RECENT STUDIES ON ALTERNATIVE POWER UNITS FOR PASSENGER AIRCRAFT

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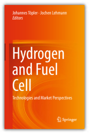

RECENT STUDIES ON ALTERNATIVE POWER UNITS FOR PASSENGER AIRCRAFT

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SUMMARY: The paper reviews some of the recent studies on the application of alternative power plants instead of common small gas turbine engines as an auxiliary power units (APU) used in passenger aircraft. More precisely the NASA led research in SOFC APU, DLR research in PEMFC APU and SWAFEA research in general fuel saving potential from APU are covered. A special attention is given to the research conducted in the department of Air Transport at Technical University of Sofia on the possible application of diesel engines as alternative APU on narrow body passenger airliners. In conclusion some remarks on the feasibility of these alternatives are made. Possible implications of the alternative APU on military transport aircraft, AEW&C aircraft, etc. are also considered.

Keywords: auxiliary power unit, APU, aviation fuel cell, aviation diesel engine.

1. Introduction

Since the beginning of the Jet airplane era the gas turbine auxiliary power units (APU) became the primary source for main engines start. The APU also took other significant functions as on-ground autonomous air-conditioning and electric power supply and in-flight emergency power supply. As long as the APU uses the standard fuel of the main engines (kerosene) and can be started with power from the airplane battery, it significantly simplifies the ground handling of the airplane. In some airplanes the APU can be used also during take-off to supply bleed air for air conditioning thus avoiding a reduction in main engine thrust caused by the use of engine bleed air. The APU system interfaces depend very much on the individual aircraft and its system architecture. Usually the required redundancies in the case of one engine out and/or the power demand during ground operations give the design point for the APU lay out.

For a long period of time the main requirements to the APU were only the small size and weight since normally it is operated briefly on the ground in the beginning of each flight and it is a dead mass in the rest of the time. The requirements gradually changed in the recent years with the APU environmental and energy efficiency problems acquiring greater relevance in the context of environmental performance and efficiency of transport aviation in general. Especially serious are the noise issues at the airport areas, but recent studies also identify the APU operation as a significant contributor to the air pollution in these areas [1].

At present the most common way to mitigate the APU environmental problems is by limiting the APU usage only for main engine start and using fixed or mobile ground energy supply units for the ground handling needs and passenger cabin pre-flight air-conditioning. This strategy is imposed on several large airports [2], but it is not always applicable for airplanes at

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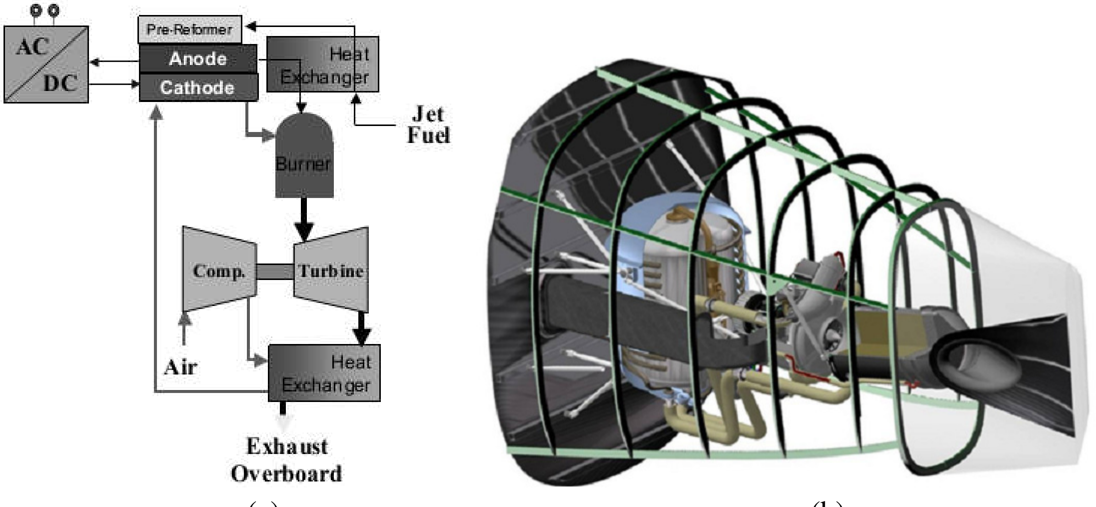
remote airport stands and on smaller airports, as it needs additional ground equipment, increases airport ground vehicle movements and complicates the ground handling in general.

The gas-turbine APU possesses a limited improvement potential and it can not address the environment issues mentioned above. In this respect a number of research efforts were initiated in the last decade, with the aim of finding alternative solutions. The most significant of these being the NASA led studies of high temperature solid oxide fuel cell (SOFC) APU and the ongoing DLR led study of low temperature proton exchange membrane fuel cell (PEMFC) APU, fueled with liquid hydrogen (LH_2). The problems of the fuel saving potential of advanced APU systems was concerned also in the European Sustainable Way for Alternative Fuels and Energy for Aviation (SWAFEA) study [3]. Beside the fuel cell alternatives SWAFEA outlined also the advanced diesel engines as possible advanced APU, without performing any evaluation of this concept. Such an evaluation of the diesel APU was performed by the authors at the Department of air transport of Technical University of Sofia. A brief description of these studies is given below.

2. SOFC APU Concept and Feasibility Studies

The idea of using SOFC APU was announced first by Boeing in 2003 [4]. The idea was tightly linked with the „More electric“ aircraft (MEA) concept that was in development at that time. Given the rate of progress in reducing the fuel cell’s weight and volume, as well as the projected capability to use common fuels, it was projected that fuel cells will reach a high enough maturity level within 10-15 years (e.g. year 2015) to be considered for use in commercial aircraft. From the beginning two major types of fuel cells, Proton Exchange Membrane and Solid Oxide Fuel Cell were considered due to their relatively high level of development and potential for commercialization. Because of the SOFCs potential to operate with less external fuel reforming and potentially achievable higher efficiency they became the primary focus of this initiative (fig. 1).



(a) (b)

Fig.1: (a) - Principal scheme of a hybrid gas turbine - SOFC APU; (b) - CAD Representation of a 440 kW SOFC APU in a Boeing 777 Tail Cone [4].

In the subsequent period NASA sponsored a number of research contracts in the field of SOFC APU systems for passenger airplanes. Different technical and technological aspects were concerned. The concluding parts of this research effort were the feasibility studies of a SOFC APU systems for a short-range aircraft [5], for a long-range aircraft [6] and for a regional jet aircraft [7]. The first two were performed by the United Technologies Research Center, using Integrated Total Aircraft Power System (ITAPS) methodologies. The third one was performed by Honeywell Engines, Systems & Services. All three studies established realistic hybrid SOFC APU system weights and system efficiencies, and evaluated the impact on the aircraft total weight, fuel burn, and emissions from the main engines and the APU during flight and on the ground. The SOFC technology considered in these studies was assumed to be available in the year 2015. The results are summarized in table 1.

Table 1: Main results from the SOFC APU feasibility studies.

Base line aircraft type	SOFC efficiency	Total Fuel Burn Reduction
A "rubber" 162 PAX Short-Range Commercial Aircraft with More electric systems, Ultra Efficient Engine Technology (UEET) engines, advanced, more electric APU (with ceramics)	70% in flight; 53% on ground	4.7 to 6.7%
Fixed B777-200ER airframe (Long Range Commercial Aircraft) with More electric systems, UEET engines and advanced APU	65.4% in flight; 51.8% on ground	0.44 to 0.7%
90-passenger More-Electric Regional Jet; mission range of up to 1,500 nmi; baseline conventional APU system efficiency of ~9 to 13%	48% in flight; 36% on ground	up to 3%

Along with the estimation of the fuel saving potential a number of shortcomings (technical challenges) of the SOFC APU were identified:

- The SOFC system specific power (kW/kg) is about three times lower than that of a conventional gas turbine APU. The corresponding weight penalty increases the amount of fuel burned by the aircraft.
- The SOFC system operation during flight cruise condition requires input air stream and providing that air from the ambient (ram air) introduces ram-drag penalty. This ram-drag penalty increases the amount of fuel burned by the aircraft.
- The SOFC system (which is a hybrid system with the SOFC stack and the turbo-machinery) generates both ac and dc power. The dc power is from the stack and the ac power is from the turbine generator. The distribution of the power (ac and dc) generated by the SOFC system in the aircraft requires additional power electronics (power converters etc), which, in turn, increase the amount of fuel burned by the aircraft.
- The current technology of the SOFC system requires a longer time (more than 30 min) to startup the SOFC system. Therefore, frequent starting and stopping cycles for the SOFC system may not be a good option for the aircraft application.
- The processing of the Jet-A fuel with sulfur levels between 300 to 1000ppm requires a bulkier de-sulfurizer, which restricts the de-sulfurization options for the aircraft.
- The exhaust gas coming out of the SOFC system is at rather high temperature (> 600 °F) and utilization of this hot stream is a challenge.

Most of these problems are not addressed until now. After the completion of these studies in 2007 the activity in the field diminished almost completely.

3. PEMFC Experimental Work at DLR

The Institute of Technical Thermodynamics of the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt, DLR) unlike NASA focused its efforts on experimental evaluation of hydrogen fueled fuel cell systems under relevant conditions (low-pressure, vibrations, reformate operation, etc.) including in-flight testing on research aircraft (A 320) [8]. The aim was to identify several fuel cell applications within the aircraft for both ground and cruise operation. A concept for Multifunctional fuel cell system was developed. The possible functions were presumed to be power supply, emission free ground operation (nose wheel drive), electrical main engine start, electrical environmental control system (EECS), water generation (potable water and water for toilets), heat generation (icing prevention, hot water generation), explosion and fire prevention and suppression (inerting of tanks, cargo and e-bay compartment), cockpit and / or cabin air humidification (fig.2).

At the present moment the experiments by DLR continue to be underway. This concept can be seen as a long term solution. The main obstacles for implementation are as follows;

- The significant volume of the hydrogen tank on board makes it hard to implement the system on the current generation of passenger aircraft.
- The addition of second fuel (hydrogen) will complicate the ground handling.
- Hydrogen storage and distribution infrastructure on the ground should be established.

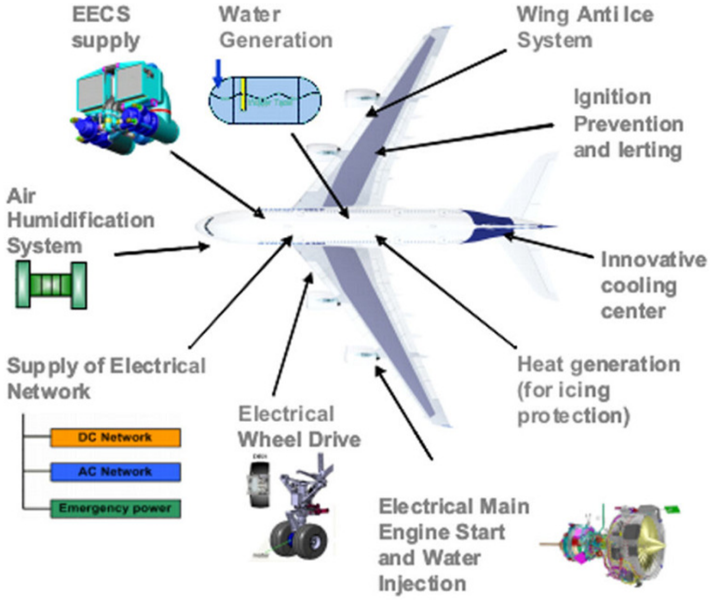


Fig.2: Possible functions of highly integrated PEMFC APU system [8].

4. Alternative APU Assessment in the SWAFEA Study

SWAFEA (Sustainable Way for Alternative Fuels and Energy for Aviation) was a study for the European Commission's Directorate General for Transport and Energy, completed in 2011. It aimed at investigating the feasibility and the impact of the use of alternative fuels in aviation. A part of the study was the evaluation of the potential of other renewable energy sources applied complementary to existing aircraft energy systems (the engines) in order to reduce conventional fuel (kerosene) burn and emissions [9]. This evaluation was based on original research efforts as well as on the research efforts in the field of fuel cell APU described above.

The evaluation of main engine performance showed that a theoretical potential of typically 3 % fuel savings from zero bleed-air and zero electrical power off-take could be expected, in practice reduced by the extra mass of the added (main-engine-independent) power system.

The theoretical upper mass limit of an alternative independent power system was given by the mass-induced fuel burn penalty, which should be less than the above defined 3 % gain. A conservative estimate, derived from the on-board power requirement and the theoretical mass limit, would require an alternative energy system to exhibit a power density of > 0.15 kW/kg in order to achieve net savings in the mission fuel burn.

Hydrogen fuel and fuel cell systems like this being studied by DLR were identify to be within the required specification because they would benefit from a high exergy density of the fuel. Additional benefits could arise from weight-saving synergies with the aircraft system, such as the use of the water generated in flight in a "multi-functional" PEM fuel cell from burning hydrogen.

One group of options for alternative on-board energy systems considered was the continuous operation of a highly efficient internal combustion engine or fuel cell as "improved APU system" that complements or substitutes the electric energy and bleed air off-take from the main engines. The savings of conventional kerosene would arise from either a significant improvement of the efficiency even in the presence of a weight penalty or the replacement of the APU kerosene with an alternative APU fuel, such as hydrogen. Fuel cells or Diesel engines (both having an efficiency of at least 40% and power-to-weight ratio of 1kW/kg) as APU replacement or improvement (compared to a conventional APU turbine with less than 20% efficiency and 2 to 3 kW/kg) would provide a higher efficiency at the expense of increased weight, volume and system complexity. The main benefit of such a system would come from energy savings and emission reduction during ground operations, and therefore has a higher benefit for short-range missions.

In summary, with fuel cell systems, the main engine kerosene consumption could be improved by 2 – 3%, and ground operations fuel efficiency could be improved by 1 – 4% of mission fuel, depending on the mission duration. Estimated net benefits were 0.7 – 3.5% total mission fuel saving.

5. Diesel Engine as Aircraft APU

This feasibility study effort was performed at Technical University of Sofia in the period 2007 - 2011. It was the doctoral study of the first author of this paper. The study was inspired by the NASA led fuel cell APU feasibility studies and by the successful return of the diesel engines in the light aviation. Because of the technology maturity of the diesel engines and the considerable efforts to continue their improvement by the automotive industry it was expected that Diesel APU could be developed at affordable cost and with minimum technical risks.

Diesel APU benefits were captured as reductions of the flight mission fuel burn and APU fuel burn at the airport. The impact on the APU emissions at the airport was also concerned.

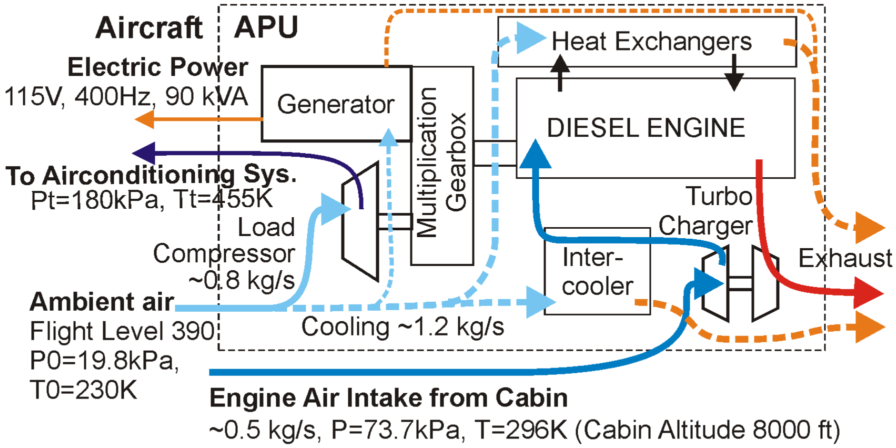


Fig. 3: Diesel APU System Architecture

The Airbus A319 was chosen as a base aircraft for the study. The characteristics of the base aircraft and its engines were identified with the use of records of regular flights from the aircraft digital flight data recorder. The aircraft characteristics were incorporated in a flight dynamics performance model, realized in Matlab.

The aircraft air conditioning system was examined and modeled as a main consumer of the engines bleed air. The influence on the fuel consumption of the bleed air and electric energy off-take from the engines in the entire flight envelope was accounted by an additionally developed model of the engine auxiliary power generation. The modeling was performed with the GasTurb 11 software. A more detailed description of this model is given in [10].

The boosted diesel engine APU concept (fig. 3) suggested that it will replace the gas turbine based APU without substantial changes in the construction of the aircraft. Important assumption was that the diesel APU workflow is taken from the passenger cabin air outflow. This would allow partial recovery of energy used to compress the air for ventilation of the cabin. The expected result was higher economy and better performance in altitude of diesel engine APU.

The performance of the diesel APU was modeled in Diesel-RK software. Historic and present day aircraft diesel engine characteristics were used as a basis. The required engine power was estimated at 300 kW. The performance of two different types of engines was evaluated – turbo and supercharged two-stroke opposed piston engine (Junkers scheme) and turbo-charged four-stroke V-8 diesel engine. It was shown that the specific fuel consumption of both diesel engines could be assumed constant in the entire flight envelope of the airplane.

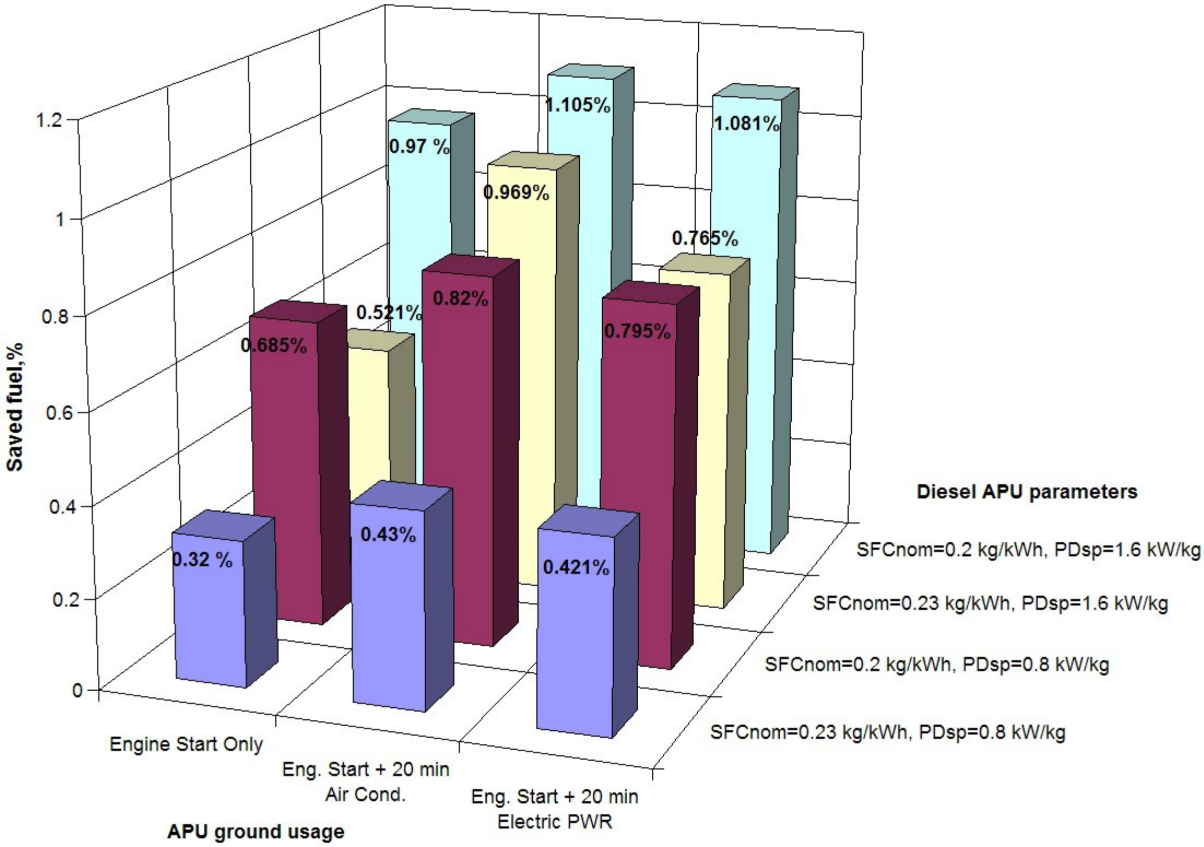


Fig. 4: Total mission fuel saving from Diesel APU

The impact of the diesel APU on the ground was evaluated for 3 cases of APU usage. First – for engine start only, second – for 20 min. cabin preconditioning and engine start, and at the end for 20 min. flight preparation without air bleed and engine start.

The evaluation of the flight performance of the airplane with the diesel APU was performed for 3 flight scenarios – flight at maximum range with full load, flight at 2500 km with 80 % payload and flight at 2500 km with 100 % payload. The evaluation was performed as a parametric study for a range of diesel APU specific fuel consumption of between 0.2 and 0.23 kg/kWh, and specific power of between 0.6 and 1.6 kW/kg.

The weight estimation of the Diesel APU showed that it would not affect significantly the aircraft mass and balance.

The results of the study showed that at the airport the diesel APU can provide a fuel saving in excess of 25 – 32 kg daily (6 – 8 flights per day). If a two-stroke diesel APU is used a significant reduction of the NOx emissions can be achieved without any special measures. In the case of four-stroke engine the reduction can be achieved by the means used in the automotive industry (EGR systems etc.).

In flight the diesel APU can provide fuel reduction of 0.5 – 1 %, with negligible or small positive (0.5%) influence on the maximum range.

The overall fuel saving on the ground and in flight from the diesel APU showed to exceed 1% (fig. 4). It will be more sensible for aircraft flying on short distances with high frequencies.

The results of the Diesel APU feasibility study at Technicak University of Sofia were in coincidence with the SWAFEA results, but they provided more accurat estimate of the fuel saving potential of the concept.

6. Discussion

The studies overviewed so far in this paper concerned the implementation of improved APU systems on turbofan airplanes as being the most numerous types of commercial airplanes. However it must be stated that such systems can be even more beneficial for turboprop airplanes. This assumption comes from the following facts:

- The turboprop engine while having higher propulsive efficiency in comparison with the turbofan possesses a lower thermal efficiency because of the smaller size of the engine core, and so the effect of the engine zero bleed-air and zero electrical power off-take will be higher.
- The turboprop airplanes serve at smaller airports were the ground equipment for substitution of APU operation not always exists.
- The turboprop airplanes serve on short routes with high total turn around times on the ground, were the effect of the improved APU system is most notable.

In this role the diesel APU will have certain additional advantages over the fuel cell variants in terms of operational and handling simplicity.

Another class of aircraft were especially the Diesel APU may have a great effect is the class of military tactical transport aircraft such as CASA C-295, C-27J Spartan, etc. In this case the above stated arguments for civil turboprop airplanes are largely valid.

Some what different is the situation for the patrol and early warning and control versions of this type of aircraft, which perform longer missions. It may be expected that because of the enhanced electric power needs of the special systems of the aircraft the implementation of improved APU will have positive effect on the maximum flight duration. It may be assumed also that the improved APU added to the main engine generators will improve also the system redundancy and reliability.

These are interesting fields of exploration that need to be addressed in the future.

7. Conclusions

In conclusion it may be stated that the fuel cell APU systems can be seen as a long term solution to minimize the fuel burn and the emissions of the passenger aircraft. However there is a bulk of unsolved technological problems, concerning the implementation of SOFC as well as PEMFC.

On the other hand the posibility to use Diesel APU as an advanced APU system is still overlooked. Although the Diesel APU may be heavier than the current conventional gas turbine APU, its weight disadvantage can be offset by fuel savings in the higher Diesel APU system efficiencies against the main engine bleed and extraction during cruise. The higher Diesel APU system efficiency compared to the conventional APU on the ground can also provide considerable fuel saving and emissions reduction. Compared to the resent fuel cell APU concepts the Diesel APU can provide comparable fuel savings, but at much lower levels of technical risk and capital costs.

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