THE AUXILIARY POWER UNIT BASED ON PEM AND HYDROCARBON FUELS FOR MORE ELECTRIC AIRCRAFT

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Abstract

The paper represents a results of theoretical and experimental researches of fuel cells application in aviation auxiliary power units (APU) fuelled by aviation kerosene. Comparative analysis of APU’s different schemes is given. The influence of air compression ratio to efficiency of APU based on proton exchange membrane fuel cells (PEM) is analyzed and shown in the paper. There is assigned that operation with a moderate compression ratio is advisable to APU on PEM.

Nomenclature

\( G \) mass flow rate
\( L \) specific work
\( H_u \) caloric value
\( \delta H_u \) fuel energy losses in reformer
\( \alpha \) excess air ratio
\( K_{H_2} \) hydrogen separation coefficient
\( n_c \) gas pressure ratio in compressor
\( T \) temperature

Subscripts

\( t \) turbine
\( c \) compressor
\( b \) battery
\( f \) fuel

Abbreviations

APU - auxiliary power unit
SOFC - solid oxide fuel cells
PEM - proton exchange membrane fuel cells

Introduction

At present a prospects for the development of civil aviation are associated with the creation of a "total electric airplane" in which all of the onboard systems operate using electric energy. Total power consumption in this airplane becomes a very high and in the perspective airplane similar to B-787 the auxiliary power unit (APU) has to provide an electric power at 1500 kW. One of the most promising ways to improve the APU characteristics is the usage of fuel cells which have a high efficiency and good environmental performances [1].

There is no combustion of the fuel in fuel cells as it takes place in heat engines. Instead of it a direct converting of chemical energy into electrical one is realized. In contrast to the rechargeable battery the fuel cells are able to operate a long time if continuously feeding of fuel and oxidant is provided. The air or oxygen is used as an oxidant. The hydrocarbons, alcohol and biogas are considered as a fuel, which can be converted into syn-gas (the mix of \( H_2 \) and CO) in special reformer.

The increase of interest to fuel cells is caused mostly via successes in creation of proton exchange membrane fuel cells (PEM) and solid oxide fuel cells (SOFC).

PEM are very perspective fuel cells type, which is able to generate a high power densities (0.5 - 0.8 kW/kg, in future up to 1.5 kW/kg). PEM typically operate...
at medium temperatures (+60 – +90°C) allowing a faster startup. On the other hand medium temperature causes the use of expensive platinum-based catalyst. PEM uses pure H₂ as a fuel and oxygen or air as an oxidant. The hydrocarbons use leads to the significant complication of construction since the extraction of pure H₂ from fuel is needed together with a need to CO suppresses which content should be not more then 10 – 50 ppm. This is due to the fact that CO poisons the catalyst and decreases power characteristics of PEM.

PEM membrane conductivity is dependent on its water saturation. Therefore, one of the problems in such fuel cells is a need for humidification of the hydrogen and sometimes the air too which is supplied to fuel cells. PEM usually have a planar structure consisting of individual cells.

SOFC is also one of the most promising types of fuel cells. At present the zirconium oxide ceramic ZrO₂ with 8 mol% of yttrium oxide Y₂O₃ is used as the electrolyte in SOFC. This electrolyte is an excellent conductor of oxygen ions at a temperature more than 800°C. SOFC operates at temperatures of 700-950°C (lower temperatures correspond to the thin-film electrolytes). Due to the increased temperature all processes (reaction, diffusion, adsorption and etc.) occur rapidly and therefore SOFC does not require the use of expensive catalysts. However SOFC requires preheating. The transition to thin-film electrolytes leads to reduce the heating time of SOFC as well as the size of the structure and allows to operate at lower temperatures. All components of SOFC are solid, so they may be formed as very thin layers with unique shapes, what is impossible in case of fuel cells with the liquid electrolyte. At present a new thin-film technology of SOFC creation is developed [2].

The SOFC advantage is relatively high resistance to the various adverse effects and the ability to use CO as fuel in addition to H₂. This makes it possible to use mixture of CO and H₂, so-called syn-gas as a fuel in SOFC. Syn-gas may be obtained from a liquid jet fuel through the autothermal reforming (ATR).

Thermal energy generated by SOFC can be used in reformer where liquid fuel is converted into syn-gas. In this case it is possible to improve the total efficiency of APU. This possibility has been discussed in [3 – 6].

All advanced countries focus on creation of a new generation of aviation APU based on fuel cells (FC) [1, 2, 6 –10]. In particular one of the most effective and simple scheme of APU based on SOFC operating on hydrocarbon fuels (fig. 1) is described in [1, 5].

![Fig. 1. The scheme of APU based on SOFC: 1 - fuel cell battery; 2 - reformer; 3 - afterburner; 4 - gas turbine; 5 - air compressor; 6 - electric generator.](image-url)
not allow to make a clear choice of the most efficient scheme of APU based on fuel cells.

This paper is intended to conduct a comparative analysis of the effectiveness of three APU schemes based on advanced fuel cells: PEM and SOFC.

**Efficiency of APU based on FC**

The first scheme considered in this paper is a scheme of APU based on SOFC which represented on (fig 1).

The basic part of unit is a SOFC battery fuelled by jet fuel converted into a syn-gas in reformer (2) due to autothermal reforming \[11, 12\]. The water and atmospheric air participates in this reaction besides an initial fuel. The afterburner (3) attached to the SOFC (1) outlet is used for an unused fuel burning because SOFC can’t convert a fuel completely.

The second important part of such APU is a gas-turbine unit (GTU) consisting of turbine (4), air compressor (5) and electric generator (6). Air compressor realizes supercharge of SOFC battery. Gas turbine has a power surplus with respect to compressor power, and so the electric generator is installed on turbine shaft. Thereby, the electric energy is generated by SOFC battery and electric generator.

The scheme of APU on aviation kerosene in case of PEM using is complicated considerably. At the first the initial fuel – aviation kerosene – is necessary to convert into syn-gas, then into hydrogen by the additional transformation of “shift reaction”: \[CO + H_2O = CO_2 + H_2\]. Received hydrogen should be cleaning from CO remains and cooling until a temperature which can be used in PEM battery.

The scheme of such unit is represented in fig 2. APU based on PEM with a direct conversion of kerosene into hydrogen consists of two autonomous subsystems: turbocompressor (A) and electrochemical (B). The first includes air compressor (1), gas turbine (2), electric generator (3) driving by the gas turbine and combusator (4) with a burning of hydrogen unused in fuel battery (11). The part of air required for the hydrogen burning passing-by in combusator, not feeds in fuel battery. Turbocompressor subsystem represents as a hot air source. This air enters in combusator (7) where conversion of kerosene into syn-gas is occurred. The increased air flow (up to \[\alpha_C \approx 0.32\]) should supplied in reactor as a heat for chemical reactions in combusator can proceed due to fuel oxidation only. The water is added into syn-gas, and this gaseous mixture participates in shift reaction on special catalyst in reactor of water shift (8). As a result the gas coming in PEM fuel battery has 100% moisture and contains 10% (mass.) hydrogen and 90% inert gases from the point of view of electrochemical reactions realization: \[N_2, H_2O, CO_2\]. Obtained gas is fed into anode area of fuel battery. Leaving the fuel battery anode and cathode gases enters in combustor (4) where burns out and forms a working agent for gas turbine (2). The air is supplied with a minor surplus in PEM battery (11) relative to hydrogen feeding in battery. The operation temperature is kept up at 90°C. The water cooling system utilizes a heat escaping in fuel battery.

Membrane technologies for a hydrogen generation \[13\] are investigated actively at the last time. They allow realizing a better scheme of APU based on PEM (fig 3). This scheme is similar to scheme of SOFC noted earlier, but reactor of water shift (8) includes a membrane for extract of hydrogen from gas mixture. The palladium membrane \[13\] or porous ceramic membranes with palladium compounds can separate hydrogen from gas mixture. Such membranes are able to operate at elevated temperature (-500°C). The
supposed APU scheme consists of two subsystems as in the previous case: turbocompressor and electrochemical. Turbocompressor is kept similar to scheme noted earlier. Condenser (9) is used for air cooling coming from compressor.

Hydrogen follows to PEM battery (14). Remaining gases from reactor is received in turbocompressor combustor.

**Fig. 2.** Scheme of APU based on PEM with kerosene conversion into hydrogen. A – turbocompressor; B – electrochemical generator; 1 – compressor; 2 – turbine; 3 – generator; 4 – combustor; 5 – heat exchanger; 6 – reformer; 7 – conversion reactor; 8 – reactor of water shift; 9, 10 – condenser; 11 – PEM battery.

**Fig. 3.** Scheme of APU based on PEM with membrane reformer. A – turbocompressor; B – electrochemical generator; 1 – compressor; 2 – turbine; 3 – generator; 4 – combustor; 5 – heat exchanger; 6 – reformer; 7 – conversion reactor; 8 – reactor with H₂ membrane extraction; 9 – condenser; 10 – PEM battery.

The calculations of SOFC battery are carried out with methods stated in [14, 15]. The specific power of perspective thin-wall SOFC is accepted at 2.7 kW/kg. On the basis of present constructions and forecast of their development the specific power of PEM is taken 1.5 kW/kg. Voltage-ampere characteristics of PEM presented in [16] are used for PEM battery calculations.

A similar turbocompressor is used to conducting a comparative analysis of characteristics of different APU. There is assumed that all schemes are fuelled by aviation kerosene and can use liquid water as additional reagent for syn-gas generation.

It should be noted that all types of APU have to provide a total
power 100 kW. Calculations for comparative analysis of different APU are made at normal conditions (288.15 K, 101325 Pa). Pressure boost degree in the compressor is assumed 5.0, efficiency of the one is 0.7 and efficiency of the turbine is 0.8.

For APU based on SOFC (variant 1) the syn-gas required for fuel cells is generated from jet by ATR. Thermodynamical analysis shows that CO and H₂ production without a coke formation is possible at temperature in reactor equal to 1150 K and fuel-to-water flow ratio equal to 0.63. It is necessary to heat leading in the reactor for guarantee a high temperature in this one at assigned air and water excess (even taking into account the air increased temperature). For this purpose it is used a heat generated by SOFC battery. The operating temperature in reformer is at 1200K. Due to the fact that SOFC uses CO, not only H₂, the fuel utilization ratio can be achieved at 0.9.

Thermodynamic analysis of kerosene conversion into syn-gas with CO reduction showed that the excess air ratio must be taken equal to 0.32 and total flow rate in both reactors – 3.4 kg per 1 kg of kerosene for variant 2.

For variant 3 based on PEM the excess air ratio in reactor of conversion is selected equal to 0.34 by optimization calculations. The optimum ratio of fuel and water in this case is 1.12.

Table 1 presents the initial data for calculation of all APU variants. Table 2 shows the additional initial data for the SOFC battery. The main results of the APU different schemes calculations are presented in diagrams (Fig. 4 – 6).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Based on SOFC (variant 1)</th>
<th>Based on PEM (variant 2)</th>
<th>Based on PEM (variant 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation temperature of SOFC battery, C</td>
<td>950</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Fuel utilization ratio in battery</td>
<td>0.9</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>H₂ utilization ratio</td>
<td>0.9</td>
<td>0.95</td>
<td>1.0</td>
</tr>
<tr>
<td>Residence time in reformer</td>
<td>0.15</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>Excess air ratio in reformer</td>
<td>0.2</td>
<td>0.320</td>
<td>0.320</td>
</tr>
<tr>
<td>Excess water ratio in reformer</td>
<td>0.49</td>
<td>2.1839</td>
<td>1.12</td>
</tr>
</tbody>
</table>

| Maximum specific surface power of SOFC at normal pressure of reaction agent and running by hydrogen, W/cm² | 0.7 |
| Maximum specific surface power of SOFC at normal pressure of reaction agent and running by syn-gas, W/sm² | 0.56 |
| CO mass fraction in CO+H₂ mixture              | 0.882                      |
| H₂ mass fraction in CO+H₂ mixture              | 0.118                      |
Analysis of results

The obtained results allow pointing out some features of these schemes.

The excess air ratio (Fig. 4) in variant 1 was significantly larger than in other variants. This is explained by air using to remove an excessive heat in SOFC battery, while in variants 2 and 3 the operating temperature is maintained by a water cooling contour. In the last three variants the air usage for cooling is not possible due to the fact that the air temperature after compressor is at approximately 160 K higher than the PEM operating temperature.

Fig. 4. Excess air ratio in different APU

Fig. 5. Mass of different APU

Fig. 6. Energy utilization ratio of jet fuel in fuel battery

Fig. 7. H₂ utilization ratio in the fuel battery

Fig. 8. Efficiency of different APU

APU based on SOFC (variant 1) provides the simplest scheme of working process with a high chemical energy utilization of
hydrocarbon fuels. In variant 1 the electrochemical part includes two important elements only: SOFC battery and reformer. And the last one is the most compact and lightweight design compared to other variants. This is related to minimal air and water excess as well as an absence of the need to CO inhibition. As a result APU based on SOFC has a smallest mass (Fig. 5). Due to the fact that the SOFC battery is used CO+H₂ mixture, not only H₂, the fuel utilization ratio can be achieved at 0.9 (Fig. 6). As a result this scheme of APU allows to get a highest efficiency at minimum weight (Fig. 8). The ensuring of 100% fuel utilization is not possible because the anode gas of SOFC is obliged to pass the reaction products from battery.

APU based on PEM with the traditional conversion reactor (variant 2) provides a worst performance by weight and efficiency. Basically this is due to large losses of chemical energy (more than 30%) of jet fuel at syn-gas conversion with a suppression of CO content by a significant water excess. In addition the fuel conversion leads to a significant amount of methane CH₄ (5% at the reactor outlet and 7% after water removing in the condenser) in the syn-gas and allows to reduce the CO content to 50 ppm by reasonable water using. Taking into account that H₂ is fed in anode chamber with inert and combustible gases in this variant, it is not possible to achieve 100% hydrogen utilization as in variant 3 (Fig. 7). The total fuel utilization ratio in PEM battery is much less than H₂ utilization due to the presence of other combustible substances. Due to the use of a large water and air excess the conversion reactor is obtained bulky and exceeds the weight of reactor in variant 1 and 3.

APU based on PEM with membrane reactor (variant 3) provides a slightly worse performance than the variant 1, but significantly better than the variant 2. Compared to the variant 1 this variant has a more complicated facilities, bulkier reactor, greater mass and a water cooling contour. It is expected that the control system will be also more complex than in variant 1. As compared with the variant 2 the given system provides the efficiency more than 2 times higher and weight less than 15%. In membrane reactor the fullness of CO and H₂ conversion in water shift reaction is achieved by H₂ removing (shift reaction product) from reaction zone, not due to water excess as in the variant 2. As a result the reactor requires a significantly less water feeding than in the case 2. In addition this type of reactor allows to reduce the CO concentration to zero and get a higher yield of H₂ compared to variant 2. The chemical energy loss of initial fuel is equal to 16%. Despite the longer residence time of reagents in membrane reactor the reactor mass is less than the weight of reactor in variant 2 due to less water consumption. The pressure in membrane reactor is equal to 5 atm. At the same time the hydrogen partial pressure is 1.8 atm and the pressure in PEM battery is 1.5 atm, which associated with the H₂ separation using. The thermodynamic efficiency of such PEM variant is maximized due to pure H₂ supplying in anode chamber. The anode cavity PEM becomes dead-end and provides a 100% H₂ utilization because this PEM uses pure hydrogen. But because the remains of other combustible gases from reactor are transferred to combustor, the total fuel utilization in electrochemical generator is smaller than in variant 1. Gases after PEM battery do not enter in combustor of turbocompressor unit and as a result its mass is a smallest of all the variants. For the same reason the generator power and weight are smallest, and the power
and weight of FC battery are maximum because a total electric power should be the same in all variants. APU total mass is smaller than in variant 2 despite the fact the power and weight of battery are maximum in this scheme. It is related to smaller masses of the conversion reactor and the cooling contour.

There is a water cooling contour in variants 2 and 3. The cooling of fuel gases at the inlet is not required, so the cooling contour is simpler and easier in variant 3. In variants 2 and 3 the water is used as a coolant, which may give its heat to kerosene (variant 2 to reset the heat flow capacity equal to 168 kW, and option 3 - 72 kW).

**Perspective of APU based on PEM efficiency increasing**

The necessary condition of power unit operation becomes combustion of fuel part in combustor before the turbine in the case of PEM which responds adversely to the APU efficiency.

Let consider the APU without electrogenerator and supplying of additional fuel into combustor (Fig. 9). We determine a compression ratio value in the compressor which provides operation of the contour.

![Fig. 9. Scheme of APU based on PEM. 1 - PEM battery, 2 - conversion reactor, 3 - combustor, 4 - turbine, 5 - compressor.](image)

The power balance on the compressor and turbine is:

\[(G_t + G_b)L_c = (G_t + G_f)L_t \approx G_t L_t, \quad (1)\]

where \(G_t, G_b, G_f\) - accordingly, the gas mass flow rate of turbine, the air in PEM battery and fuel; \(L_c\) - the compression specific work of air compressor; \(L_t\) - the gas specific work on turbine.

From equation (1) it follows:

\[G_b L_c = (L_t - L_c)G_t, \quad (2)\]

where the reduced free energy of the turbine \(g_t = \frac{G_t}{L_t}\).

The energy of jet fuel supplied to the APU is equal to \(u_H G_f\), where \(u_H\) - lower calorific value of fuel. The hydrogen energy produced in reactor will be equal to \(H_u G_f (1 - \delta H_u)\), where \(\delta H_u\) - the energy loss of hydrogen relative to jet fuel. If the hydrogen separation ratio through membrane is \(K_{H2}\), the energy of hydrogen supplied to PEM battery will be equal to \(H_u G_f (1 - \delta H_u) K_{H2}\).

Thus the energy of combustible gases coming from reactor into combustor is equal to:

\[\Delta Q = H_u G_f \delta H_u + H_u G_f (1 - \delta H_u) (1 - K_{H2}). \quad (3)\]

Knowing the value \(\Delta Q\) it is possible to determine the gases temperature at turbine inlet: \(T_t = T_c + \Delta Q / (C_p G_t)\), where \(C_p\) - the heat capacity of gases. Using (3) we find:

\[T_t = T_c + H_u G_f \frac{\delta H_u + (1 - \delta H_u) (1 - K_{H2})}{C_p G_t} G_t. \quad (4)\]

Hydrogen flow in battery can be determined by the ratio:
Air flow in PEM battery can be expressed as 
\[ G_b = \alpha_b L_0 H_2 f, H_2 \alpha \]
where \( \alpha_b \) - the excess air ratio in PEM battery, \( L_0 H_2 \) - the stoichiometric ratio of hydrogen and air.

Using (5), we can define:
\[ G_b = \alpha_b L_0 H_2 \frac{H_u (1 - \delta H_u) K_{H^+}}{H_u, H_2} G_f \]  

(6)

The air flow in combustor is equal to \( G_t = G_b / G_f \).

Using (6), we can get:
\[ G_t = \frac{1}{L_g} \frac{H_u (1 - \delta H_u) K_{H^+}}{H_u, H_2} G_f \]  

(7)

These equation allows to obtain dependences \( T_t, G_t/G_f \) and \( L_g \) vs. air compression ratio. Fig. 10-12 shows these dependences obtained for different values of turbine and compressor efficiency. \( L_g \) is calculated at \( T_t = 900 \text{K} \). Thus \( \pi_K \) can be found graphically (Fig. 10) which ensures the temperature at turbine inlet 900 K (see the dashed lines in Fig. 10-12). From the results it follows that the efficiency of this APU (Fig. 10) with a temperature of 900 K at turbine inlet may be provided at \( \leq 2 \) if compressor efficiency is 0.75 and turbine efficiency is 0.85. If the compressor efficiency is equal to 0.7 and the turbine - 0.8 it should be less than 1.2. The increase is involved by the additional fuel supplying in combustor.

Fig. 10. The temperature in turbine inlet vs. air compression ratio. Efficiency: 1 - compressor 0.75, turbine - 0.85; 2 - compressor 0.7, turbine - 0.8.

Fig. 11. The ratio of mass flow rate of gas vs. air compression ratio. 1 - compressor efficiency 0.75, turbine - 0.85; 2 - compressor efficiency 0.7, turbine - 0.8.
Fig. 12. Given free energy of the turbine \( T_g = G_b/G_t \) vs. air compression ratio. Efficiency: 1 - compressor 0.75, turbine - 0.85; 2 - compressor 0.7, turbine - 0.8.

If conduct a similar calculations for various temperatures at turbine inlet it is possible to build the ultimate functional dependence \( T_c = f(\pi_c) \) that does not required an additional supply of fuel into combustor. This curve forms two typical zones (Fig. 13): zone 1 which does not require the fuel supply to combustor and zone 2 which requires submission of additional fuel to combustor.

Thus at a low compression ratio of compressor (\( \pi_c < 2 \)) and a mild temperatures at turbine inlet (at 900K) the turbocompressor operation without an additional fuel burning in combustor becomes possible. The efficiency of such schemes increases in comparison of described schemes based on PEM and is at 30%.

Fig. 13. Typical zones of APU based on PEM vs. \( \pi_c \)

Conclusions

The analysis of three schemes of APU based on the fuel cells shows that the most effective is APU based on SOFC. In APU based on PEM the energy utilization of jet fuel is reduced compared to SOFC due to the need to get hydrogen and to eliminate carbon oxide.

Among the considered APUs based on PEM the APU with membrane technology of hydrogen separation is the most promising.

The efficiency of APU based on PEM can be improved by using small compression ratio in air compressor (\( \pi_c < 2 \)). This eliminates the extra fuel supply into the combustor as well as the electric generator. APU efficiency is increased in this way up to ~ 30%.

Since APU based on PEM does not need a large excess air ratio in order to keep a heat balance, as it is needed in SOFC battery, air supply to APU may be realized from the passenger cabin where air pressure is hold at 0.85 atm.
Aknowledgement

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References