THERMODYNAMIC ASSESSMENT OF HYDROGEN-FUELED SOLID OXIDE FUEL CELL - GAS TURBINE (SOFC-GT) SYSTEMS FOR LOW-EMISSION AIRCRAFT PROPULSION

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Abstract

One solution to reduce the climate impact of aviation is the use of hydrogen-based electric propulsion. The EU-funded project HYLENA (Hydrogen Electrical Engine Novel Architecture), which will investigate, develop and optimize an innovative, highly efficient and integrated aircraft propulsion system, is presented. HYLENA aims to evaluate and demonstrate the feasibility of an engine type that integrates Solid Oxide Fuel Cells (SOFC) into a turbomachine to utilize the heat generated by the fuel cells in addition to the electrical energy. This submission presents the HYLENA project and the way-of-working as well as a SOFC-gasturbine (SOFC-GT) concept in which the heat integration is done by additional heat exchangers. In particular, the position of the hot gas extraction is varied. Under otherwise identical conditions, the change of the extraction location affects the system efficiency as well as the air and hydrogen mass flow. It is shown that the hot gas extraction downstream of the turbines achieves the highest system efficiency. This is due to the higher temperature and therefore a higher enthalpy level upstream of the turbines. This effect can be seen in the needed number of cells as well as the SOFC power share. While the system efficiency with SOFC exhaust gas utilization is 50.9 %, there is an increase of 17.4 percentage points to 68.3 % (based on the mechanical shaft output power in each case). With almost constant operating conditions for the SOFC itself, the gas turbine can be better utilized due to the higher temperature. While the SOFC's share of the total output power is 86.3 % after preheating with combustion exhaust, the share is reduced to 63.8 % with LPT exhaust gas utilization. Overall, it can be seen that the position of the heat exchanger has a significant influence on the system behavior. In addition to the increase in efficiency under the given boundary conditions, there is an influence on the system mass flows with reduced air and hydrogen mass flows.

Keywords

Solid Oxide Fuel Cell; SOFC-GT; Low-emission Propulsion; Hydrogen-based Engine

NOMENCLATURE

Formula Symbols

η_{SOFC}	SOFC efficiency	%
η_{sys}	System efficiency	%
$LHV_{\mathrm{H_2}}$	Lower Heating Value (Hydrogen)	J/mol
$\dot{n}_{\mathrm{H_2}}$	Hydrogen mole flow	mol/s
P_{HPT}	High Pressure Turbine Power	W
P_{LPT}	Low Pressure Turbine Power	W
P_{sys}	System power	W

Abbreviation

A	Heat transfering Area	m^2
DLR	German Aerospace Center	
FU	Fuel Utilization	%
GT	Gasturbine	
HPT	High Pressure Turbine	
HX	Heat Exchanger	
HYLENA	Hydrogen Electrical Engine Novel Architecture	
ICAO	International Civil Aviation Organization	
ISA	ICAO standard atmosphere	
U	Overall heat transfer coefficient	$\mathrm{W/(m^2\,K)}$
LEPMI	Laboratory of Electrochemistry and Physical-Chemistry of Materials and Interfaces	
LPT	Low Pressure Turbine	
Ma	Mach Number	
NTU	Number of Transfer Units	
OU	Oxygen Utilization	%
SOFC	Solid Oxide Fuel Cell	
TRL	Technical Readiness Level	
UA	Heat transfer capability	W/K
WP	Work Package	

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1. INTRODUCTION

The aviation industry has been growing rapidly in recent decades. Furthermore, a recent ICAO Post-Covid 19 forecast indicates that aviation will recover with a growth rate ranging from 2.9 % to 4.2 % (low to high scenario) from the COVID-19 pandemic by 2050 [1]. One way to reduce the impact on the climate is to use new technologies that enable CO_2-free or even climate-neutral flying [2]. The EU-funded project HYLENA (Hydrogen Electrical Engine Novel Architecture) sees such a possibility in the use of high-temperature fuel cells, or more precisely, solid oxide fuel cells (SOFCs). Due to their high operating temperatures between 650 and 850°C, they also offer the option of integration into a gas turbine system. The development of such an integrated system as the main aircraft engine is the aim of the project.

HYLENA has been launched in the framework of Horizon Europe and is a consortium of Airbus, Leibniz University Hannover (Institute of Thermodynamics), Technical University Delft, Bauhaus Luftfahrt, German Aerospace Center (DLR, Institute of Engineering Thermodynamics) and LEPMI (Laboratory of Electrochemistry and Physical-Chemistry of Materials and Interfaces) Grenoble. The HYLENA consortium will investigate, develop and optimize an innovative and highly efficient hydrogen powered, electrical aircraft propulsion concept for short and medium range with the aim for TRL 3. It will achieve significant climate impact reduction by being completely carbon neutral with an increased overall efficiency. The synergistic use of an electric motor as the main propulsion driver, hydrogen-fuelled SOFC stacks and a gas turbine system will enable highly efficient engine concepts. HYLENA aims to evaluate and demonstrate the feasibility of this new engine type which integrates SOFCs into turbomachinery, in order to utilize the heat generated on top of the electrical energy. Integrated in the overall workflow (Fig 1), the HYLENA methodology covers on:

- SOFC cell level: experimental investigations on new high power density cell technologies;
- SOFC stack level: studies and tests to determine the most light-weight and manufacturable way of stack integration;
- Thermodynamic level: engine cycle simulations of novel concept architectures;
- Engine design level: exploration of the best engine design, sizing and overall component integration through resilient calculation and simulation;
- Overall engine efficiency level: demonstartion that the HYLENA concept can reach an outstanding overall efficiency increase compared to state-of-the-art engines;
- Demonstration level: a decision dossier for a potential ground test demonstrator to prove that the concept works in practice during a second follow-up project phase.

The present study refers in particular to work package 3 (engine thermodynamic investigation) and shows

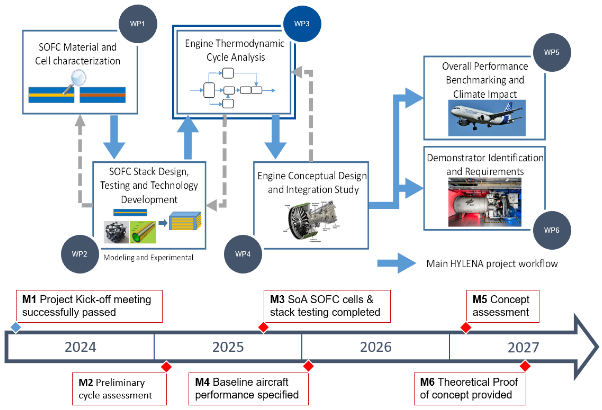

FIG 1. HYLENA overall workflow

the influence of the thermodynamic analysis on the overall system by means of various options for heat integration and preheating. Preheating is necessary in order to achieve the appropriate operating temperatures while maintaining the limiting temperature gradients of the SOFC. Heat integration as part of preheating, on the other hand, is the key factor in maximizing the efficiency of the system. The first step of the thermodynamic evaluation of the SOFC-GT-Engine is the systematically investigation of different cycle layouts. Presented in different studies, e.g. [3], [4] or [5], the use of heat exchangers (HX) is a solid option for preheating and high efficiencies. As shown in Fig 2, the heat exchangers can be fed by using either the hot-gas exhaust after the SOFC, combustor, high-pressure turbine or low-pressure turbine to preheat the incoming fluid flows. As the preheating will be achieved for all the variants, the analysis will show clearly the increasing efficiency through heat-integration.

2. METHODOLOGY

The analysis presented here is a steady-state examination of a selected cruise operating point for a turboprop engine. The ISA0 standard conditions at 25 kft (7.62 km) are selected for the operating conditions for a flight Mach-Number of Ma = 0.5. All systems are controlled to a mechanical power output of 2597 kW. The remaining boundary conditions of the simulation are shown in Tab. 1, the system layout used is shown schematically in Fig 2. The turbomachinery is simulated using isentropic efficiency (85 % compressor, 88 % turbine). Heat exchangers (HX) are modeled using the NTU method [6]. The heat transfer capability (UA value) is controlled in a way that the inlet temperatures in the SOFC are precisely reached (if possible). In all cases, the larger air mass flow is preheated first, followed by the hydrogen mass flow. The SOFC is modeled using a 1D-discretized model based on the work from [7] and [8]. The electrical energy of the SOFC is converted into mechanical shaft power by power electronics and an electric motor. Efficiencies of 95 % are estimated for both the power electronics

Operating conditions	
Pressure (System)	1 bar
Current density	0.5 A/cm^2
Fuel Utilization	80 %
SOFC Inlet Temperature	973.15 K
Max. Cell Temperature	150 K

TAB 1. Operating Conditions

and the motor. The required fuel mass flow rate is calculated individually for each case using the fuel utilization factor (FU), the current density and cell number. The air mass flow is obtained due the oxygen utilization (OU) from the cooling air requirement of the SOFC model, taking into account the maximum cell temperature (see Tab. 1). The constraint that the compressor power is balanced by the power of the high-pressure turbine (HPT) is specified for all configurations. To do this, the respective outlet pressure of the HPT is controlled accordingly. The total power of the system is thus obtained from equation (1).

(1) $$P_{sys} = P_{SOFC} + P_{LPT}$$

The control of the specified total output power is done via the number of cells, since this directly influences the output of the turbomachinery via the mass flows and the output of the SOFC as a scaling factor. To determine the influence of the heat exchanger position, the efficiency of the SOFC

(2) $$\eta_{\text{SOFC}} = \frac{P_{\text{SOFC}}}{\dot{n}_{\text{H}_2} \cdot \text{LHV}_{\text{H}_2}}$$

and the efficiency of the overall system

(3) $$\eta_{\text{sys}} = \frac{P_{\text{sys}}}{\dot{n}_{\text{H}_2} \cdot \text{LHV}_{\text{H}_2}}$$

are defined. Here, $\dot{n}_{\text{H}_2}$ is the supplied hydrogen molar flow rate, LHV_{H_2} is the lower heating value of hydrogen and P is the power in W. The possibility of burning additional fuel in the combustion chamber is given, but is not considered in the framework presented here.

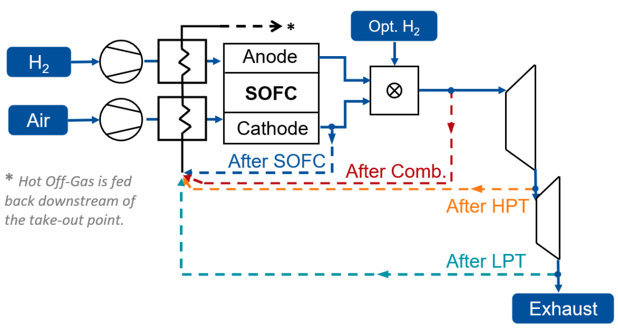

FIG 2. Schematic layout of the analyzed system configurations

3. RESULTS

The investigation of the presented possibilities for heat integration and preheating, respectively, by the different feedings of the heat exchanger shows a significant influence on both the system behavior and the resulting overall efficiency. While the efficiency of the SOFC, as shown in Fig 3 (blue bars), lies in the range between 48.3 % and 48.6 % and is thus almost constant, the efficiency of the system varies significantly (red bars). While using the warmest exhaust gases after the SOFC and after the combustion chamber only achieves efficiencies of 50.9 % (Comb.) respectively 51.5 % (SOFC), using the turbine exhaust gases can achieve 56.7 % when using HPT exhaust gases or 68.3 % when using LPT exhaust gases. Since in all cases the incoming air mass flow reaches the desired temperature, the operating conditions for the variants shown are approximately constant. However, due to the low temperatures downstream of the turbines, the inlet flow into the anode (hydrogen) is not sufficiently preheated. The resulting temperature difference at the inlet is equalized as the gas flows through the SOFC. The resulting deviation in the set-point temperature has only a minor influence on the operating behavior of the SOFC and is neglected for the following considerations. Due to the constant operating parameters assumed for the SOFC, the resulting changes can be explained directly by the modified hot gas supply of the heat exchanger.
The main cause of the changes in efficiency shown is the differences in the temperature curve through the system since the working fluid is not cooled before it enters the turbines when the (low pressure) turbine exhaust gases are used. As can be clearly seen in Fig 4, the inlet temperature in the case of preheating with SOFC exhaust gases is 659 K (HPT) and 578 K (LPT) and 636 K (HPT) and 549 K (LPT) when using the combustion exhaust gases. If, on the other hand, the heat exchanger is fed with the exhaust gases from the low-pressure turbine, inlet temperatures of 1255 K respectively 1184 K can be achieved in the HPT and

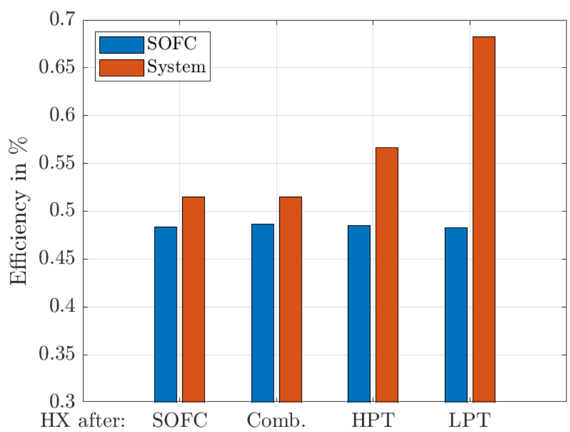

FIG 3. Efficiency of the SOFC (blue) and the overall system (red) with variations in hot gas utilization

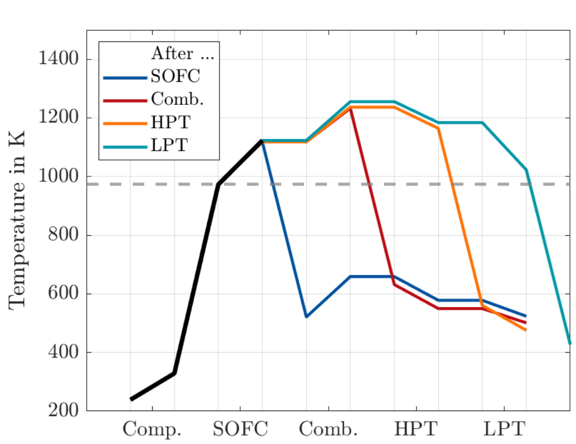

FIG 4. Temperature curve through the entire system depending on the hot gases used for preheating

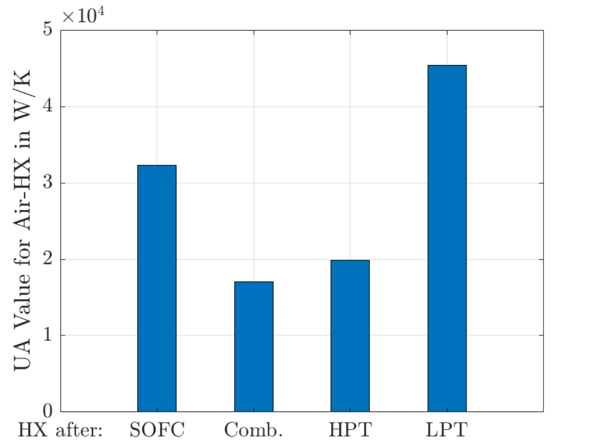

FIG 6. Influence of hot gas utilization on the UA coefficient of the air preheater

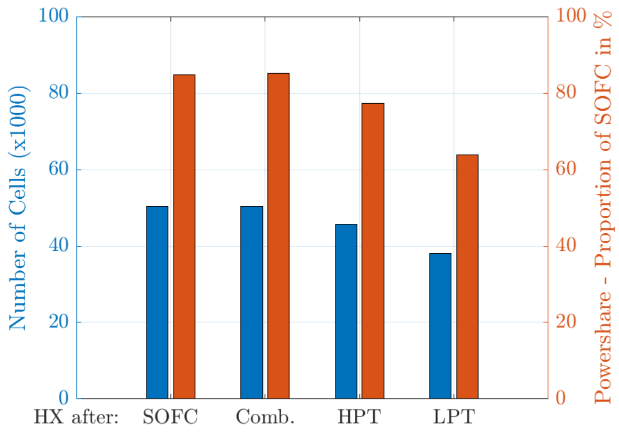

FIG 5. Influence of hot gas utilization on the power split between SOFC and LPT (red) and the number of cells (blue)

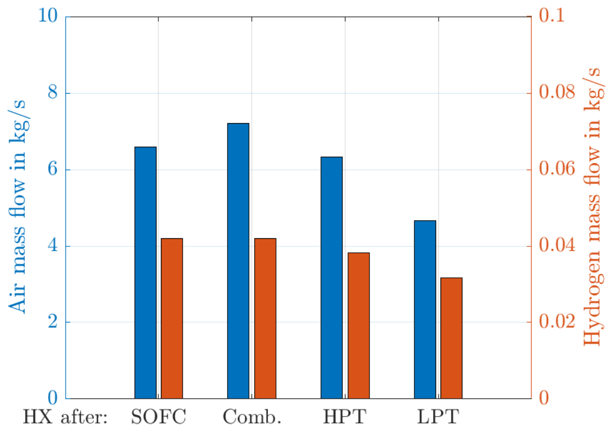

FIG 7. Changes in the air and hydrogen mass flows due to modified preheating

the LPT. However, it should be noted that the reduced temperature level after the turbines is also accompanied by a reduction in the preheating capacity. This can mean that the desired inlet temperatures can no longer be achieved. Therefore the outlet temperature of the SOFC must also be lowered to prevent impermissible temperature gradients and the associated thermomechanical stresses. Furthermore, the lowered temperature level also reduces the cell voltage, which negatively affects both the efficiency of the SOFC and the cell output power. This work does not go into further details on insufficient preheating.
The described effect of increased turbine output due to a higher inlet temperature can also be seen directly when considering the power distribution between SOFC and LPT and the required number of cells to achieve the target output (Fig 5). Due to the constant power per SOFC cell and the higher inlet temperature of the turbines, a higher power potential of the turbomachinery is available. Since the same system power is used in all cases, the power share of the SOFC (red bar) is reduced from 86.3 % with using the warmest combustor exhaust gases to 63.8 % using the coldest LPT exhaust. Furthermore, the relatively higher power share of the turbine has the consequence that a smaller number of cells (blue) is sufficient to achieve the target power when using hot gases from the turbines. Such a reduction in the number of cells from 50,988 to 37,996 cells suggests a significant reduction in overall weight, which is essential for applicability in mobile applications, especially in aviation.
On the other hand, there is the influence on the expected size of the heat exchanger. While a small temperature difference – as is particularly the case with LPT exhaust gas utilization – is generally preferred for the exergetic efficiency of the heat exchanger, the utilization of exhaust gases further downstream shows a significant increase in the UA value in the case of LPT exhaust gas utilization. Disregarding the temperature dependency of the overall heat transfer coefficient U, higher UA values indicate a higher volume and thus weight of the heat exchanger due to the heat transfer surface A. It can be seen that in the case of the highest efficiency (use of LPT exhaust gases), the (for the boundary conditions chosen here) expected UA Value increases from 17175 W/K (using combustion

exhaust) to 45362 W/K. This is contrary to the reduction in weight due to the reduced number of cells and requires further analysis, in particular to be able to estimate the system weight. Furthermore, Fig 7 shows that due to the reduced number of cells, the absolute value of the hydrogen supplied decreases from 0.0420 kg/s (SOFC and Comb.) to 0.0317 kg/s (LPT). The air requirement also decreases when turbine exhaust gases are used compared to the use of SOFC or combustion chamber exhaust gases. In particular, the change in air mass flows in reality has a significant impact on the turbomachinery, which has not been taken into account in the current state of the work.

4. CONCLUSION AND OUTLOOK

It can be stated that the first results of HYLENA's work package 3 (engine thermodynamic investigation) were presented. The significant influence of the heat exchanger and the use of hot gas, respectively, illustrates the importance of a thorough thermodynamic system study with regard to system configurations. It can be concluded that with the chosen boundary conditions the highest system efficiency can be achieved by using the LPT exhaust gases (68.3 %). This is offset by a significant increase in the UA value of the air heat exchanger (from 17175 W/K using combustor exhaust to 45362 W/K LPT exhaust). The resulting increase in volume and weight requires more detailed investigations. Furthermore, the influence of the boundary conditions, which are kept constant here, requires a precise analysis, which will be carried out as part of the project. In particular, the effects of parameter variation on the preheating of the fuel cell constitute a challenge.

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