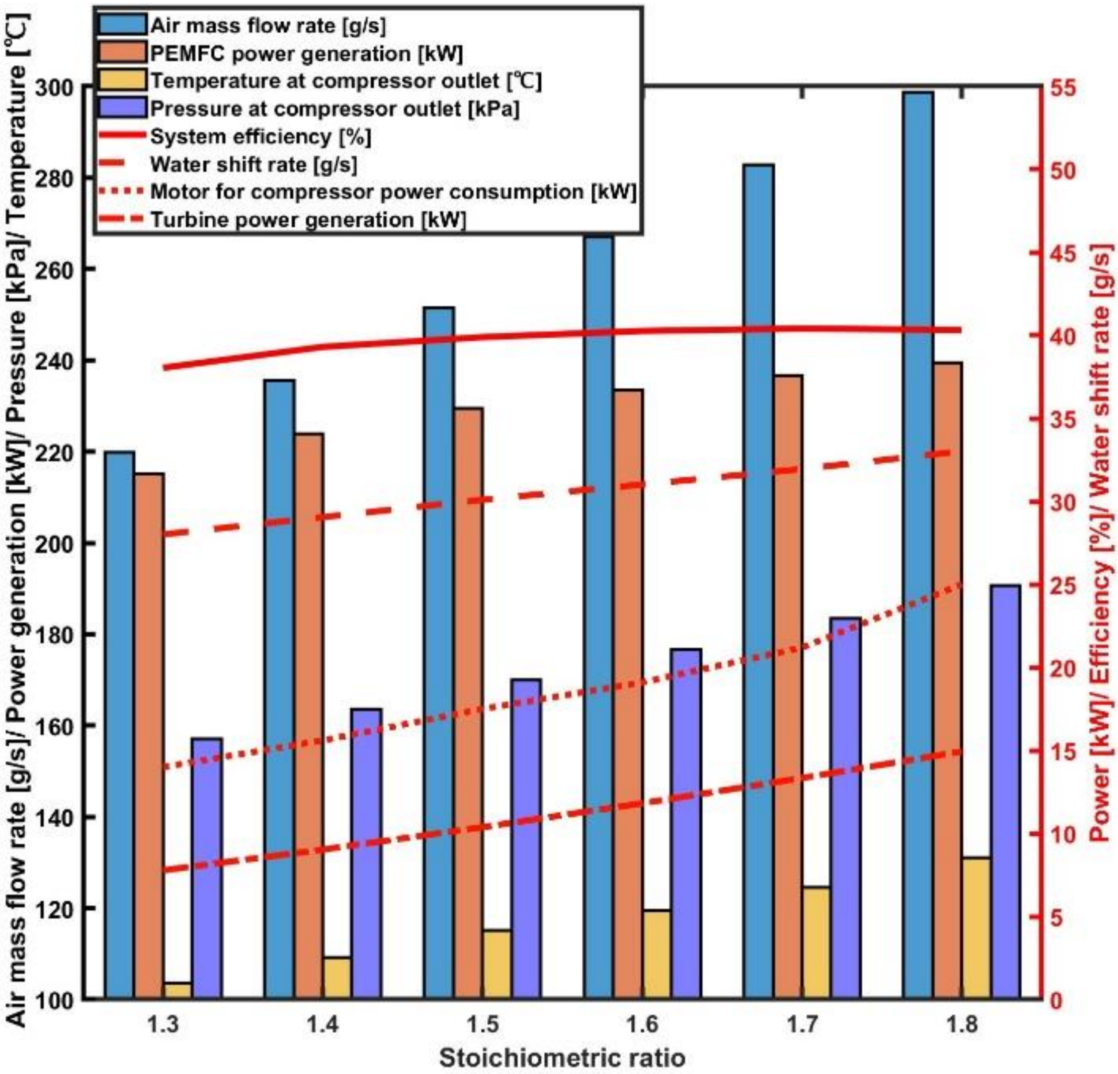


Figure 3.4 System information at turbo-compressor system at ascend condition with stoichiometric ration sweep

Figure 3.4 shows information about turbo-compressor components at ascend condition. Performance of fuel cell increases when stoichiometric ratio grows because the temperature and pressure of air increases (Equation 2.1, Equation 2.2). As stoichiometric ratio increases, motor for compressor consumes more power than low stoichiometric ratio, since compressor should pressurize air more than lower stoichiometric ratio to make air overcome the pressure losses occurring at the fuel cell and pipes. Rate of water shift from humidifier increases when stoichiometric becomes large, because air entering the compressor dries as altitude increases. Furthermore, after the air pass through the compressor, the temperature of air is high, part of air throws the heat to the outlet air at humidifier while gets the water from the outlet air. Accordingly, state of air from fuel cell inlet becomes low temperature with high humidity compared to compressor outlet, while temperature at fuel cell outlet air has low humidity, high temperature and pressure state that can be utilized at turbine.

3.3. System efficiency comparison at ascend section

System comparison group was selected corresponding to maximum system efficiency condition of turbo-compressor system. Stoichiometric ratio at the anode was controlled same with cathode, to supply enough fuel for react.

Comparison condition for ascend section were 160 kPa back pressure and 1.7 stoichiometric ratio. These conditions were selected by figuring out the highest system efficiency value, stoichiometric ratio, and the pressure before the turbine, since the number of parameters in turbo-compressor fuel cell system is smaller than conventional compressor system. After that, conventional compressor system model had been adjusted with same back pressure using the back pressure valve and stoichiometric ratio controller matched with the maximum turbo-compressor system conditions. The comparison results for ascend section are summarized as below (Table 3.1).

Table 3.1 System efficiency comparison at ascend section

	Conventional compressor	Turbo-compressor
Stack power [kW]	236.9	236.6
Stack efficiency [%]	58.2	58.2
Coolant mass flow rate [kg/s]	2.5	2.4
Compressor efficiency [%]	68.6	68.8
Motor power [kW]	34.9	21.2
System efficiency [%]	35.8	40.4

In the ascend condition, the system efficiency improvement was the greatest compared to the other sections, because the power output was greater than other sections, resulting the largest inlet air mass flow rate into the fuel cell (282.3 g/s). Consequently, it increases the pressure just before the turbine and made the turbine to generate the most power (Table 2).

The power produced by the fuel cell is almost identical between two models, but the system efficiency of turbo-compressor system increased due to reduction of the power consumed by the motor for the compressor.

3.4. System efficiency comparison for total mission profile

Same process of ascend system comparison was conducted at total mission profile sections.

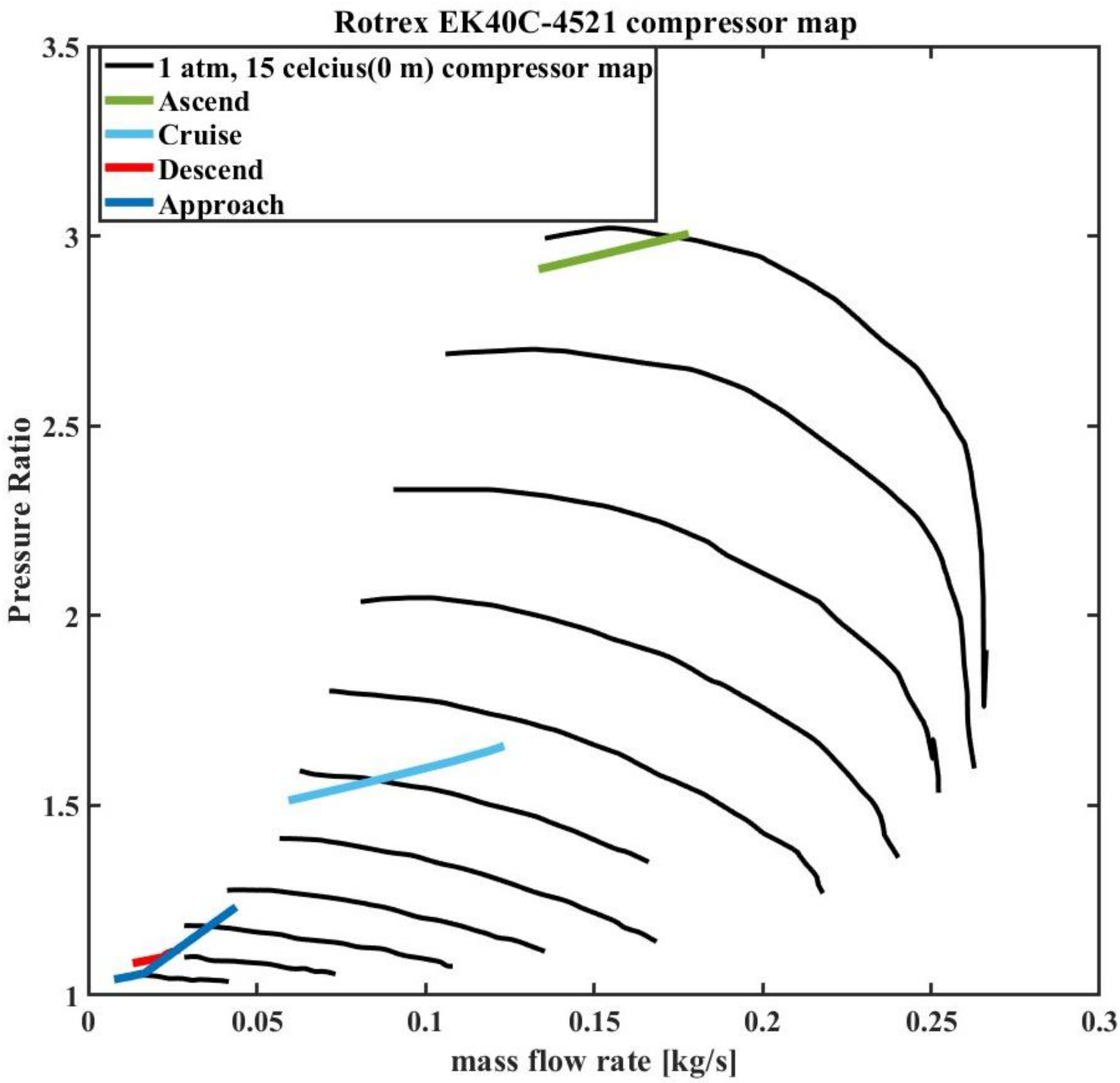


Figure 3.5 Operation range of compressor in each section of mission profile

From Figure 2.3 and Figure 2.4, two compressor had been used to overcome the huge amount of air compressing in ascend section. And Figure 3.5 is the total operating range of Rotrex EK40C-2429 compressor during mission profile propulsion. As it shown, descend and approach range were almost near the surge line and choke line, respectively. Also, operation range at ascend section was near the rpm limit, that is, compressor can act as fuel cell power limiting condition with air supply limitation. These represents that the compressor operation range should be wide to make fuel cell generate propulsion from 19 kW to 250 kW.

Surge line refers the maximum amount of pressure that compressor can produce while flowing at least amount of air, while choke line is the maximum amount of air that the compressor can flow at a given ratio. Also, mass flow that would pass through a compressor corresponded to reference temperature and pressure, and normally compressor map was represented from 15 ℃, 1 atm, which is called 'corrected mass flow rate'. If the operating condition differs, pressure and temperature affect to density, so the operation range of mass flow changes. Figure 3.6 shows that the operation range of compressor decreases as the altitude increases. It induces ascend and descend sections operate at critical condition of compressor.

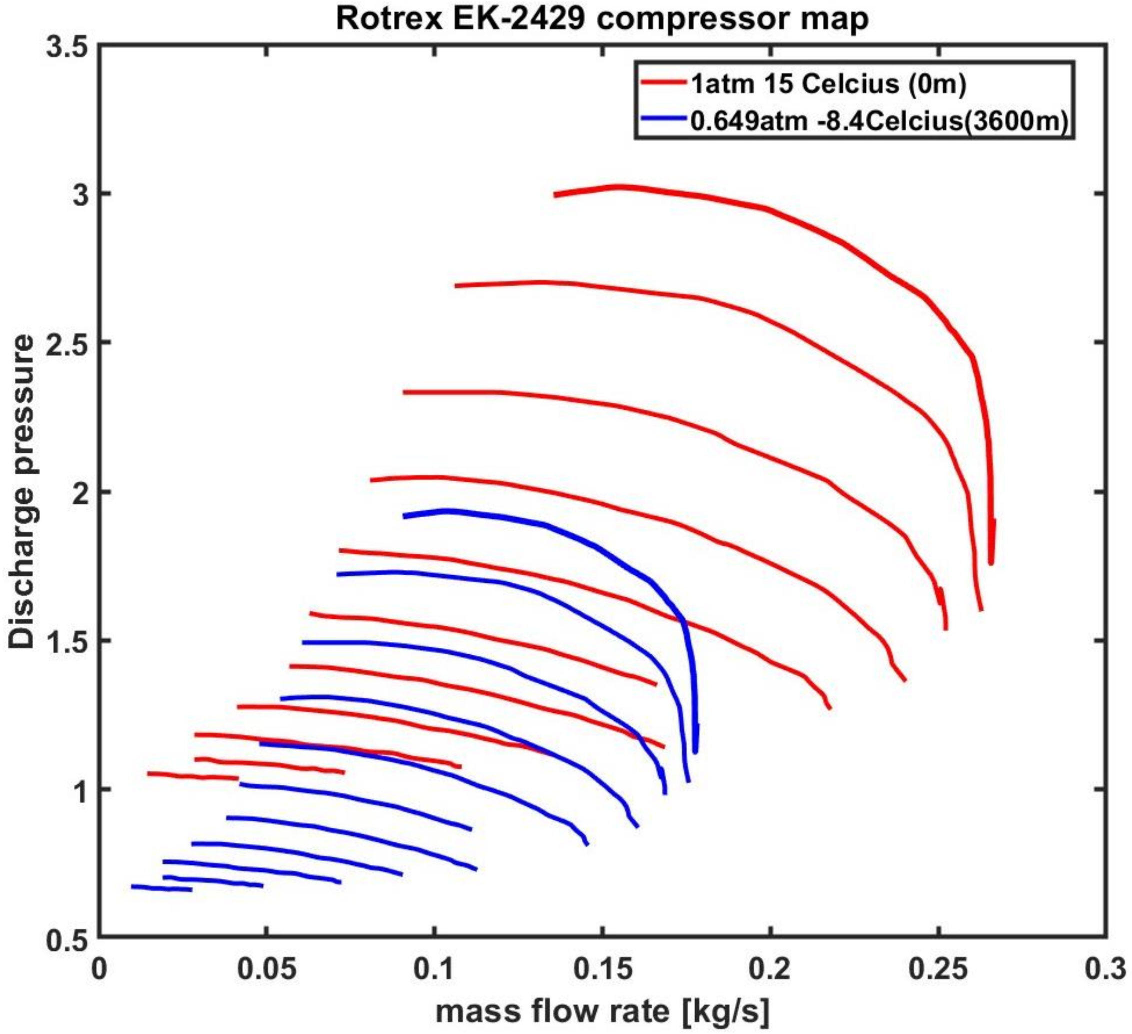


Figure 3.6 Operation range transition of compressor map with altitude

The pressure ratio at the compressor is set to compensate for the pressure drop starting from compressor, through the fuel cell, humidifier, and pressure in front of the back pressure valve.

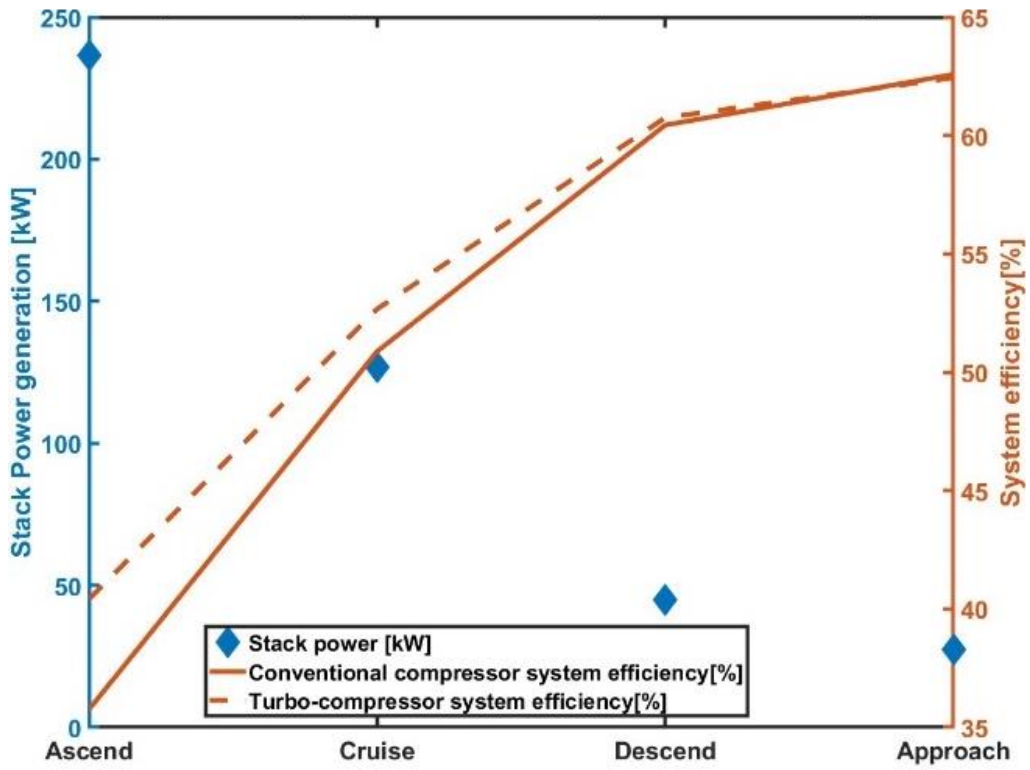


Figure 3.7 Motor power consumption during mission profile section in conventional compressor and turbo-compressor systems

Table 3.2 Stoichiometric ratio and back pressure conditions for comparison in each section in mission profile

Ascend		**Cruise**	
Stoichiometric ratio	Back pressure [bar]	Stoichiometric ratio	Back pressure [bar]
1.7	1.6	2.1	0.9
Descend		**Approach**	
Stoichiometric ratio	Back pressure [bar]	Stoichiometric ratio	Back pressure [bar]
2.5	1	2.5	0.97

Table 3.2 shows the comparison conditions for each section. For each section, best turbo-compressor system efficiency was achieved by making a trade-off between air mass flow rate, motor power consumption, stack power generation, and back pressure due to stoichiometric ratio change, as explained in chapter 3.1. and chapter 3.2.

Figure 3.7 shows the system efficiency comparison for the whole sections of mission profile. About 5% at ascend and 3% at cruise system efficiency improvement occurred by using turbo-compressor, while similar system efficiencies have been resulted at descend and approach sections. Since the power required for aircraft propulsion had been low compared to other two sections, mass flow rate of air was not enough for turbine to generate power.

Chapter 4. Discussion & Conclusion

Aim of this study was to figure out the applicable sections of turbo-compressor in mission profile which represents UAM mission profile. It was expected that the result of this study can reinforce the feasibility of using turbo-compression system for aircraft propulsion system, especially for UAM. To compare the system efficiency, two models of fuel cell system for aircraft propulsion had been designed, one had conventional compressor, and another had turbo-compressor. From simulation results, turbo-compressor was feasible in ascend and cruise section while use of turbo-compressor was valueless in descend, approach section.

As shown in Figure 2.2, the use of a turbo-compressor is considered effective in enhancing overall system performance because the ascend and cruise section take up most of the energies in total mission profile.

The performance of the fuel cell system may change since the output power of the fuel cell depends on the operating temperature, humidification performance, and the operating range of the various components. For this reason, it is likely that there will be a control method to achieve the highest efficiency during specific mission profile for each aircraft. Future study of the turbo-compressor system efficiency should be conducted in the operation strategy to achieve better system efficiency for each section.

Total weight of turbine and motor used in this model was about 35 kg. It could be a disadvantage point to aircraft propulsion, however, increasing system efficiency refers that aircraft can propel identically with less fuel. While 91.6 kg of hydrogen tank is needed to store 5 kg of hydrogen [23], the amount and volume of tank to store hydrogen can be reduced by improving system efficiency.

By using turbo-compressor, we expect that there can be an optimized amount of fuel for use in aircraft propulsion and results in weight reduction when the aircraft takes off. In conclusion, by increasing system efficiency, using turbo-compressor in fuel cell aircraft propulsion system seems feasible.

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초록

고분자 전해질 막 연료전지 항공기 추진시스템에서의 터보 컴프레서 이용 적합성 연구

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배유정

환경오염의 문제성과 화석연료 고갈의 우려가 증가함에 따라, 산업 분야에서 친환경 동력을 쓰고자 하는 노력이 커지고 있다. 이로 인해, 항공기 분야에서도 친환경 동력 연구가 많이 진행되고 있고, 친환경 동력을 이용하는 방법으로는 수소와 전기를 이용하는 기술이 각광받고 있다.

연료전지는 수소와 산소를 이용하여 전기를 생산해내는 에너지 변환 장치로, 항공기 분야에서는 중요시되고 있다. 고도 변화에 따른 대기압의 변화가 연료전지 스택 운전에 미치는 악영향을 최소화하기 위해 압축기를 통한 가압 운전을 수행함에 있어서, 압축기 운행에 필요한 BOP 전력 소모를 줄이는 데 터빈에서 발생된 축 동력을 활용함으로써 기존 시스템 대비 전반적으로 효율을 높일 수 있다.

해당 논문에서는 고분자 전해질 막 연료전지 시스템을 도심형 항공기 (UAM) 추진 시스템으로 이용한다. GT-Suite 를 이용하여 연료전지 추진 시스템

내의 기존 압축기 시스템 모델과 터보 컴프레서 시스템 모델 구성을 소개한다. 그 다음으로, 두 시스템의 공기라인에서 나타나는 변수인 과급률과 후단압력 밸브의 시스템 효율 영향을 분석해본다. 시스템 모델 분석을 통해 특정 UAM 비행 프로필에서 터보 컴프레서 설계의 적용 가능성을 설명한 뒤, 이를 이용하여 UAM 비행 프로파일 중, 터보 컴프레서가 유용할 수 있는 운전 영역을 제시함으로써 실제 적용에서 고려해야 할 측면에 대해 논의한다.

주요어: 항공기 추진 시스템, 터보 컴프레서, 고분자 전해질 막 연료전지,
시스템 효율, 압축기, 터빈

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