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CONSIDERATIONS REGARDING DEVELOPMENT OF ALTERNATIVE PROPULSION IN AVIATION

SUMMARY

Ecological indications and the depletion of fossil fuel resources are the main reasons for current studies of alternative propulsion in aviation i.e. for searching for new regenerative energy sources. The technical and technological presumptions for the transfer from the conventional to alternative fuel are more radical than the transition from piston to jet propulsion. The main problems include the production of liquefied hydrogen, the necessary aircraft structure modifications, and the required infrastructure support.

1. INTRODUCTION

Aircraft as well as vehicles of other branches of transport belong to the group of anthropogenetic polluters with harmful impact on the environment due to the pollution caused by the combustion of fossil fuels. The growing efforts of the international community regarding environmental protection have resulted lately in a number of restrictive measures of protection as well as in announcing operative restrictions which present a limiting factor in the further development of conventional traffic forms.

The discrepancy of relation between the stricter ecological regulations and the planned growth of traffic, presents the aviation with a new task of finding out an alternative, environmentally friendly source of energy.

Research of the new fuel has been at the same time also supported by the fact that the resources of fossil fuels have been estimated to about 40 years (of natural gas to about 60 years) provided that the current annual consumption is retained.

The expected fluctuations on the world oil market will certainly have repercussions in the form of economic limitations regarding the usage of aircraft, more so, since the fuel costs have a significant share, of 20-30%, in direct exploitation costs, i.e. 10-20% in the overall costs of the airline companies.

2. AIR TRAFFIC AND THE CLIMATE

The emissions of CO_2, CO, CH_4, NO_x, caused by traffic as well as the incomplete combustion of hydrocarbons, significantly affect the balance in the global climate in all the three ecological indications:

- the change of balance in the Earth radiation due to anthropogenetic greenhouse effect linked with the change of the global climate, i.e. the global warming up of the lower layers of the troposphere,
- the change of the ozone content in the atmosphere which affects, on the one hand, the intensity of radiation to the Earth surface and the filtration of the harmful UV-radiation, while on the other hand, the ozone is a significant greenhouse-gas,
- the change of the atmospheric oxidation capacity due to the increased tropospheric concentration of ozone, and by the impact on the bio-geo-chemical circulation of other, ecologically important oligo-substances.

In evaluating the role that certain traffic forms play in the change of climate, air traffic has a special place.

Although air traffic participates in the overall emissions of CO_2, NO_x, CH_4 and CO with quantitatively small volume, the most significant is the pollution at cruising altitudes, i.e. in the region of tropopause, where the aircraft are the only anthropogenetic polluters.

These are the altitudes (8-12 km) marked by the following:

- naturally conditioned concentrations of these oligo-gases are very small,
- their resistance period (time until decay) is many times longer than in the lower layers of the troposphere,
- the measured values of atmospheric temperatures are the lowest, and the pollution has greater impact than the analogue concentrations above the Earth surface,

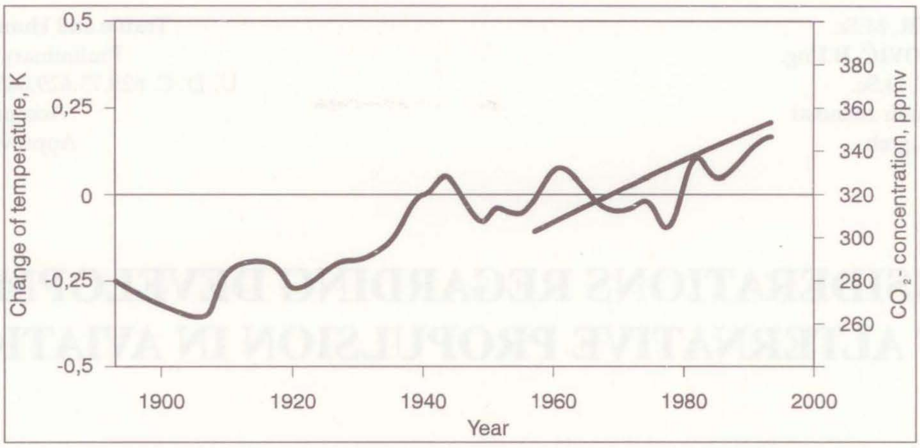

Figure 2.1. The change of temperature depending on the increase of tropospheric concentration of carbon dioxide[1]

The world aviation participates with about 60% in the overall annual fuel consumption, and 70% of that is in commercial aviation.

About 3% of the overall annual CO_2 emission is caused by the air traffic.

The amount of water vapour caused by the aircraft is negligible compared with its amount in the atmosphere caused by evaporation from the Earth. However, it is significant that the vapour in the stratosphere and at the upper boundary of the tropopause, where it has an extremely harmful impact and dominates compared to other greenhouse-gases, is caused exclusively by the aircraft.

The amount of emitted nitric-oxide, mainly at the cruising altitudes is generated by air traffic with only 3% in the overall anthropogenetic NO_x-emissions, but this amount is of the same order of magnitude as the natural pollution of this gas from the stratosphere into the troposphere.

The proportion in the atmospheric content of CO, CH_4 and SO_2, generated by air traffic is insignificant.

Aircraft pollution is most intense in the northern hemisphere, mainly above the European and American continents and in the main air corridors over the Atlantic and the Pacific.

The increase of NO_x-concentrations at the central latitudes of the northern hemisphere are significant. The proportion caused by air traffic in the overall NO_x-emission of the upper troposphere has been quantified with 40%.

Table 2.1. Comparison of the amount of pollution caused by air traffic and by other sources

FUEL CONSUMPTION			
Air traffic (mill. t/year)		Total (mill. t/year)	
176		3140	
EMISSIONS			
Pollutant	Air traffic (mill. t/year)	Other sources (mill. t/year)	Source
CO_2	554	20900	Fossil fuel combustion
H_2O	222	45 25000	Methane oxidation into the stratosphere Evaporation from the Earth
NO_x	3.2	2.9 ± 1.4 90 ± 35	Transfer stratosphere - troposphere Anthropogenetic sources
CO	0.26	600 ± 300 1490	Methane oxidation Anthropogenetic source
CH	0.1	90	Anthropogenetic sources
Soot	0.0025	–	–
SO_2	0.176	0.0625 134	Stratospheric aerosol Fossil fuel combustion

Source: Enquete-Kommission "Schutz der Erdatmosphäre" des Deutschen Bundestages, Mobilität und Klima, Economica Verlag, Bonn, 1994.

Apart from the direct impact on the greenhouse-effect, which is ten times greater at the boundary of the tropopause than in the lower layers, the pollution of water vapour caused by air traffic has an additional influence on the climate due to the formation of the so-called condensation trails which facilitate the formation of high, icy cirrus-clouds.

At poles, where the tropospheric boundary is at the altitude of 8-9 km, the cruising aircraft fly regularly through the stratospheric layer, where the pollution of vapour is doubly harmful: on the one hand, it is indicated by the formation of polar stratospheric clouds which affect the ozone depletion, and on the other hand, in the cumulation of cirruses which increase the greenhouse effect[2]. The sources estimate that the aircraft H_2O-emission participate in the increase of cloud formation between 0.4-2%.

NO_x-pollution has an indirect impact on the climate in increasing the ozone content in the area of the tropopause due to the chain photochemical reaction with CH_4, CO and OH.

The new estimates regarding the proportion of air traffic in the ozone formation range from 7-12%, and assuming further increase of air traffic at the annual rate of 5%, the air traffic conditioned increase in the ozone concentrations at the cruising altitudes will amount to 20-30%.

SO_2-emissions of aircraft also affect the climate indirectly, since they contribute to the depletion of the ozone layer by means of the sulphate-aerosol, and over the last twenty years its stratospheric concentration has shown an annual increase of 5%.

2.1. Conventional propulsion (kerosene)

The composition of kerosene used in aviation is specified by the IATA standards.

Thus specified kerosene denoted as "Jet A1/J-A1" contains: 85.5% carbon, 14.25% hydrogen, 0.2% oxygen and 0.05% sulphur (mass %).

The specific fuel density is 0.79 kg/l.

Primary products resulting from kerosene combustion are at the same time the most relevant atmospheric pollutants, indicated by the anthropogenetic greenhouse-effect: carbon dioxide and vapour.

Studies (DASA, MTU)[3] regarding prevention of harmful exhausts from aircraft using conventional propulsion, consider exclusively technical improvement, which includes two aspects of reduction measures:

- improvement of the overall aircraft aerodynamics, primarily by the application of the so-called variable wing (flying surfaces) curvature, which, due to the reduced aerodynamic drag results in substantial reduction of fuel consumption and thus also in the reduction of the absolute magnitude of pollution.

Table 2.2. Mass of pollutants caused by combustion of 1 kg kerosene with 3.4 kg oxygen in cruising flight

Pollutant	$g_{\text{harmful substance}} / kg_{\text{kerosene}}$
Carbon dioxide (CO_2)	$3.15 \cdot 10^3$
Water vapour (H_2O)	$1.24 \cdot 10^3$
Nitric oxide (NO_x)	6 - 19
Carbon monoxide (CO)	0.7 - 2.5
Incombustible hydrocarbons (CH)	0.1 - 0.7
Sulphur dioxide (SO_2)	1
Soot (C)	0.01 - 0.03

- design of the new generation of propfan-engines with the new concept of the combustion chamber with a substantially reduced specific fuel consumption as well as the relative proportion of pollutants, especially nitric oxide.

3. COMPARISON OF ALTERNATIVE AND CONVENTIONAL FUEL

A comprehensive research and the study of the aircraft alternative propulsion have been included in the German - Russian project "Cryoplane".

The leading companies included in this project (DASA, MTU, Dornier, Tupolev, Trud etc.) are currently concentrated on the technology of critical components, and the maiden flight of the demonstration aircraft is scheduled for the first decade of the next century.

The liquefied hydrogen has come out as the only long-term solution both from the aspect of environmental protection and from the aspect of energy resources.

The study of liquefied methane has indicated the possibility of its application as alternative fuel in the transition phase or in special cases, e.g. in the Russian Federation which has significant resources of natural gas.

In normal atmospheric conditions, hydrogen and methane are gases, and they are converted into liquefied state by cooling (Cryo-technique), thus reducing their volume.

The ratio between energy and mass in liquefied hydrogen is approximately 2.8 times greater, and in liquefied methane approximately 1.2 times greater than in kerosene.

On the contrary, the volume of the liquefied hydrogen is 4 times greater, and the volume of liquefied methane is 1.6 times greater than the volume of energy-equivalent kerosene.

Comparative analysis of kerosene, natural gas, and hydrogen is based on the products of their combustion.

Table 3.1. Products of combustion of conventional and alternative fuel

	KEROSENE	METHANE	HYDROGEN
Primary product	CO_2	H_2O	H_2O
	H_2O	CO_2	
Secondary product		$CH_4 \rightarrow H_2O + CO_2$	
	$NO_X \rightarrow O_3$	$NO_X \rightarrow O_3$	$NO_X \rightarrow O_3$
	$CH \rightarrow O_3$		
	$CO \rightarrow O_3$	$CO \rightarrow O_3$	
	$SO_2 \rightarrow H_2SO_4$		
	Soot		

Primary products of kerosene and methane combustion are carbon dioxide and water vapour in various proportions, whereas the only product of hydrogen combustion is the vapour.

The combustion of alternative fuels avoids to a great extent the harmful secondary products immanent to kerosene, except for nitric oxide.

Significant, however, is the production of vapour in hydrogen combustion, which is 2.6 times greater compared to kerosene.

The basic criteria in analysing alternative fuel i.e. application of alternative propulsion in aviation are summarised in two questions:

- Is the change of combustion primary products environmentally more friendly (ratio H_2O/CO_2)?
- Can NO_x-emission be reduced?

3.1. Comparison of vapour and carbon dioxide influence

At the altitudes of up to 6 km the influence of water in gaseous state as pollutant in the greenhouse effect is less than the influence of carbon dioxide.

Table 3.2. Comparison of physical properties of kerosene and alternative fuels

	Unit of measure	Kerosene (J-A1)	Liquefied hydrogen (LH_2)	Liquefied methane (LCH_4)
Mass (energy equivalent)	kg	1	0.357	0.856
Volume (energy equivalent)	l	1	4	1.6
Ratio energy/mass	kJ/g	42.8	120	50
Liquefying temperature	°C	-	-253	ca. -160

Source: Daimler-Benz Aerospace Airbus GmbH.

With the increase in altitude, the ratio of H_2O/CO_2 effect is multiplied almost up to the factor 200 provided the number of emitted molecules remains the same, which at the first glance suggests that pollution caused by hydrogen combustion has a more harmful impact on the environment than the pollution caused by the combustion of kerosene.

However, in estimating the overall influence, the resistance time of water and carbon dioxide in the atmosphere should not be neglected.

Whereas the time of resistance (τ) of water ranges from two weeks at lower altitudes to approximately 1 year at the altitudes of 15 km, the resistance time of anthropogenetic carbon dioxide takes approximately 100 years and does not depend on the altitude of emission.

Therefore, overall influence on the greenhouse effect should be estimated as the function of:

- current effect of one molecule (fn_{to})

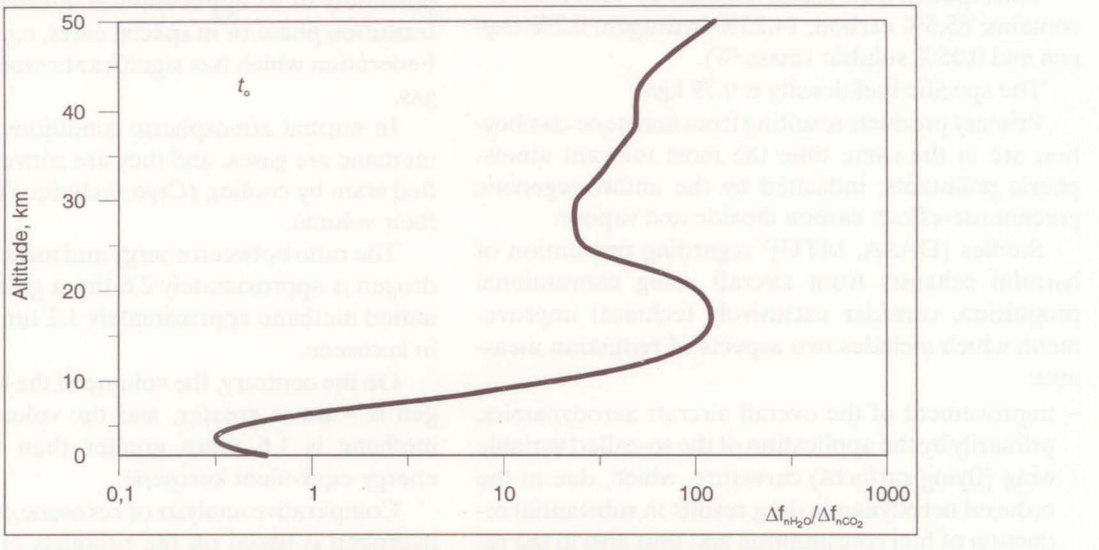

Figure 3.1. Relation of unit influence of vapour and carbon dioxide

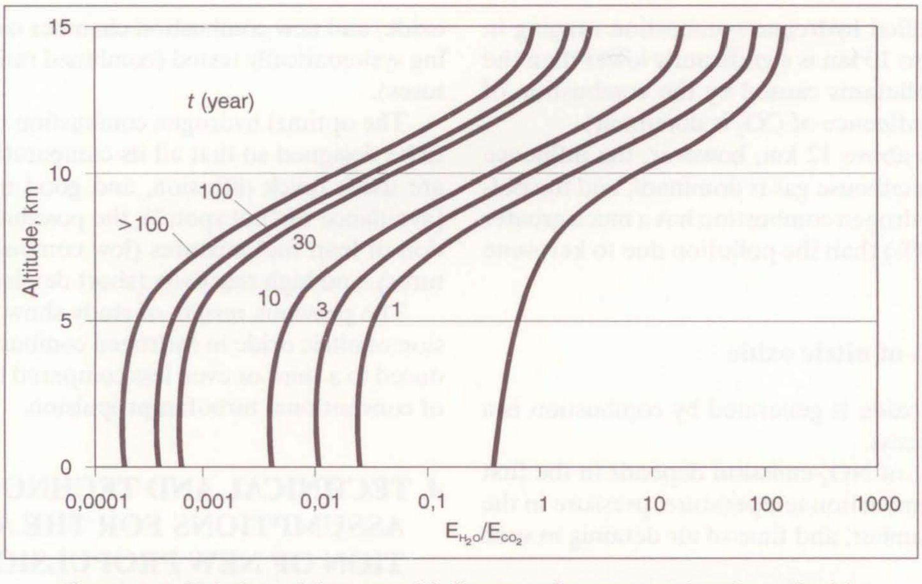

Figure 3.2. Relation of the overall influence of vapour and carbon dioxide

- number of emitted molecules (n)
- time of molecule resistance (τ)

The number of molecules is expressed by the exponential function:

$$n = n_{t_0} \cdot e^{-t/\tau}$$

The overall influence is determined by integration in time:

$$E = \Delta f_n \cdot \int_0^t n\,dt = \Delta f_n \cdot n_{t_0} \cdot \left(1 - e^{-t/\tau}\right)$$

The relation of the influence of pollutants can be expressed as follows:

$$\frac{E_{H_2O}}{E_{CO_2}} = \frac{\Delta f_{nH_2O}}{\Delta f_{nCO_2}} \cdot \frac{\left(1 - e^{-t/\tau_{H2O}}\right)}{\left(1 - e^{-t/\tau_{CO2}}\right)}$$

provided that the same number of pollutant molecules has been emitted over the time to.

Based on the numerical results of the relation of the overall H_2O/CO_2 influence, the following can be concluded:

- the influence of H_2O compared to CO_2 increases with the emission altitude,
- the longer the studied time, the lesser is the influence of H_2O compared to CO_2,
- the overall influence of H_2O is only at altitudes of over 12 km proportionate to the influence of CO_2,
- at altitudes lower than 10 km the influence of H_2O is at least by 1-2 power of ten weaker than the influence of CO_2,

The analysis of the influences by pollutants of the alternative fuel and kerosene shows that the pollution

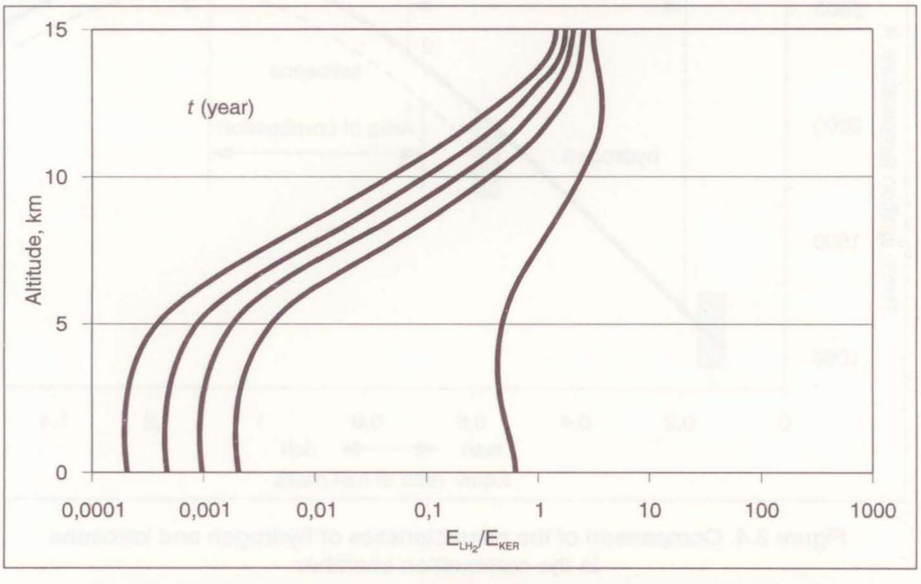

Figure 3.3. Relation of the unit influence of the liquefied hydrogen and kerosene

caused by liquefied hydrogen combustion ranging in altitudes of up to 10 km is significantly lower than the influence of pollutants caused by the combustion of kerosene (the influence of CO_2 is dominant).

At altitudes above 12 km, however, the influence of vapour as greenhouse gas is dominant, and the pollution due to hydrogen combustion has a much greater effect (up to 60%) than the pollution due to kerosene combustion.

3.2. Reduction of nitric oxide

How nitric oxide is generated by combustion is a well known process.

The amount of NO_x-emission depends in the first place on the combustion temperature, pressure in the combustion chamber, and time of air detainig in such conditions.

The development of aircraft engines up to now has been focused on the reduction of specific fuel consumption, and with this function the tendency to increase pressures and temperatures in the combustion chamber has influenced the increase in NO_x pollution.

Therefore, the potential regarding reduction of nitric oxide within the conventional technology of the combustion chamber is limited.

Hydrogen as alternative fuel has the advantages of lower ignition temperature limits, and very fast reactions even in lean combustion mixtures, where full combustion can be realised at significantly lower temperatures compared to kerosene.

Within the European - Canadian project - EQHHPP[4], various technologies of hydrogen combustion are being studied, in order to reduce the nitric oxide, and new combustion chamber concepts are being systematically tested (combined ratios of fuel mixtures).

The optimal hydrogen combustion chamber needs to be designed so that all its comparative advantages are used: quick diffusion, and good mixing with air (avoidance of "hot spots"), the possibility of combustion of lean fuel mixtures (low combustion temperatures), and high reactivity (short detaining of air).

The previous results of study show that the emission of nitric oxide in hydrogen combustion can be reduced to a third or even less compared to the emission of conventional turbofan-propulsion.

4. TECHNICAL AND TECHNOLOGICAL ASSUMPTIONS FOR THE APPLICATION OF NEW PROPULSION

The introduction of the alternative propulsion in aviation presupposes the development of the hydrogen mass-production technology.

Apart from the nuclear energy, considerations include the possibility of applying solar energy as the renewable energy source and water as raw material.

According to the previous experience, one of the available procedures for hydrogen mass-production is certainly the water electrolysis, which has good prospects for technological application by means of hydroelectric power plants and in the future, solar and wind power plants, as energy sources.

The design of the new compatible infrastructure which would accompany the introduction of the alternative fuel is very expensive.

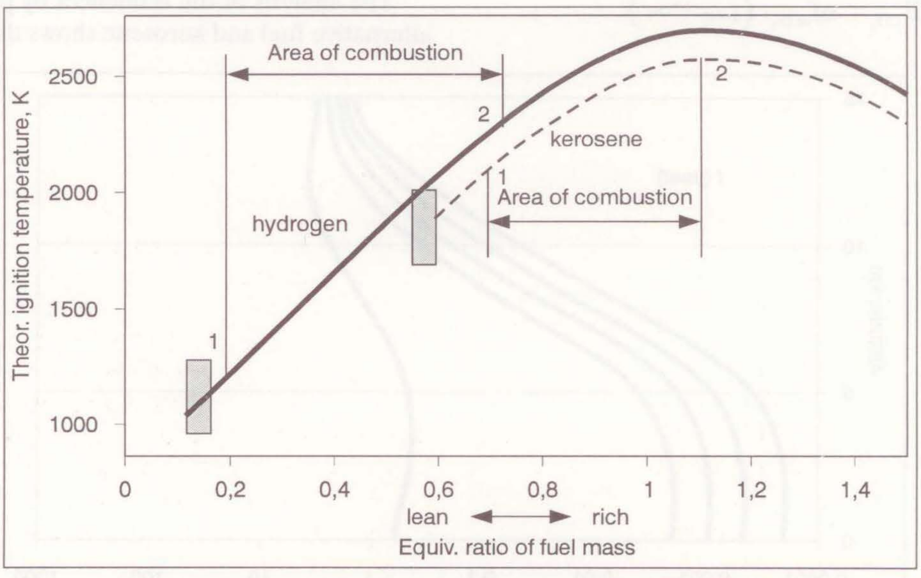

Figure 3.4. Comparison of the characteristics of hydrogen and kerosene in the combustion chamber

Source: DASA Airbus GmbH

In order to transport great amounts of hydrogen as gas to remote distances, the exploitation efficiency of the pipework becomes questionable.

To apply hydrogen as fuel in aviation, it needs to be liquefied, in order to reduce its volume rendering it more compact, and this requires special plants for the preparation of liquefied hydrogen ready for exploitation, as well as tanks for its storage.

For a big airport such as Frankfurt, whose daily need is about 4500 tons of kerosene (1991), 1500 tons of liquefied hydrogen would need to be prepared daily, corresponding to 50 times bigger daily capacity of the existing plant.

In the European proportions, 6000 tons of liquefied hydrogen would need to be produced daily for the exploitation of aircraft using alternative propulsion, instead of the today's daily production of 20 tons.

The question regarding the economy of applying the liquefied hydrogen as alternative to kerosene is connected with its production cost.

At the current production costs, the competitiveness of kerosene is not in the least endangered.

The production cost of 1 kg of liquefied hydrogen ranges from 3,00 - 4,00 DEM out of natural gas, 5,50 DEM by electrolysis using nuclear power, to 6,60 DEM by electrolysis using hydro-energy (according to EQHHPP).

The long-term tendency should, however, be directed towards the price competitiveness, and the process may be additionally quickened by political means, e.g. increased taxes on fossil fuels, requirements for using regenerative energy sources, marketing incentives of applying environmentally friendly fuels, etc.

The necessary design modifications on the aircraft refer first of all to the position and dimensioning of the fuel tanks.

For the energy equivalent of liquefied hydrogen compared to the conventional fuel, the tank needs to be enlarged in volume, and due to temperature of fuel storage i.e. the necessary insulation, the aircraft flying surfaces cannot be used.

For design and safety reasons, the preliminary concepts of aircraft using alternative propulsion foresee locating of a number of special tanks, aerodynamically blended, in the fuselage above the passenger cabin.

The leading European aircraft manufacturer Airbus, plans the implementation of the new propulsion system based on the A-310 type.

Due to the smaller fuel weight, such an aircraft would be 30% lighter in taking off, or, in case of the same weight in takeoff, it would allow for the greater pay load compared to conventional propulsion.

The aerodynamic characteristics of the aircraft are, however, questionable, since the increase of parasitic surfaces (fuselage) also means an increase in aerodynamic drag, as well as greater fuel consumption.

By fitting the tank in the fuselage, the wet fuselage surface is increased (the surface open to air flow), thus increasing the parasitic drag due to bigger surfaces on which friction forces act. The increase of wet surface significantly disturbs the aircraft lift-drag parameter, which is the measure of the overall aircraft aerodynamic efficiency. For supersonic aircraft, the volume distribution and the wave-drag implication have a great influence as well.

Consequently, the increase in drag requires a greater thrust i.e. a more demanding propulsion engine group. The possible savings in the fuel weight might be "lost" due to a bigger and heavier engine, which would counter the additional drag and because of the necessary insulation material for the fuel tanks.

The performance of the existing aircraft would be significantly changed by changing the lift-drag ratio of the aircraft, and a completely new design approach would be needed in order to optimise the flying performance.

Applicability in the supersonic aircraft category is questionable, due to the excessive heating of the hull, and the need for a better (more voluminous) insulation of the tanks, which is directly in contrast to the control requirements and manoeuvrability of such aircraft (mainly military aircraft, such as e.g. relatively small interceptors).

The engine architecture could be kept provided design modifications of certain components are made, mainly of the combustion chamber.

Because of the quick reaction and combustion of hydrogen at lower temperatures, the combustion chamber can be significantly shortened, thus allowing for the room for installing a special block (alternator) for hydrogen evaporation before entering the combustion chamber.

5. CONCLUSION

In the selection of alternative fuel which would have a regenerative source on one hand, and be environmentally friendly on the other, hydrogen has proven to be a long-term optimal solution.

The main comparative advantage of liquefied hydrogen is that during its combustion the critical production of carbon dioxide has been completely eliminated from its polluting composition, which otherwise has the strongest impact (over 50%) in the greenhouse effect, as well as almost all secondary products immanent to kerosene.

Vapour occurs as the only primary product in hydrogen combustion, and the nitric oxide as the inevitable secondary product.

Therefore, the current studies regarding the possible application of hydrogen as alternative fuel in aviation are directed towards the main criteria of studying the extent of harmful impact of vapour on the atmosphere, and the technical and technological possibilities of reducing the NO_x-emissions.

The results of the research carried out until now, confirm a substantially lower influence of H_2O-pollution in hydrogen combustion compared to the pollution in kerosene combustion in altitudes ranging up to 10 km.

As possible methods of preventing the harmful impact of vapour at the boundary layer of tropopause, lower exploitation flight levels are suggested, which would, however, mean an increase in fuel consumption by 6-8% (proportionate to the increase in aerodynamic drag in greater air density condition).

Specific characteristics of hydrogen are substantially lower ignition temperatures, good diffusion, and good mixing with air, as well as quick combustion even in case of lean fuel mixtures with great stability reserve, guaranteeing significant reduction of NO_x-emission compared to conventional fuel.

Introduction of aircraft using alternative propulsion into the regular service depends on the possibility of establishing the mass production of liquefied hydrogen and on infrastructure support, which, from today's point of view, means big investments.

However, with time, the announced ecological restrictive measures, as well as the constant depletion of fossil fuel resources, will eventually lead to the competitiveness of alternative fuels.

SAŽETAK

PRETPOSTAVKE RAZVOJA ALTERNATIVNOG POGONA U ZRAKOPLOVSTVU

Ekološke indikacije i smanjeni resursi fosilnih goriva osnovni su kriteriji aktualnih istraživanja alternativnog pogona u zrakoplovstvu odnosno pronalaženja novog energenta regenerativnog izvora. Tehničko-tehnološke pretpostavke prijelaza s konvencionalnog na alternativno gorivo radikalnije su od svojevremenog prijelaza sa stapnog na mlazni pogon, a glavni se problemi vežu za proizvodnju tekućeg vodika, potrebne konstrukcijske preinake zrakoplova te potrebnu infrastrukturnu podršku.

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