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ANALYSIS OF SAFE OPERATION ZONE FOR A TURBINE-LESS AND SOLID OXIDE FUEL CELL HYBRID ELECTRIC JET ENGINE ON UNMANNED AERIAL VEHICLES

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ABSTRACT

Hybrid electric aircraft are developed to reduce emission and save energy. However, the thermal efficiency of turbo-electric aircraft and the endurance of battery-electric aircraft are both limited, respectively. Aircraft powered by fuel cells can achieve long endurance, low emission, and fuel consumption reduction. Solid oxide fuel cell hybrid electric jet engines without turbines for unmanned aerial vehicles was proposed in our previous work in which compressors are powered by fuel cells instead of the turbines. The hybrid electric jet engine combining the merits of a turbo-electric engine and a fuel cell powered engine. To avoid component malfunctions and engine performance deterioration, determination of safe operation zone is necessary.

In this study, the performance analysis model of the hybrid electric jet engine is built and the main conclusions are as follows. The off-design performance of the hybrid electric jet engine is achieved by adjusting the mass flow of fuel injected into the reformer. The safe operating zone of the hybrid engine is not restricted by turbine inlet temperature. Under low fuel flow and low air flow, too low reforming temperature zones or too low SOFC open voltage zones exist. Additionally, the unbalanced energy zone exists under high fuel flow and low air flow. The power produced by the SOFC is over the one consumed by the compressor. In the safe zone, the hybrid engine has a characteristic of high specific thrust (837.6 $N/kg.s^{-1}$) and high thermal efficiency (70.43%) with high rotational speed, vice versa.

Keywords: safe operation zone, solid oxide fuel cell, turbine-less jet engine, unmanned aerial vehicles, hybrid electric;

NONMENCLATURE

Abbreviations	
SOFC	solid oxide fuel cell

1. INTRODUCTION

Conventional gas turbine architectures are approaching an area of diminishing returns with respect to the level of effort required to achieve further gains in fuel burn, noise, and emission reduction [1]. In recent years, the aerospace industry has seen the emergence of aircraft electrification [2]. There are multiples reasons that electric aircraft can result in air transportation. The reduction of fuel consumption, emission and noise can be achieved by the electric aircraft.

1.1 Electric aircraft overview

Electric aircraft are mainly based on batteries, turbogenerators and fuel cells. Aircraft based on batteries have disadvantages in endurance. The weight of a battery continuously increases with the increase of endurance. Schäfer [3] et al. indicated that progress in battery technology, especially specific energy, would enable the scaling up of battery-aircraft designs to larger vehicles within the range of 1111km, first to regional jets and then to narrow-body aircraft. However, Sliwinski [4] et al. revealed that a turbo-electric aircraft is promising in aerospace engineering since it combines the advantage of internal combustion systems and electric propulsion systems although limiting the environmental emission. Xie [5] et al. showed that the retrofitted turbo-electric aircraft have better cruising and climbing performance and the maximum fuel reduction reaches 17.6% compared with prototype aircraft.

But fuel cell aircraft combine the advantages of turbo-electric aircraft and batteries-aircraft. The thermal efficiency of the fuel-cell aircraft is further higher than that of the turbo-electric aircraft. The emission of the fuel-cell aircraft is considerably low. Papathakis [6] et al. integrated the concept for fuel cell power system into the X-57 "Maxwell" light commuter aircraft. Defense Advanced Research Projects Agency (DARPA) [7] designed and tested the world first UAV powered by Solid oxide fuel cells (SOFCs). The endurance of the UAV is obviously higher than the one powered by batteries. Boeing [8] has successfully designed and tested the word first manned airplane powered by fuel cells. The advantages of aircraft based on fuel cells in emission and thermal efficiency enable it to become an important develop orientation for the future.

1.2 SOFC gas turbine hybrid systems overview

SOFC gas turbine hybrid systems have been widely studied for distributed power plants [9, 10]. SOFC gas turbine hybrid system also be applied to mobile vehicles, such as aircraft, ships, locomotives and so on [11]. Unmanned aerial vehicles with long-range are sensitive to efficiency and are not sensitive to power weight ratios. The hybrid system is suitable for high altitude long endurance unmanned aerial vehicles because its thermal efficiency is very high [12, 13]. There is a huge need for clean electric energy in the distributed airplanes. The hybrid system can also achieve this. But a compromise between thermal efficiency and weight must be made [14, 15]. Borer [16] et al. and Stoia [17] et al. investigated hybrid systems for primary propulsive power on light commuter aircraft X-57 "Maxwell" to reduce emission and specific fuel consumption. Water [18] et al. and Ji [19] et al. analyzed the performance of gas turbine engines combined with bypass SOFCs. In addition, Martinez [20] et al. showed that a natural-powered SOFC gas turbine locomotive is more competitive than a diesel-powered SOFC gas turbine locomotive in the respect of thermal efficiency. Ahn [21] et al. assessed the performance and availability of a marine generator-SOFC-gas turbine hybrid system in a very large ethane carrier.

In a nutshell, most hybrid systems for distributed generation is compared with the ones for mobile vehicles, the thermodynamics principle of which is similar. However, the hybrid system for aircraft in the literature [22] is quite different from the systems described above. For the system, compressors are powered by SOFCs instead of turbines [22]. There are no turbines in the system. The function of the system is outputting propulsion power rather than electric energy. The hybrid system is specialized for aircraft.

1.3 Safe operation region overview

Hybrid systems considering safety limitation has been studied by some researchers [23]. The safety zone of SOFC gas turbine hybrid systems is restricted by the constraints of compressor surge, too high turbine inlet temperature or SOFC working temperature and ejector malfunction, etc. Lv [24] et al determined the safe operating area of the hybrid system in a wide range of operating conditions. It is spanned by the dimensionless reduced air mass flow rate and the relative fuel flow rate. Stiller [25] showed the steady-state operation of the hybrid system, which is enclosed by the safety limitation including voltage too low, turbine speed to high and ejector malfunction, etc. In addition, stiller [26] et al. proposed the method for safe operating of a SOFC gas turbine in case of load variation and off-design operation. Sharifzadeh [27] et al. presented trade-off research between the safe operation and energy efficiency by multi-objective design in the triple combined-cycle power generation systems.

All aforementioned studies on the safety operation zone of hybrid systems are based on SOFC gas turbine hybrid systems for electric generation. However, there are big differences between SOFC gas turbine hybrid systems [9, 10] and SOFC hybrid electric jet engines [22] in respect of scheme and principle. The constraint of turbine inlet turbine of the engine disappears. It would thus be of interest to learn how to determine the safe operating zone of the engine.

1.4 Primary objectives and novelties of this paper may be summarized as:

To show differences and characteristic among three type SOFC systems integrated with gas turbines for aircraft.

To demonstrate parameter matching relationships in the SOFC hybrid electric jet engine.

To build the performance analysis model by integrating T-MATS gas turbine toolbox with customized SOFC power system model in MATLAB/Simulink.

To determine the safe operating zone of SOFC hybrid electric jet engines under all operating conditions.

2 THERMODYNAMIC SYSTEM DESCRIPTION

Figure 1 shows the layout of the turbine-less and solid oxide fuel cell hybrid electric jet engine (SOFC hybrid electric jet engine). Compressors are powered by

SOFC power systems instead of turbines. Balance of Plants supply working fluids for SOFCs.

Figure 2 illustrates the detailed schematic diagram of SOFC hybrid electric jet engines. Air from ambient is compressed by intakes and compressors in turn. Then, it is divided into two parts. Some are provided for reformers, and others are provided for the cathode. Fuel is mixed with recirculating anode exhaust. After that, the mixtures are compressed and enters the reformer. Reformate can be utilized by SOFCs. Next, SOFC cathode exhaust, part anode exhaust and some fresh fuel enter combustor. Combustor exhaust preheats the air entering SOFC cathode. Finally, it expands and output propulsion power by the nozzle.

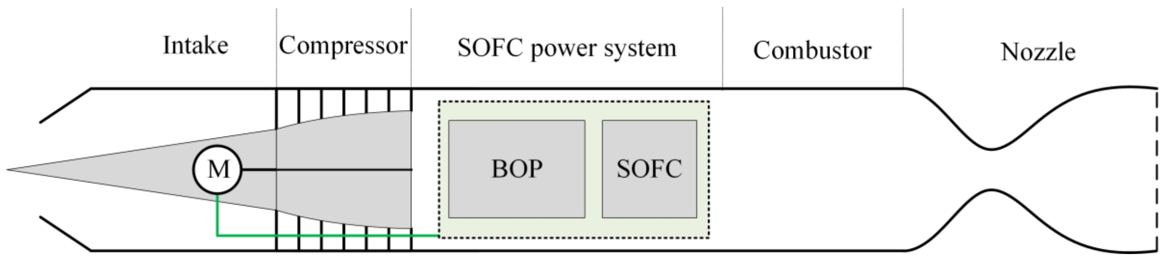

Fig 1 Schematic diagram of the SOFC hybrid electric jet engine

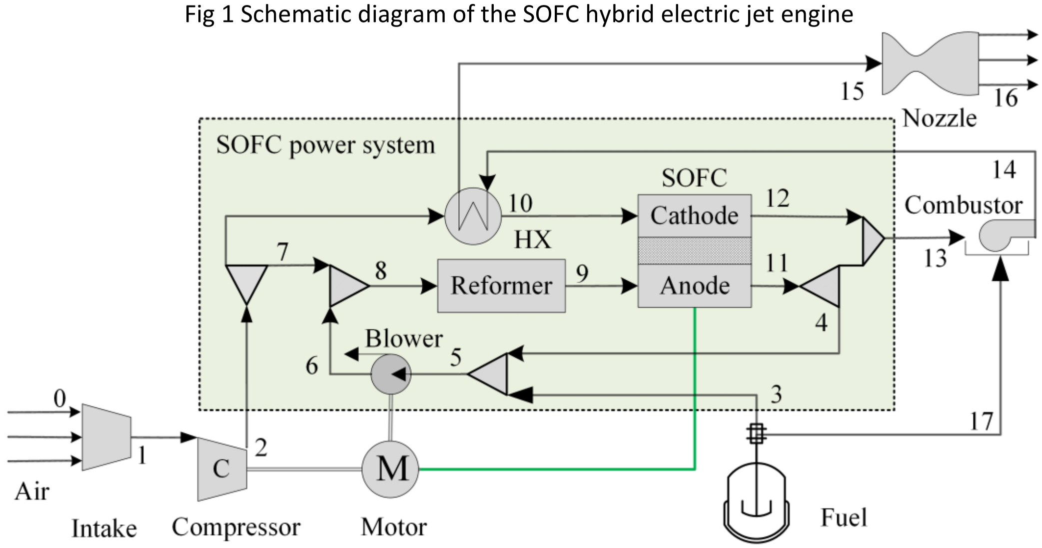

Fig 2 Process flow of the SOFC hybrid electric jet engine

In brief, the layout of SOFC hybrid electric jet engines is different from the layout of previous systems consisting of SOFCs and gas turbines to a large degree. From the view of the propulsion system, SOFC hybrid electric jet engines are promising. The compressor power and propulsion power can be adjusted in a wide range. Performance of the engine is further better than that of turbojet engines because temperature ratios and pressure ratios are both remarkably improved. In addition, fuel cell power is equal to the compressor power rather than propulsion power. The power-weight ratio of the engine is high.

3 MATHEMATICAL MODELING

In general, the SOFC hybrid electric jet engine mode is based on the Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS) in MATLAB. Reformer and SOFC models are built and integrated into this toolbox. The steady performance of the hybrid electric jet engine is solved by Iterative Newton Raphson Solver with Jacobian Calculator in the toolbox.

Jet engine component models including ambient, an inlet, a compressor, a burner, a turbine, a nozzle, and a shaft model are from the Toolbox for the Modeling and analysis of Thermodynamic Systems (T-MATS), which utilizes MATLAB/Simulink. Free and open source thermodynamic components T-MATS packages enable the easy creation of complex systems containing everything required for the generation of gas turbine models [28]. Validation of this tool in an engine model application was performed.

The compact and highly efficient auto-thermal reforming reaction occurs in the reformer. The required oxygen is supplied from compressors. The required steam is supplied from anode recirculation exhaust. The reforming reaction is assumed as an equilibrium state. The equilibrium parameters are solved with the open source software Cantera.

This work uses the model of anode-supported SOFC model developed by Chan [29]. We have previously studied the detailed mathematical model of SOFC fitted into a hybrid system [19]. A fuel cell with direct internal reforming has been used, where the reforming heat is provided by the electrochemical reaction heat. SOFC polarization models are considered, which include concentration, activation, and ohmic polarizations.

The safe zone of the SOFC hybrid electric jet engine is restricted by some constraints, such as compressor surge and choke, reformer and SOFC carbon deposition, SOFC operating temperature, which is shown in Table 1. The constraint of turbine inlet temperature doesn't exist, because there are no turbines in the engine.

Table 1 hybrid electric jet engine operation constraint

Reformer working temperature	850K<T<950K
SOFC working temperature	973K<T<1073K
Compressor surge margin	>12%
SOFC open voltage	0.65V<V0.85V
Boundary value of the RS/C	>2

4 RESULTS AND DISCUSSION

4.1 Performance analysis of SOFC hybrid electric jet engine at design condition

The values at each node and operation performance under the design condition are obtained by using the above established SOFC hybrid electric jet engine mathematic model in Section 3, as shown in Table 2.

The reformer outlet temperature is 911.82K with H_2 yield and energy efficiency of 1.14 and 99%, respectively in Table 2. The temperature of the gas mixture entering the reformer is 907.39K. There is a small temperature difference between the reformer inlet and outlet, which means that the reforming reaction is similar to the autothermal reforming. In this case, C_3H_8 is not completely converted into CO and H_2, with residual amounts of 7.14% CH_4. The working temperature of SOFC is 1054K, meeting the safety constraints. The open-circuit voltage is 0.83V and the electric efficiency is 52.77%. To preheat the air entering SOFC cathode, some fresh fuel is added to the combustor. It is mixed with the SOFC exhaust. The ratio of the amount of the fuel added to the combustor and the one added to the reformer is 13/11.

The combustor exit temperature is 1227.59K. The nozzle inlet temperature of the hybrid electric jet engine is far lower that that of the traditional jet engine. It makes sense that the huge nozzle pressure ratio of 31.8 will obviously reduce the temperature of nozzle exit (node 15) of 440.36K. Therefore, the infrared radiation from the nozzle will be reduced, which is beneficial to stealth aircraft. Table 2 shows that the thermal efficiency is 69.17%, which is remarkably higher than that of traditional combustion engines. The overall efficiency is 27.69%. The specific thrust and specific impulse are 826.45 N/(kg.s^{-1}) and 4876.63 s, respectively.

Table 2 Performance parameters of the engine

Components	Parameters	Unit	Value
Compressor	Pressure ratio	/	20.00
	Efficiency	%	85.20
	Mass flow	kg/s	21.26
	Stall margin	%	17.96
Reformer	H_2 yield	/	1.14
	Energy efficiency	%	0.99
SOFC	Actual voltage	V	0.83
	Electric efficiency	%	52.77
Hybrid engine	Specific thrust	N/(kg.s^{-1})	826
	Specific impulse	s	4876
	Overall efficiency	%	27.69
	Thermal efficiency	%	69.17
	Propulsion efficiency	%	40.03

4..2 Safe zone determination of SOFC hybrid electric jet engine in all operations

In this study, the SOFC hybrid electric jet engine operates at Mach 0.9 with an altitude of 10 km. The relative air flow and relative fuel flow are used to represent the operational range for the SOFCs, reformers, and compressors. Figure 3 shows the component safe and unsafe zones.

The red zone on the upper left (low air flow rate and high fuel flow) represents a regime where SOFC power too high or SOFC working temperature too high state exists. The fuel is injected into the hybrid engine from two positions, which are the reformer and the combustor. If the amount of fuel injected into the combustor is too high, the cathode inlet temperature will increase. Therefore, the SOFC working temperature will be too high. If the amount of fuel injected into the reformer is too high. The hybrid engine unbalanced energy state produces. The power produced by SOFCs is over the power consumed by the compressor. Another compressor choke zone is caused by too much air flow, which is depicted in gray.

The purple zone represents that reforming temperature is too high in the reformer. This is because lower fuel flow causes reformer oxygen/carbon ratios to increases. The increase of oxygen/carbon ratios means that the reforming temperature increases in an adiabatic reformer. The blue zone represents that SOFC open voltage is too low. This is because the lower SOFC working temperature leads to an increase of ohmic polarization. Therefore, the open voltage decreases.

The safe operation zone of the hybrid engine in all operations is shown in Figure 3. In the safe zone, specific thrust change can be achieved by combining air flow and fuel flow. An important result is that the hybrid engine has an operating characteristic of high efficiency and high specific thrust in high air flow zone, vice versa. With increasing relative air flow and fuel flow, the minimum specific thrust of the hybrid engine decreases for 432.5N/kg.s^{-1} with a relative air flow rate of 0.12 and relative fuel rate of 0.35 to 837.6 N/kg.s^{-1} with a relative air flow of 1.04 and relative fuel flow of 1.10. The efficiency increases from a minimum of 14.6% to a maximum of 70.43%.

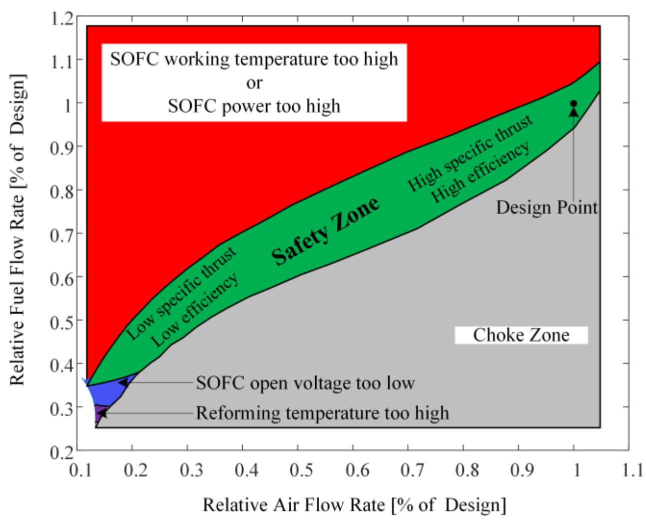

Fig 3 Map of safe operation region for the hybrid electric jet engine in all operation

5 CONCLUSION

At present, there are three types of combination systems consisting of SOFCs and gas turbines (jet engines). In this paper, a turbine-less and SOFC hybrid electric jet engine are studied. To determinate the safe operation zone of the hybrid engine, the thermodynamic analysis model is built, which is based on the combination of the open source gas turbine toolbox in Matlab and customized SOFC and reformer models. Through simulations, the following key points are observed.

1) It is key to match fuel cell power and compressor power for the hybrid engine. The low oxygen/steam ratio (1/30~1/6) for the reformer is suitable to adjust H2 yield. The compressor power under the off-design condition can be satisfied by varying H_2 yield.

2) The thermal efficiency, specific impulse and specific thrust of the hybrid engine under the designed condition are 69.17%, 4876.63s and 826.45 N/kg.s^{-1}, respectively. The nozzle outlet temperature is low to 440.36K.

3) The mapping relationship between the air flow and the fuel flow will be not injective if the fuel flow is equal to the one injected into the hybrid engine. The fuel flow hardly changes. Therefore, the amount of fuel flow is equal to the one injected into the reformer instead of the one injected into the hybrid engine under all of performance diagrams. The performance parameters of the hybrid engine such as specific thrust and thermal efficiency increase with increasing air flow or fuel flow. It makes sense that the hybrid engine operates at the high air flow and fuel flow.

4) Under all operations, there are several unsafe zones. Under high fuel flow and low air flow, the power produced by SOFCs is over the power consumed by the compressor. The unbalanced energy zones exist. Under high air flow, compressor choke occurs. Under low fuel flow and low air flow, too low reforming temperature zones or too low SOFC open voltage zones is shown. The minimum specific thrust of the hybrid engine increases from 432.5N/kg.s^{-1} with a relative air flow rate of 0.12 and relative fuel rate of 0.35 to 837.6 N/kg.s^{-1} with a relative air flow of 1.04 and relative fuel flow of 1.10. The efficiency increases from a minimum of 14.6% to a maximum of 70.43%.

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