

Simulation of Ammonia-SOFC-integrated engine with intercooling

Kai Xu¹, Xiaoqing Zhang¹, Xiao Ma², Shijin Shuai¹

¹Institute for Aero Engine, Tsinghua University, Beijing, 100084, China; ²State Key Laboratory of Intelligent Green Vehicle and Mobility, School of Vehicle and Mobility, Tsinghua University, Beijing, 100084, China

National Key R&D Program of China (Grant Number: 2021YFB250040)

Abstract: Simulation and analysis of an ammonia-SOFC integrated aero engine show that specific impulse can achieve 42% of conventional airliner turbofan engines at cruise conditions, whereas the specific thrust is significantly higher at 213%. The modelled engine has a reduced bypass ratio and increased fan pressure ratio to fit the operation conditions of the SOFC and heat exchange systems consisting of an intercooler and a turbine recuperator. The compressor bleed air is cooled to enhance turbine cooling. Sensitivity analysis of the baseline case suggests modification toward a higher fan pressure ratio, smaller compressor pressure ratio and bypass ratio can further optimize the performance. The adjustment of the SOFC fuel utilization ratio can help engine thrust control. The compatibility of ammonia-based hybrid engines with medium-range, medium-size platforms is shown.

Keywords: Ammonia fuel; SOFC hybrid turbofan engine; Intercooling

1 Introduction

Ammonia is considered a promising candidate for non-carbon fuels in many transportation factors, especially maritime^[1]. However, due to low energy density and erosion, there is less interest in ammonia fuel in the aviation sector. Bicer et. al.^[2] have pointed out that ammonia fuel has a potential cost-effectiveness equivalent to conventional kerosene, owing to its readiness in production and storage. Ammonia can be liquified at room temperature, which provides it with better volumetric energy density than hydrogen and a relatively high heat sink from phase change. Otto et. al. further investigated the feasibility of ammonia aviation power and found that the introduction of intercooling of turbo engines by ammonia is vital to improve overall efficiency^[3]. The work also detailed the implementation of ammonia heat exchangers. Another advantage of ammonia fuel is its compatibility with multiple energy conversion methods, from conventional combustors in the aero engines to fuel cells. Ammonia is especially compatible with solid oxide fuel cells (SOFCs) operating at 600-800°C, capable of completely decomposing on the active sites of anode nickel, with a minor degradation effect on the fuel cell^[4,5]. The combination of SOFC and turbo engines has long been viewed as optimal. The former has an electrical efficiency of over 50%, suitable for developing advanced propulsion methods such as hybrid-electric turboprops. The turbo engine can provide pressurized cathode air for the SOFC, thereby increasing system power^[6], and utilizing the high-temperature exhaust gas from the SOFC to recuperate or generate power. The combined system of SOFC and gas turbine, often referred to as SOFC-GT system, has been practically proven to be highly efficient as a power plant^[7]. The integration of SOFC into an aero engine could improve system efficiency and fuel economy^[8].

Ji et. al.^[9-11] studied the feasibility of SOFC-integrated engines of various configurations. Fewer turbine levels or lack of the turbine, internal reforming of the fuel, as well as multistage heat exchangers to fully exploit the SOFC exhaust heat, are vital factors to the overall performance of the hybrid engine. This paper put together the concept of aviation ammonia fuel and SOFC-integrated turbo engine to show the optimized performance of ammonia propulsion. An ammonia hybrid engine configuration with ammonia SOFC, electrically powered fan, fan outlet intercooler, turbine outlet recuperator, and only one stage of the turbine is proposed through simulation based on lumped engine components and SOFC models. Section 2 details the simulation models, and section 3 discusses the baseline performance and sensitivity analysis of the hybrid engine.

2 Simulation description

The system diagram is given in Fig. 1. The liquid ammonia is stored in 280 K under 1.1 MPa, in the liquid state. The liquid ammonia first enters the intercooler located at the fan outlet to fully evaporate. The temperature rise of ammonia vapour through the intercooler is neglected since the fan outlet temperature is a little higher than the liquid ammonia. The ammonia then flows into the heat exchanger RX to cool the compressor outlet gas. The final stage of ammonia heating takes place in the turbine outlet in a recuperator with an exit temperature of 500°C, which is suitable for internal reforming of the ammonia gas in the SOFC anode. The pressure loss of the airflow or turbine exhaust flow due to heat exchangers is neglected according to ref [3]. Ammonia is fully decomposed into hydrogen and nitrogen in the SOFC stack, with a fuel utilization ratio of 70%. The engine fan is driven by the electrical power generated by the SOFC. Due to system complexity restrictions in aero engines, no anode circulation component is involved in the design. Instead, 30% unreacted hydrogen enters the engine combustor for lean combustion. The fuel utilization ratio is in fact the equivalent of the “hybrid ratio” of the configuration. In this paper, the operation temperature of the SOFC is 1073K, and the stack exit temperature is around 1100K. This leads to low combustor outlet temperatures below 1400K, which is beneficial for simplifying the turbine cooling requirement and reducing the formation of NO_x.

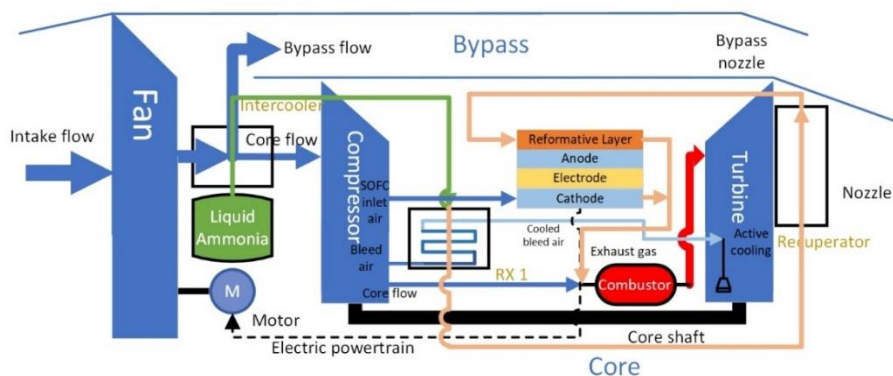


Fig. 1 System diagram

To cope with the intercooler and recuperator, the engine has a fan pressure of 3 and a bypass ratio of 3.5. Other engine parameters are listed in Table 1. The SOFC is set to operate under various elevated pressures depending on the compressor outlet pressure. Both simulations and experiments proved that pressurization could improve SOFC's power density. The heat exchanger RX cools the compressor's bleed air to enhance turbine cooling, with a cooled cooling air temperature of 400 K.

The performance of the hybrid engine is evaluated for thrust production and fuel economy, represented by

specific thrust and specific impulse of the engine, respectively:

$$\text{Specific thrust} = \frac{\text{Core thrust} + \text{Bypass thrust}}{\dot{m}_{\text{air}}}$$

$$\text{Specific impulse} = \frac{\text{Specific thrust} \cdot \dot{m}_{\text{air}}}{\dot{m}_{\text{fuel}}}$$

Modelling equations of the SOFC and the turbo engine components are shown in Table 1. Table 2 lists the model parameters.

Table 1 Modeling equations

Component	Equations	
Engine component	Intake	$T_{\text{Intake,out}} = T_0 \left(1 + \frac{\gamma - 1}{2} MA^2 \right)$ $p_{\text{Intake,out}} = p_0 \left(1 + \eta_{\text{intake}} \left(\frac{T_{\text{intake,out}}}{T_0} - 1 \right) \right)^{\frac{\gamma}{\gamma-1}}$
	Fan	$T_{\text{fan,out}} = (1 + \eta_{\text{fan}}^{-1}) \left(\pi_{\text{fan}}^{\frac{\gamma-1}{\gamma}} - 1 \right) T_{\text{intake,out}}$
	Compressor	$p_{\text{CP,out}} = p_{\text{Fan,out}} \pi_{\text{CP}}$ $T_{\text{CP,out}} = (1 + \eta_{\text{CP}}^{-1}) \left(\pi_{\text{CP}}^{\frac{\gamma-1}{\gamma}} - 1 \right) T_{\text{Fan,out}}$
	Combustor	$\dot{m}_{\text{CB,out}} \sum_{j=\text{species}} \omega_j h_j(T_{\text{CB,out}}) = \dot{m}_{\text{CB,in}} \sum_{i=\text{species}} \omega_i h_i(T_{\text{CB,in}})$ $p_{\text{CB,out}} = \sigma_{\text{CB}} p_{\text{CB,in}}$
	Turbine	$\sum_{j=\text{species}} \omega_j h_j(T_{\text{TB,out}}) = \sum_{i=\text{species}} \omega_i h_i(T_{\text{TB,in}}) - w_{\text{TB}}$ $p_{\text{TB,out}} = p_{\text{TB,in}} \left(1 - \frac{1}{\eta_{\text{TB}}} \left(1 - \frac{T_{\text{TB,out}}}{T_{\text{TB,in}}} \right) \right)^{\frac{\gamma}{\gamma-1}}$
	Nozzle	$u_e = \sqrt{2\eta_{\text{nozzle}} C_p T_{\text{nozzle,in}} \left(1 - \left(\frac{p_0}{p_{\text{nozzle,in}}} \right)^{\frac{\gamma-1}{\gamma}} \right)}$
	Heat exchanger	$q_{rx} = \dot{m}_1 (h_1(T_{1,\text{in}}) - h_1(T_{1,\text{out}})) = \dot{m}_2 (h_2(T_{2,\text{out}}) - h_2(T_{2,\text{in}}))$
SOFC component	Open-circuit voltage	$U_{\text{OCV}} = U_0 - \frac{RT}{2F} \ln \left(\frac{P_{\text{H}_2\text{O}}}{P_{\text{H}_2} P_{\text{O}_2}^{0.5}} \right)$
	Cell Voltage	$U_{\text{cell}} = U_{\text{OCV}} - \eta_{\text{act}} - \eta_{\text{ohm}} - \eta_{\text{conc}}$
	Activation polarization	$i = i_0 \left[\exp \left(\frac{\alpha n_e F}{RT} \eta_{\text{INT}} \right) - \exp \left(-\frac{(1-\alpha) n_e F}{RT} \eta_{\text{INT}} \right) \right]$
	Ohmic polarization	$\eta_{\text{ohm}} = i \left(\frac{\delta_{\text{anode}}}{\sigma_{\text{anode}}} + \frac{\delta_{\text{anode}}}{\sigma_{\text{anode}}} + \frac{\delta_{\text{anode}}}{\sigma_{\text{anode}}} + r_s \right)$
	Concentration polarization	$\eta_{\text{conc,anode}} = -\frac{RT}{2F} \ln \left(\frac{X_{\text{H}_2} X_{\text{H}_2\text{O}}^0}{X_{\text{H}_2}^0 X_{\text{H}_2\text{O}}} \right) (\text{anode})$ $\eta_{\text{conc,cathode}} = -\frac{RT}{2F} \ln \left(\frac{X_{\text{O}_2}}{X_{\text{O}_2}^0} \right) (\text{cathode})$
Fuel utilization ratio	$\mu_{\text{F}} = 1 - \frac{\dot{n}_{\text{anode,out}} (3X_{\text{NH}_3,\text{out}} + 2X_{\text{H}_2,\text{out}})}{\dot{n}_{\text{anode,in}} (3X_{\text{NH}_3,\text{in}} + 2X_{\text{H}_2,\text{in}})}$	

Table 2 System parameters

Parameters	Value
Altitude	10668 m
Mach number	0.8
Fan pressure ratio	3
Compressor pressure ratio	10
Bypass ratio	3.5
SOFC operation temperature	1023 K
Cooled turbine bleed air temperature	400 K
Fan driving motor efficiency	90%

More details about the model can be found in Ref^[9-13]. The simulation scheme is shown in Fig. 2. Fig. 3 shows the comparison between the ammonia SOFC model used in this paper and the experiment results^[14].

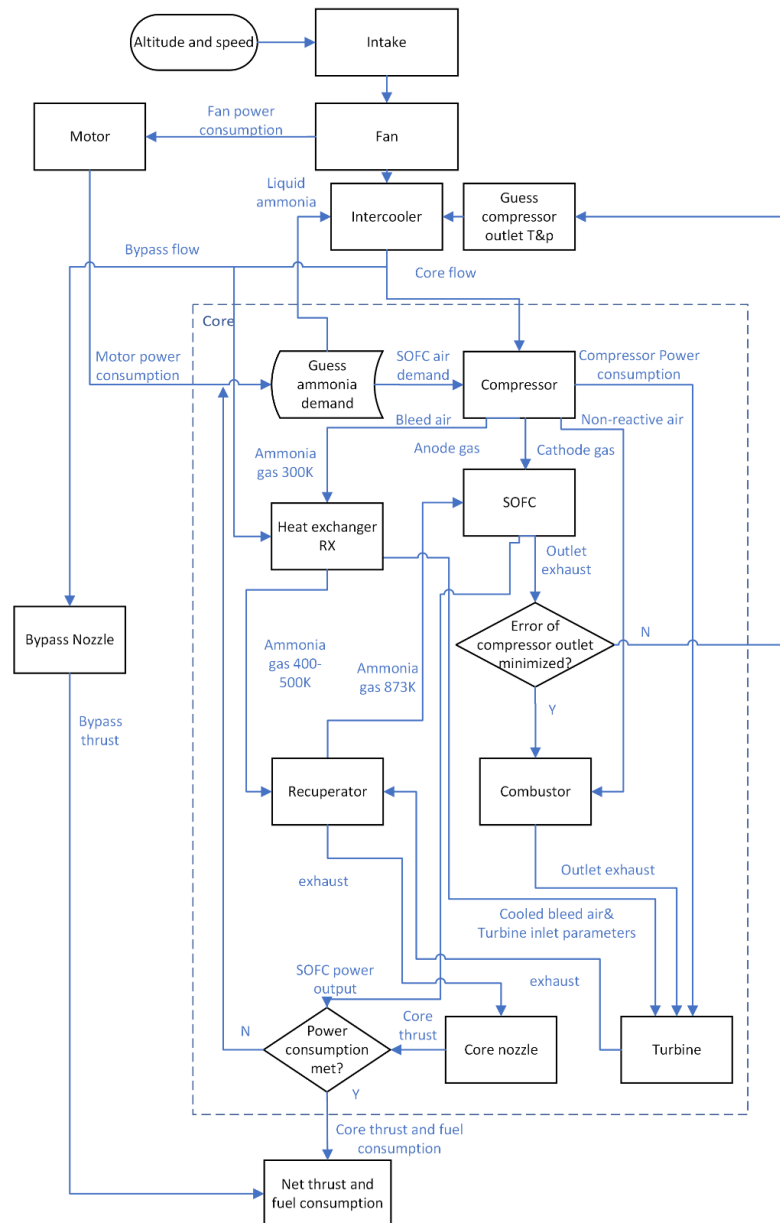


Fig. 2 Simulation scheme

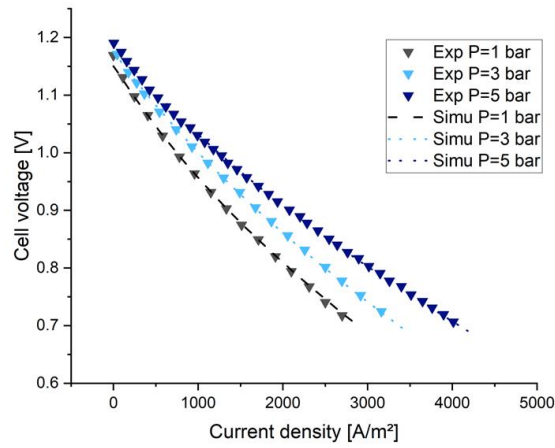


Fig. 3 SOFC model polarization curve

3 Results and discussion

3.1 Baseline performance

Simulation results of the baseline case are given in Table 3. A reference cruise performance at the same altitude and MA number of the CF56-7B powered by traditional jet fuel [15,16] is provided. Due to the smaller bypass ratio and larger fan pressure ratio of the modelled hybrid engine, the specific thrust is significantly larger at 213% of the reference, whereas the specific thrust is 42% of the reference. Table 4 provides stream data for different stations of the engine.

Table 3 Simulated Performance

Parameters	Model	Reference
Specific impulse (N·s/kg)	23932	57000
Specific thrust (m/s)	372	175

Table 4 Stream data of different engine stations

Station	Intake outlet	Fan outlet	Intercooler outlet	Compressor outlet	Combustor outlet	Turbine outlet	Recuperator outlet	Bypass nozzle inlet
Temperature [K]	246.9	354.0	334.7	688.7	1235.6	941.5	794.7	354.0
Pressure [bar]	0.328	0.983	0.983	9.830	9.732	3.597	3.597	0.983

Due to the high core nozzle exhaust speed, the specific thrust is improved for the hybrid engine. The efficiency data of the baseline case is shown in Table 5. The SOFC efficiency is 54.9%, which is higher than that of the conventional turbofan engines around 40%. Owing to the higher efficiency of the electrical powertrain, the thermal efficiency of the entire hybrid engine is 49.2%. However, the lack of a low-pressure turbine leads to more energy waste in the nozzle exit flow and a reduced propulsion efficiency of 61.9%.

Table 5 Baseline case efficiency data

parameter	value
SOFC efficiency	54.9%
Thermal efficiency	49.2%
Propulsion efficiency	61.9%

Overall, the hybrid engine under the baseline condition has a higher thrust than the high-bypass turbofan reference, while its specific impulse is slightly less than half of the former. Considering that the energy density of ammonia is about 40% of that of jet fuels, the above performance is acceptable. It also implies that the ammonia hybrid engine simulated in this paper is suitable for medium and small regional aircraft, which is consistent with the predictions in the literature.

3.2 sensitivity analysis

Sensitivity coefficients of the impact of key engine parameters and temperature points of the heat exchangers on the engine performance are calculated near the baseline condition. The sensitivity coefficients are calculated as follows:

$$S_i = \frac{\delta X/X}{\delta q_i/q_i}$$

X is performance data, q_i is the i th parameters. Parameter step δq_i is universally set to be 2% of the baseline value.

The results of the sensitivity coefficients are plotted in Table 6. The fan pressure ratio and the fuel utilization rate have a more evident impact on both specific thrust and specific impulse than other parameters. The fan pressure ratio determines the power output of the SOFC and the fuel utilization ratio determines the energy distribution in the SOFC, respectively. Temperatures of the intercooler outlet ammonia gas and cooled bleed air have only a minor influence on the performance data. Adjustments in the fan pressure ratio, the compressor pressure ratio, and the fuel utilization ratio lead to a trade-off between thrust and impulse, the latter is closely related to the flight range. Note that the Fuel utilization ratio is an operation state that can altered during flight, like the heat exchanger settings.

Table 6 Sensitivity coefficients

Parameters	Sensitivity coefficients	
	$X = \text{Specific thrust}$	$X = \text{Specific impulse}$
Fan pressure ratio	1.343	-0.712
Compressor pressure ratio	-0.0537	0.0921
Bypass ratio	-0.0336	-0.0333
Intercooler outlet ammonia temperature	-0.00671	-0.00717
Cooled bleed air temperature	0.00940	0.00965
Fuel utilization ratio of SOFC	-0.486	0.304

The above sensitivity coefficients suggest that, from the baseline condition, by simultaneously increasing the fan pressure ratio and decreasing the compressor pressure ratio and the bypass ratio, the overall performance of the hybrid engine considering both thrust level and flight range can be optimized to a further extent. These optimizations are the increase of the portion of the electrical drivetrain. During the flight, by altering the fuel utilization ratio of the SOFC, the engine can switch from a higher thrust output mode to a more fuel-economic mode. Moreover, the heat exchange system can be fine-tuned according to actual flight conditions without significantly affecting engine performance. The performance variation due to fuel utilization ratio change in the range [0.4, 0.9] is shown in Fig. 4.

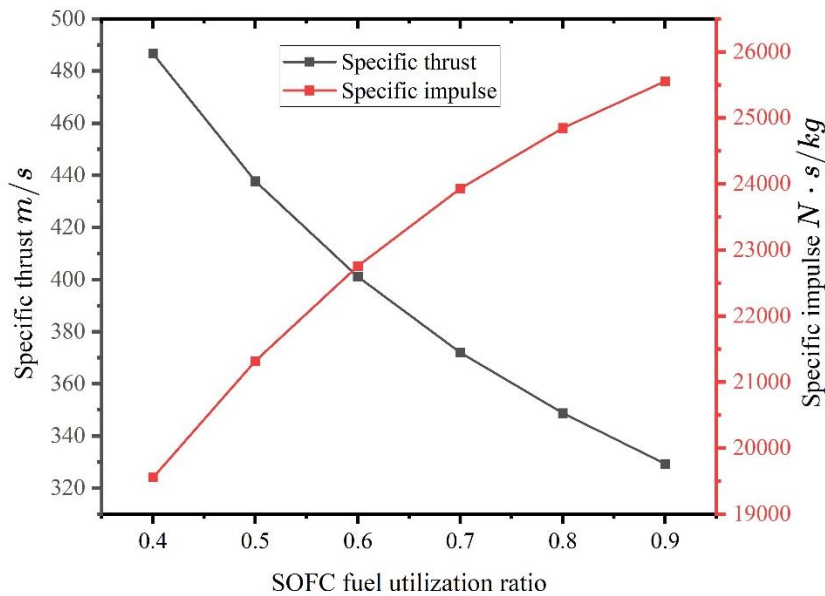


Fig. 4 Performance variation due to fuel utilization ratio change

The maximum relative changes of specific thrust and specific impulse based on the base case are 42.3% and 25.1%, respectively.

4 Conclusion

Based on the simulation and analysis, the following conclusions are presented to help future ammonia or other alternative fuel-based hybrid engine research:

(1) The ammonia hybrid engine has an improved thermal efficiency of 49.2% due to the integration of SOFC and electrical powertrain. The propulsion efficiency yet suffered from the reduction of turbine levels.

(2) The hybrid engine can generate 213% of specific thrust with 42% of specific impulse relative to the reference, more suitable for regional jets or general aviation.

(3) The one-turbine, electrical-driven-fan configuration can be further optimized by an increase of fan pressure ratio, and reduction of compressor and bypass ratio as an increase in the electricity power fraction. the heat exchange system and SOFC operation condition change in terms of fuel utilization provide the system with more flexibility.

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