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FAKULTA STROJNÍHO INŽENÝRSTVÍ
LETECKÝ USTAV

ALTERNATIVE PROPULSION FOR AIRCRAFT OF GENERAL AVIATION CATEGORY

ALTERNATIVNÍ POHONY LETOUNŮ KATEGORIE VŠEOBECNÉHO LETECTVÍ

SHORT VERSION OF DOCTORAL THESIS
ZKRÁCENÁ VERZE DISERTAČNÍ PRÁCE

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1. Introduction

The doctoral thesis focused on using alternative energy source (fuel, motor) in aviation in order to reduce emission produced by aircraft.

Air transport as all other transport contributes in producing emissions greenhouse gases, which is the main reason of climate changes. In 2005, it was estimated that the airlines industry produces 5% of total emission that affect global warming (CO_2 emission is 2-3%) and it is expected that this ratio will continue to rise due to the increasing in demand for air transport (passenger and cargo).

In recent years, it have been fought intensively against pollution, a number of programs have launched by the EU that introduce measures to help the member of states in the context of economical emission reduction and greenhouse gases.

On the other hand, the majority of aircraft engine burns one of two main fuel types, Avgas (100, 100 LL) or Jet-A fuel. Both types of fuel are naturally made from petroleum, and this is the main disadvantage. Petroleum reserves are limited, its price has been growing throughlong term and the dependence on one source of energy from a strategic point of view is a mistake.

Since 2000, air transport is confronted with the problem of the huge increase in aviation fuel prices, while during 1990 these prices were very stable. Therefore, today there is an effort to find an alternative source of fuel to break away the dependence on petroleum.

1.1 Goals of doctoral thesis

The main goals of this work are:

1) Mapping the global air traffic and exhaust emissions, and description the ICAO's initiative about emission standard
2) Statistical study using Delphi method on the views of experts group about the most effective alternative solution to reduce emission from aviation and minimize fuel consumption.
3) Measuring emission produced by aircraft.
4) Information about daily flight plan (flight time, number of take-offs, and number of individual flights) for several airplanes from the category of LSA, ULA.
5) Verifying the possibility of using alternative source of energy, and how that will effect on aircraft performance (three options were selected, Lpg fuel, electric motors and adding catalytic converter to the exhaust system for aircraft with the current propulsion).

2. Currrent state of the art

Commercial air traffic, both passenger and freight, as well as business aviation are expected to continue to grow for the foreseeable future, bringing about benefits to people and economies in both developed and developing nations, and that will in turn increase the amount of contaminants emitted to the atmosphere.

The world's airlines carry around 2.3 billion passengers and 38 million tonnes of freight on scheduled services, representing more than 531 billion tonne kilometres combined. Passenger traffic is expected to grow at an average rate of 4.8% per year through the year 2036.

Overall, global trends of aviation noise, emissions that affect local air quality, and fuel consumption predict an increase through the year 2036 at less than the 4.8% growth rate in traffic.

The technology of jet engines currently relies on fossil fuel combustion, which emits combustion products primarily at cruise altitudes. These emissions affect atmospheric composition differently than emissions from fossil-fuel combustion at the surface. In addition, aviation operations cause changes in cloudiness through contrail and contrail cirrus formation. Present and future changes in atmospheric composition and cloudiness from aviation have the potential to affect future climate.

In 2010, international aviation consumed approximately 142 million metric tonnes of fuel, resulting in an estimated 448 million metric tonnes (mt, 1 kg x 109) of CO_2 emissions. It is projected that, by 2040 fuel consumption will have increased by between 2.8 and 3.9 times the 2010 value,

2.1. EU aviation's contribution to climate change

Direct emissions from aviation account for about 3% of the EU's total GHG emissions. The large majority of these emissions come from international flights.

Therefore, the overall impact is estimated to be higher. The IPCC has estimated that aviation's total impact is about 2 to 4 times higher than the effect of its past CO_2 emissions alone. Recent EU research results indicate that this ratio may be somewhat smaller (around 2 times).

EU emissions from international aviation are increasing fast – doubling since 1990 – as air travel becomes cheaper without its environmental costs being addressed.

Emissions are forecast to continue growing for the foreseeable future. Emissions from aviation are higher than from certain entire sectors covered by the EU ETS, for example refineries and steel production. When aviation joins the EU ETS it is forecast to be the second largest sector in terms of emissions, second only to electricity generation

2.2. EU initiatives

Preventing dangerous climate change is a strategic priority for the European Union. Europe is working hard to cut its greenhouse gas emissions substantially while encouraging other nations and regions to do likewise.

In parallel, the European commission and some member states have developed adaptation strategies to help strengthen Europe's resilience to the inevitable impacts of climate change.

EU initiatives to reduce greenhouse gas emissions include:

- The european climate change programme (ECCP).
- The EU emissions trading system.
- Adopting legislation to raise the share of energy consumption produced by renewable energy sources, such as wind, solar and biomass, to 20% by 2020.
- Setting a target to increase europe's energy efficiency by 20% by 2020 improving the energy efficiency of buildings and of a wide array of equipment and household appliances.
- Binding targets to reduce CO_2 emissions from new cars and vans.
- Supporting the development of (CCS) technologies to trap and store CO_2 emitted by power stations and other major industrial installingations.

The EU has agreed that at least 20% of its €960 billion budget for the 2014-2020 period should be spent on climate change-related action. This represents around a threefold increase from the 6-8% share in 2007-2013.

The EU emissions trading system (EU ETS) is a cornerstone of the european union's policy to combat climate change and its key tool for reducing industrial greenhouse gas emissions cost-effectively.

The first - and still by far the biggest - international system for trading greenhouse gas emission allowances.

- Operates in the 28 EU countries and the three EEA-EFTA states (Iceland, Liechtenstein and Norway)
- Covers around 45% of the EU's greenhouse gas emissions
- Limits emissions from more than 11,000 heavy energy-using installingations in power generation and manufacturing industry, flights to and from the EU and the three EEA-efta states.

3. Measuring of aircraft emissions

In accourdance with global trends to fight against pollution, Ministry of Transportation and Communications pursuant to 91 part of law No.56/2001 on conditions for operating vehicles on road and amending law No. 168/1999 on liability insurance for damage caused by vehicle, established decree about roadwothiness and vechicle emissions.

As the aircraft, in particular LSA and VLA, fly in the vicinity of the city, therefore they affect the atmosphere of the area as well as the road vehicle. However, they fly during very short times and most frequently, consequently their effect is concerning on specific area.

Therefore, aircraft of these categories must be encluded in the environmental policies for limiting emissions. Following, there are a group of emissions measurment for aircraft of previously mentioned category.

3.1. Measurement of aircraft emissions

I measured the gases emitted from ultralight aircraft engine at the airport of Medlanky using analyzer Bosch BEA050.

Aircraft used in measuring is TL-3000 Sirius with four-stroke engine Rotax 912 ULS 100 HP, engine power and another parameters are in Table 1

Table 1 Engine data

Power	73,5 KW
Max speed	5800 rpm
Fuel	Leaded, unleaded, Avgas 100LL or ethanol 10
Weight	69,5 kg

Gases that were measured are: HC, CO, CO_2, NOx, O_2 .

Measurment was done during four flight regimes:

- Idle
- Cruise
- 75% power
- Full power

The emission were measured again for the engine after adding a catalytic converter to the exhaust system, to compare how affect a cats on gases emited.

Because of the difficulty of installation catalytic converter to the exhaust system, it was used engine similar to the aircraft engine. It is 30 KW power engine, type Skoda 1.0 MPI , speed range 1500-4500 rpm. Mesurement was made at the institute of Automotive Engineering laborator.

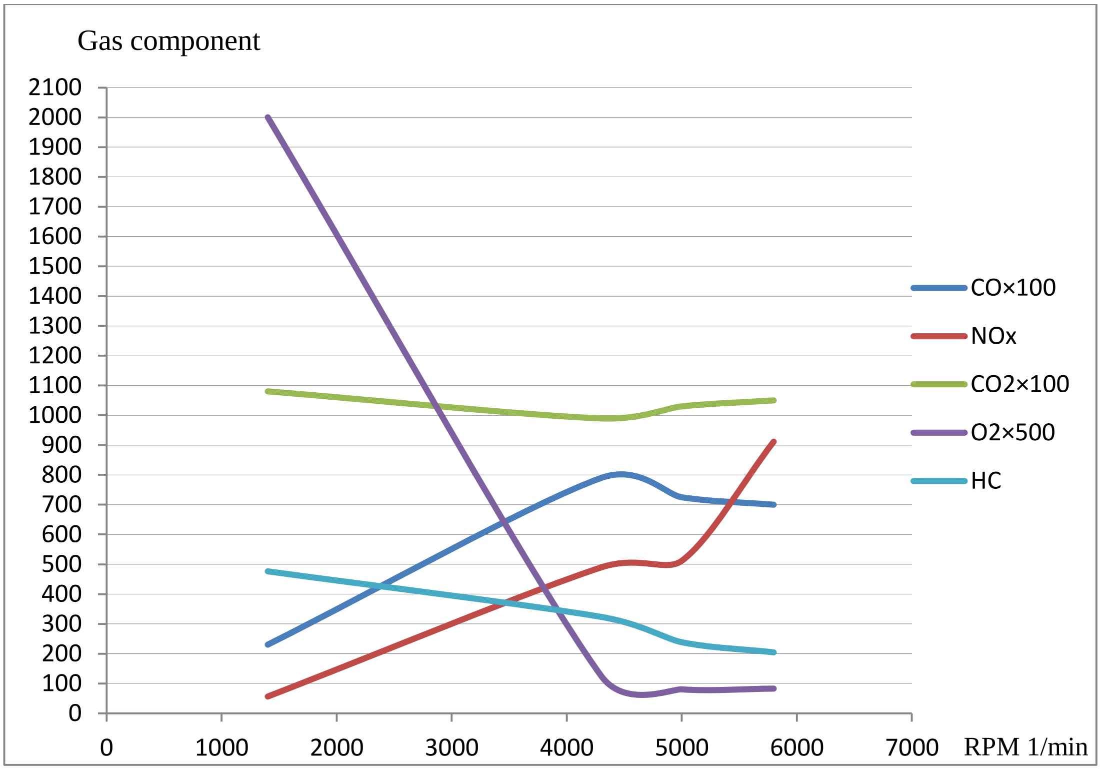


Fig 1 Exhaust gas composition depending on the speed (without cat's)

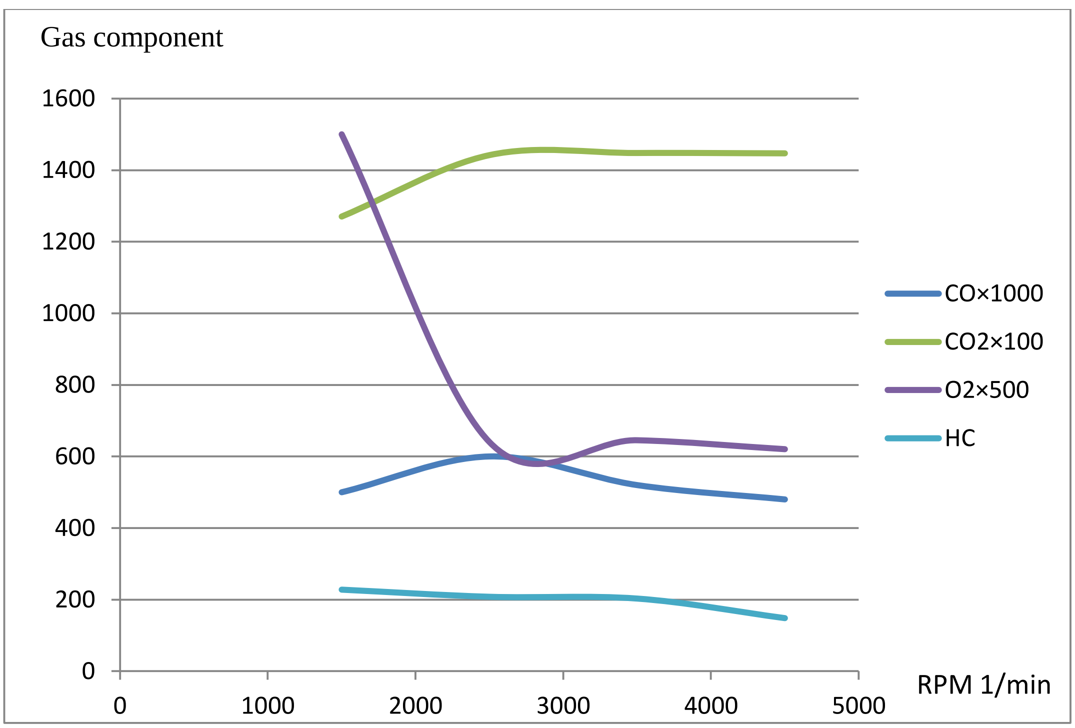


Fig 2 Exhaust gas composition depending on the speed (with cat's)

Table 2 comparing exhaust gas emission with and without catalytic converter

Rpm	HC[ppm]		CO_2[%]		O_2[%]		CO[%]	
	No cat's	+cat's	No cat's	+cat's	No cat's	+cat's	No cat's	+cat's
1400	476	230	10,8	12,5	4,04	3,08	2,39	0,485
4300	323,3	160	9,97	14,5	0,25	1,26	7,93	0,49
5000	238,5	115	10,37	14,5	0,16	1,2	7,2	0,46
5600	204	100	10,56	14,5	0,16	1,2	7,09	0,46

Table 2 compares the gases ratio for engine equipped with cats and another without cats, at the same speed. All values are taken from Fig 1 and Fig 2 considering the difference of speed, so values were calculated proportionally with speed. From this table we can conclude that using catalytic converter in the engine exhaust system leads to significantly less emission of hydrocarbons HC and carbon monoxide CO. This is due to the oxidation of CO, meanwhile, this is the reason of the decreasing of CO_2 emissions. While the incressing of oxygen ratio in exhaust emission refers to the preserving a stechiometric mixture during combustion, using Lambda sensor.

4. Daily flight plan for aircraft

At the end of 2007 a total of 6.066 aircraft were estimated to be in category LSA. The forecast assumes, that the fleet will increase approximately 930 aircraft per year until 2013 including both newly built aircraft and conversions from ultra-light trainers. Thereafter the rate of increase in the fleet tapers considerably to about 300 per year. By 2025 a total of 15.865 light sport aircraft are projected to be in the fleet.

The engine used in this kind of aircraft is piston engine (internal combustion engine) which burns aviation gasoline Avgas, eventually automobile gasoline Mogas. These aircraft are often used for training, fly frequently for short periods and near the city. Therefore, they emit a significant amount of pollutants, which not only pollutes the air but also obscure the sunrays.

This part of my research provides details about daily flight plan (flight time, number of takeoffs, number of individual flights) for several airplane from the category of LSA, ULA.

These timelines which are similiar for all airplanes using for training, give us an idea about the most frequent flight time and the maximum probable one, and this allows the flexibility to change the maximum fuel amount in the airplane, or suggest another alternative motor which may be more suitable.

I choose airplanes which are used for training at the airport of Medlanky/ Brno, and made statistic for the flight period on 2012 and 2013. According to that, it is noticed that the more number of occurrences is for the shorter flight time 0-10 min, and for 10-20 min, as shown inFig 3. This piece of information leads us to an important idea, that is no need for these aircraft to hold on a big amount of fuel which will be sufficient to fly for long time.

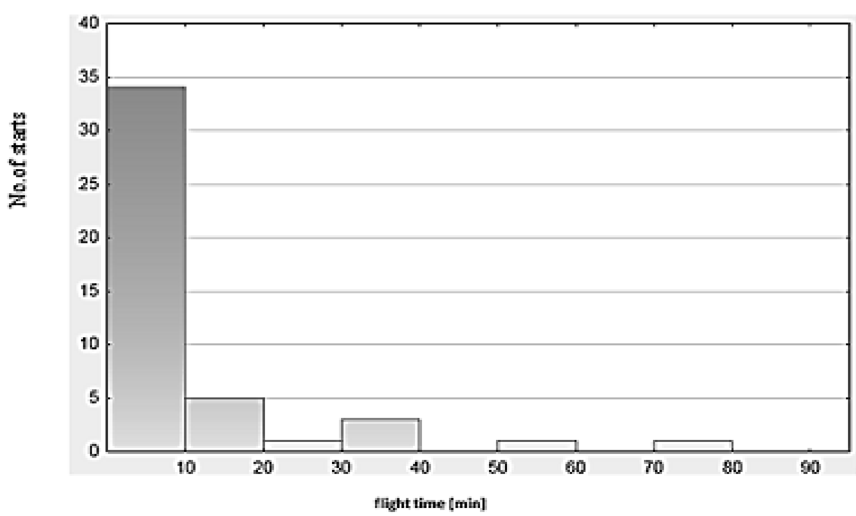


Fig 3 Histogram flight time [min] for airplane Z226 MS OK MGM, year 2013

5. Experts opinions about alternative propolsion

Trying to reach to the more suitable alternative solution for aircraft, there are several options that may be used as alternative propolsion for airplanes. Taking into account the ecological aspect, it seems the electric motor to be the ideal option. However, considering the other aspects it will be more complicated to decide which is the most appropriate option. Therfore, it was better to know the opinions of experts working in the field of aerospace. These opinions were statically examined using Delphi method.

Following is an overview about Delphi, hereafter the experts opinions.

5.1. Applying of Delfi for the case of two seats aircraft

A set of questions were sent to a group of 60 experts. These questions (written bellow) are about their opinions on the development of new engine or modification to drive two-seats sport aircraft category CS VLA.

Opinion about the development of new engine or modification to drive two-seat sport aircraft category CS VLA

Recommended numbers 1-7 (1 strongest, 7 weakest)

- ☐ Using the current types of engines working on gasoline and focusing on increasing their efficiency, reliability, durability, weight reduction, emission and noise.
- ☐ Using the current types of engines equipped with catalytic converter.
- ☐ Modifying the current engines or developing new engines working on fuel gas such as Lpg, natural gas or biogas with better emission ration.
- ☐ Developing a set of electric drive with rechargeable batteries, which will be charged from ordinary electrical outlet.
- ☐ Developing system of electric propulsion with hydrogen fuel cell.
- ☐ Developing hybrid drive (internal combustion engine + electrical motor working on battery)
- ☐ Other recommendation.

Is it appropriate to propose experimental aircraft that would allow easy installation of the first two recommendations (selected) drive species to measure the operating characteristics of these drives? (delete what you do not agree with)

Yes No

61.6% of them voted strongly for using the current types of engines working on gasoline and focusing on increasing their efficiency, reliability, durability, weight reduction, emission and noise. 30% said that adding catalytic converter for current aircraft is on the second place, 28% said that using Lpg is in the third place and 21% gave it the fourth place.

53% of experts think that it would be appropriate to propose experimental aircraft that would allow easy installation of the first two recommendations to measure their operating characteristics.

5.2. Applying Delphi for the case of four seats aircraft

Another group of question were sent to the experts about their opinion about the developement new engine or modifications to drive four seat sport aircraft (category CS23-N).

Opinion about developing a new engine or modifications to drive four seat sport aircraft category CS 23 – N

Recommended no. 1-7 (1 the strongest,7 the weakest)

☐ Using the current types of gasoline engines and focusing on increasing their efficiency, reliability, durability, weight reduction, emissions and noise.

☐ Modifying the current engines or developping new engines working on fuel gas (Lpg, natural gas, biogas) with acceptable emission ratio.

☐ Using turboprop engines with acceptable emission ratios.

☐ Developing a set of electrical drive with rechargeable batteries,which will be charged from ordinary electrical outlet.

☐ Developing system of electric motor and hydrogen fuel cell.

☐ Developing hybrid propulsion system.

☐ Other recommendation

Would be appropriate to hold a working meeting of responsible workers (representatives) selected manufacturing companies, VZLÚ, CAA, Czech Technical University in Prague, Brno UO, VSB-TU Ostrava, that focus on the issue of development of small aircraft with alternative drive? (delete what you do not agree with)

Yes No

65 % of experts voted strongly for using the current types of gasoline engines and focusing on increasing their efficiency, reliability, durability, weight reduction, emissions and noise.

28.3% said that using turboprop engines with acceptable emission ratios is on the second place, 23.3 % said that using Lpg is in the third place.

67% of experts think that it would be appropriate to hold a working meeting of responsible manufacturing companies focusing on developoing small aircraft with alternative drive.

6. Using Lpg as alternative fuel

Lpg for internal combustion engines is labeled as HD5 and it requires a minimum propane content (C_3H_8) of 90%.

Lpg is considered as "clean" fuel because it does not produce visible emissions. However, gaseous pollutants such as nitrogen oxides (NO_x), carbon monoxide (CO), and organic compounds are produced as are small amounts of SO_2 and PM.

Greenhouse gases (carbon dioxide (CO_2), methane (CH_4), and (N_2O) emissions) are all produced during Lpg combustion. Nearly all of the fuel carbon (99.5 percent) in Lpg is converted to CO_2 during the combustion process. This conversion is relatively independent of firing configuration. Although the formation of CO acts to reduce CO_2 emissions, the produced amount is insignificant compared to the amount of CO_2 produced. The majority of the 0.5 percent of fuel carbon not converted to CO_2, that is due to the incomplete combustion in the fuel stream.

Formation of N_2O during the combustion process is governed by a complex series of reactions and its formation is dependent upon many factors. Formation of N_2O is minimized when combustion temperatures are kept high (above 1475) and excess air is kept to a minimum (less than 1 percent).

Methane emissions are highest during periods of low-temperature combustion or incomplete combustion, such as the start-up or shut-down. Typically, conditions that favor formation of N_2O also favor emissions of CH_4.

Therfore, as shown in Table 3, the N_2O and CH_4 emission factor for Lpg and Avgas is the same for energy unite, but it is less for the volume unite and it is due to the less calorific value of Lpg comaring with Avgas. On the other hand. CO_2 factor for Lpg is less than that for Avgas.

Table 3 Comparison emission factor Lpg and Avgas

Fuel	CO_2 kg/mmbtu kg/MJ	CH_4 g/mmbtu, g/MJ	N_2O g/mmbtu, g/MJ	CO_2 kg/l	CH_4 g/l	N_2O g/l
Avgas	69.25/0.065	3/0.002	0.6/0.0005	2.19	0.095	0.018
Lpg	61.71/0.059	3/0.002	0.6/0.0005	1.5	0.07	0.015

6.1. Proposal of Lpg fuel system

Lpg system was proposed for airplane VUT-081 Kondor, which is a two-seat airplane of mixed construction with a conceptual layout representing the fuselage gondola tandem seat arrangement with thrust propulsion unite and tail hanging from the wing fuselage using two beams. The chassis is retractable, nose type with controlled front wheel.

The power unit consists of piston engine with fuel injection Rotax 912 is (100 hp).

Table 4 Engine characteristic

Regime	Power [kW]	Engine speed [rpm]	Propeller speed [rpm]	Consumption [lit/h]
Take off	73.5	5800	2387	26.1
Permenant	69.8	5500	2263	23.6
75%	61.4	5000	2054	16.5

The aircraft is equipped with a three-blade pusher propeller that is adjustable constant speed woodcomp SR-3000. Propeller diameter is 1650 mm.

Due to the lack of information on the propeller, it is used for the calculation a characteristics for propeller of similar category, hoffmann HO-V62R. Factor reduction in the efficiency of its buildings propeller airplane was set at 0.9058 .

Calculating Lpg amount and tank capacity:

Lpg amount in the proposed system was calculated based on the energy produced by the maximum fuel of BA 95 used in the aircraft.

Energy content of avgas: 31.33 MJ/dm^3

Energy content of Lpg: 23.39 MJ/dm^3

Airplane Kondor have max. fuel 120 dm^3

To produce amount of heat from Lpg the same from avgas will be needed

$\frac{31.33 \times 120}{23.39} = 160\ dm^3$ of Lpg

Therefore the total max fuel of LPG will be 160 liter, I propose to use two tanks, each of them will carry half of fuel quantity. Because one tank must be filled to maximum 80% so that the total capacity of each tank must be 100 dm^3 and the usable is 80 dm^3. Aircraft will be equipped with two pressure tanks, each of them has 102 liter capacity.

Table 5 Parameter of selected Lpg pressure tank

Diameter [mm]	Height [mm]	Capacity [dm^3]	Usable capacity [dm^3]	Mass [kg]
720	300	102	81	45

In case of airplane Kondor (similar airplane), because of the lack of available place, it will be not possible to add two Lpg pressure tanks. Therefore I suggest Lpg system with max fuel capacity 81 dm^3, the aircraft will be equipped with one fuel tank. The position of pressure tank onboard the aircraft is in Fig 4.

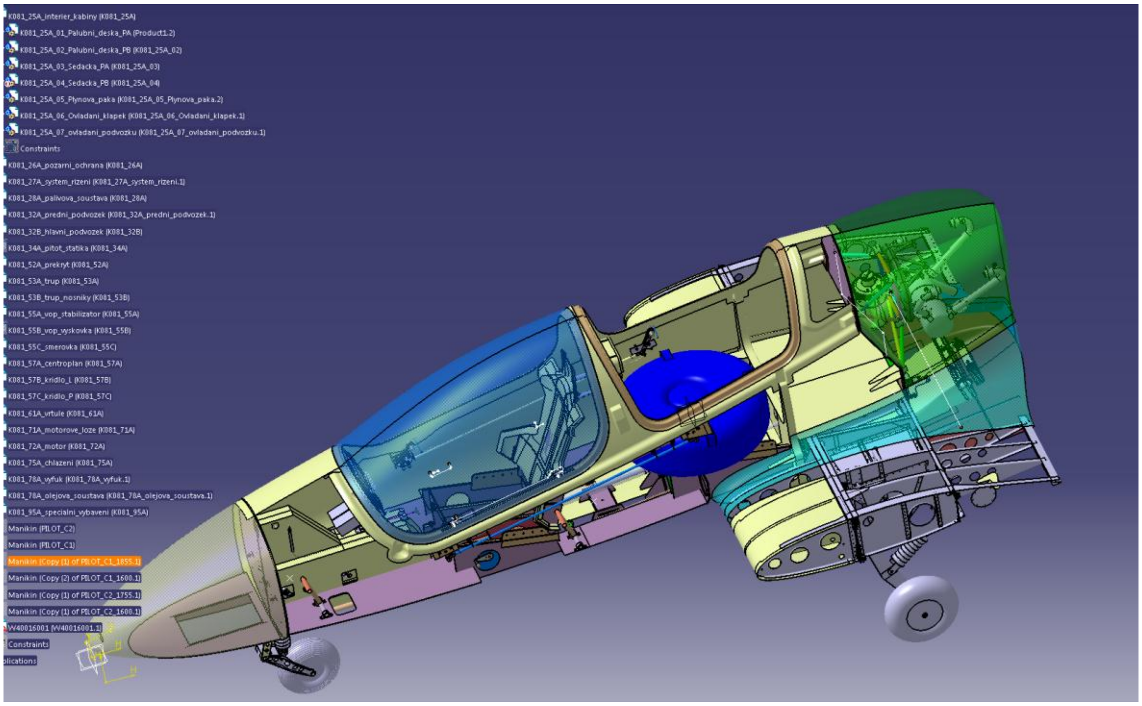


Fig 4 Position of Lpg pressure tank on board airplane VUT 081 Kondor

Changing fuel system causes changes in max.take-off weight and engine power. Therefore affects on aircraft performance. Aircraft with Lpg will carry 45 kg Fuel, weight of pressure tank is 45 kg, so the max take-off weight is 600 kg.

Engine power decrease about 7% when using Lpg fuel, and fuel consumption at this power will be 27 l/h. The calculation of aircraft performance is in chapter 9.

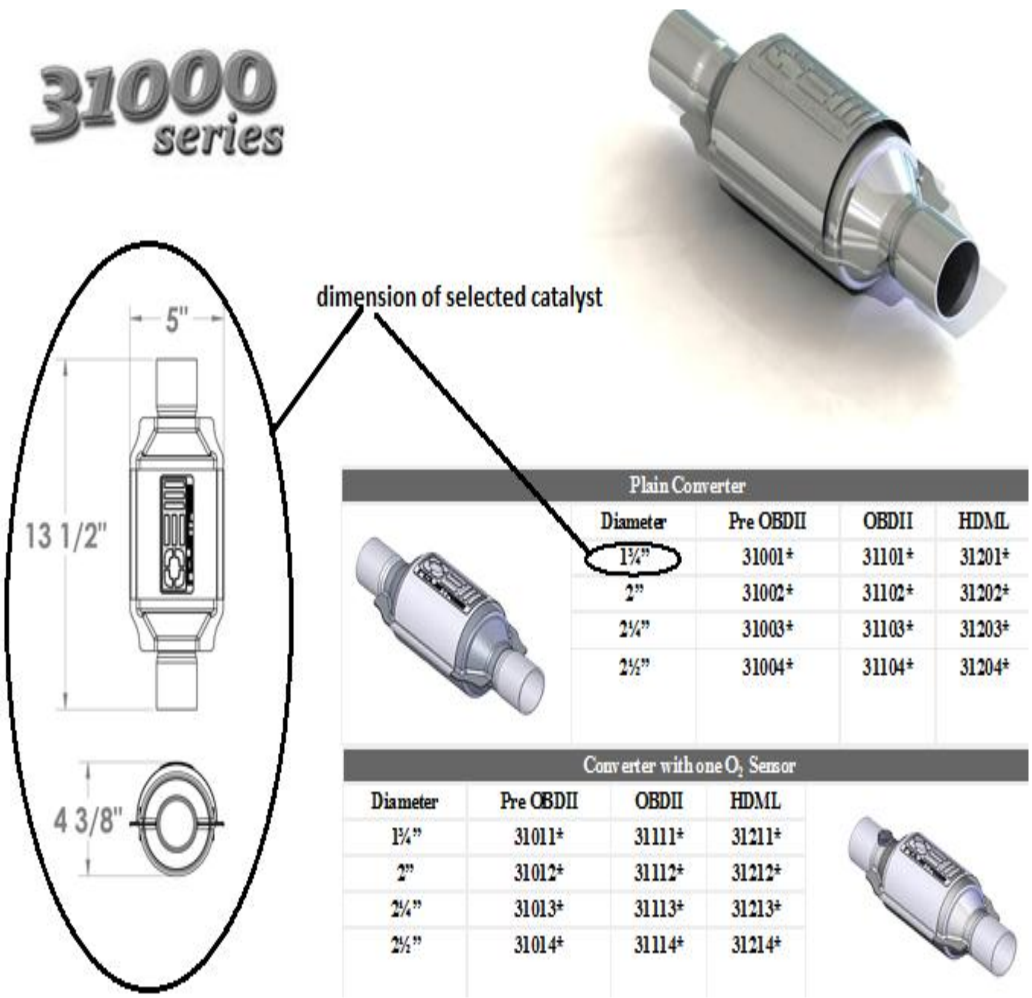
7. applying catalytic converter

7.1. Proposal of catalytic converter for airplane VUT-081 Kondor

Choosing catalytic converter depends on design specification from manufacturer take into account engine power, exhaust system dimension, and emission level.

Given that there is no design specifications determines, the catalytic converter model will be choosen according to the exhaust pipe dimensions, and emission level.

A catalytic converter type OEM 31000 was selected , according the diameter of exhaust pipe, the selected catalytic is shown in Fig 5.



Plain Converter			
Diameter	Pre OBDII	OBDII	HDML
1¾"	31001*	31101*	31201*
2"	31002*	31102*	31202*
2¼"	31003*	31103*	31203*
2½"	31004*	31104*	31204*

Converter with one O_2 Sensor			
Diameter	Pre OBDII	OBDII	HDML
1¾"	31011*	31111*	31211*
2"	31012*	31112*	31212*
2¼"	31013*	31113*	31213*
2½"	31014*	31114*	31214*

Fig 5 Parameters of selected catalytic converter

However it must point out that, adding catalytic converter to the aircraft exhaust system reduces engine power about 11%, and that causes changing in aircraft performance.

8. Electric motors

8.1. Suggestion of electric propulsion system for airplane VUT-081 Kondor

Thermal dimensioning of electric motor:

Optimal choice of electric motor is based on two criterias:

1- Motor temperature must not exceed 150 C^0 in all working cycle.
2- The weight of motor and battery must be the minimum.

Based on motor dimensioning for aircraft VUT051 RAY it will be used the same reference motor with 40 KW power and 2000 rpm speed.

Fig 6 shows the changes of motor temperature during all working cycles and for different power. It can be observed that temperature of 30 KW motor exceeds 150 C^0 at specific work phases.

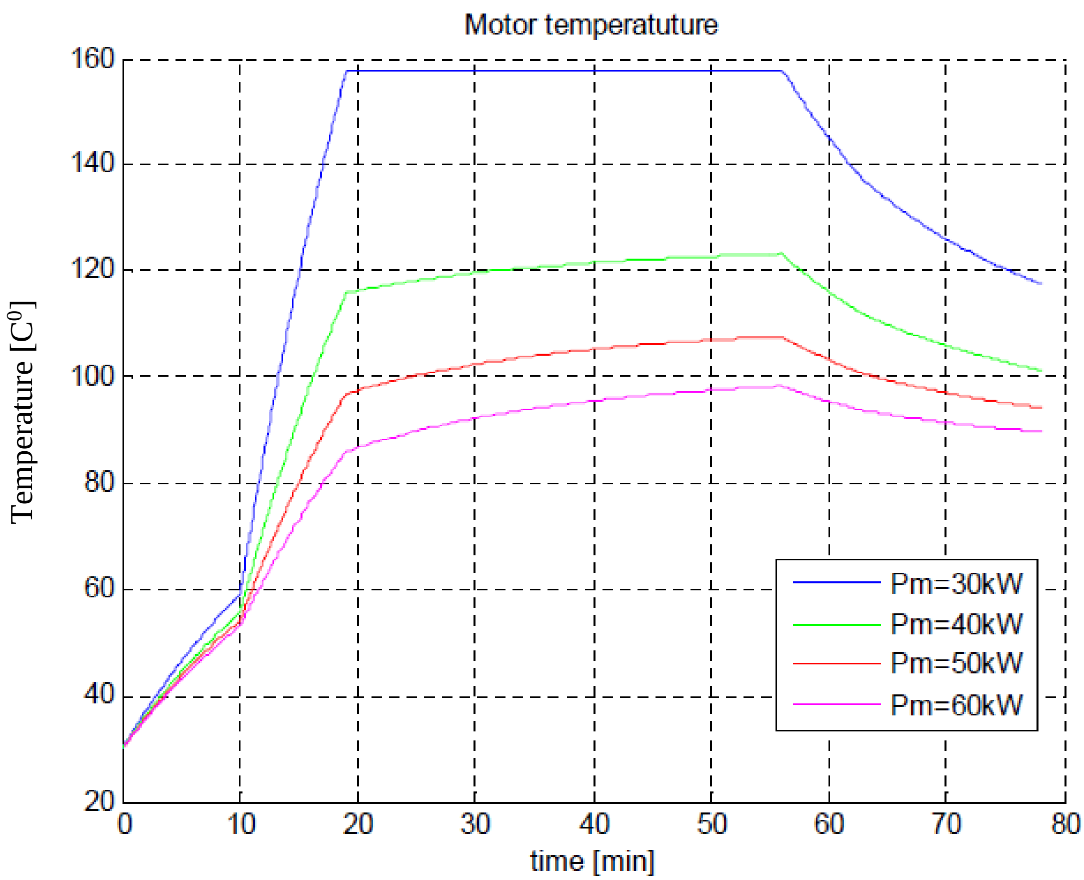


Fig 6 Motor temperature in all flight stages and for different power

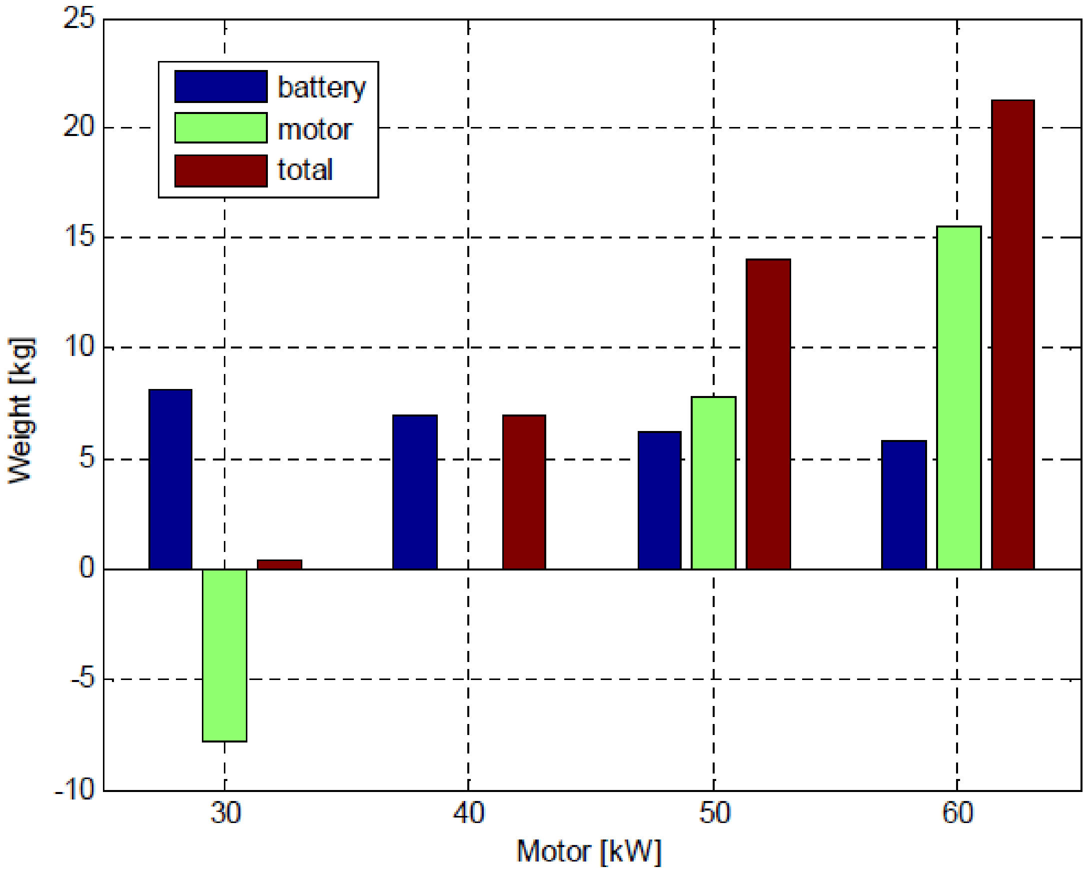


Fig 7 Addition weight for losses compensation

From Fig 6, Fig 7 it can be noticed, that motor with power over than 40 KW will achieve the criteria of temperature. However the weight of motor+battery combination will be increased with motor power increasing.

I suggest to use the same electric motor that was used in airplane VUT 051 RAY, which is HS 019 00 Aveko, 53 KW power and 2300 rpm speed.

According to the selected motor, available and consumed power for all flight phases is shown in the Table 6

Table 6 Motor powers for all flight phases

Flight phase	T [min]	T [sec]	P_m [KW]	P_t[KWh]
Taxing	10	600	15	2.5
Takeoff	0.83	50	52.4	0.73
Climbing	6.12	367	52.4	5.34
Horizontal	30	1800	29.6	14.8
Descent	6.67	400	9.4	1.04
Taxing	5	300	15	1.25
Total	53.62	3217		24.41

Power consumed during all flight phases is 24.41 KWh on the motor shaft. Power losses in 40 KW motor during flight type is about 1.1 KWh. Inverter efficiency is assumed to be about 0.95.

The value of stored energy using to suggest the battery is 27KWh. A combination of 3041 battery Panasonic NCR18650A will be the ideal option. It is lithium-ion battery with energy density 27 KWh, all its parameters are listed in Table 7.

Table 7 Parameters of the selected combination of battery

Type battery	Voltage [V]	Capacity [Ah]	Battery weight [kg]	Density [Wh/kg]	No.battery	Weight of all battery	D [mm]	H [mm]
NCR18650A	3.7	2.4	0.045	197.33	3041	136.845	18.2	64.7

It was used two battery packages, first consists of two series-connected pack and every pack is consisting of 5 blocks each of them contains 102 battery. The second pack consists of four series-connected pack and every pack is consisting of 5 blocks each of them contains 102 battery. Total number of used batteries will be 3060.

The first battery pack will be placed behind the seat of the aeroplane, so I recomment to replace the second seat with this battery pack. The second pack will be placed at the rear of the airplane near the motor. The two battery packages and their dimensions are illustrated in Fig 8.

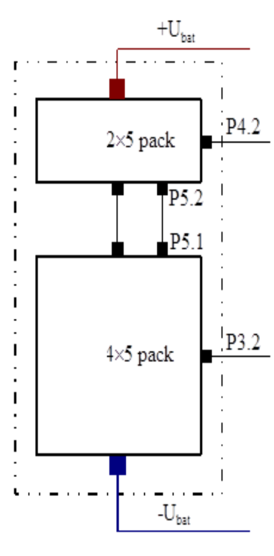


Fig 8 Block diagram of battery

9. Aircraft flight performance

9.1. Characteristics of airplane VUT- 081 Kondor

The aircraft is equipped with a three-blade pusher propeller that is adjustable constant speed woodcomp SR-3000. Propeller diameter is 1650 mm. Wing area S= 11,85 m^2.

The power unit consists of piston engine with fuel injection Rotax 912 (100 HP). Engine characteristics are shown in Table 8, Fig 9 and Fig 10.

Table 8 Engine characteristic

Regime	Power [KW]	Engine speed [rpm]	Propeller speed [rpm]	Consumption [lit/h]
Take off	73.5	5800	2387	26.1
Permenant	69.8	5500	2263	23.6
75%	61.4	5000	2054	16.5

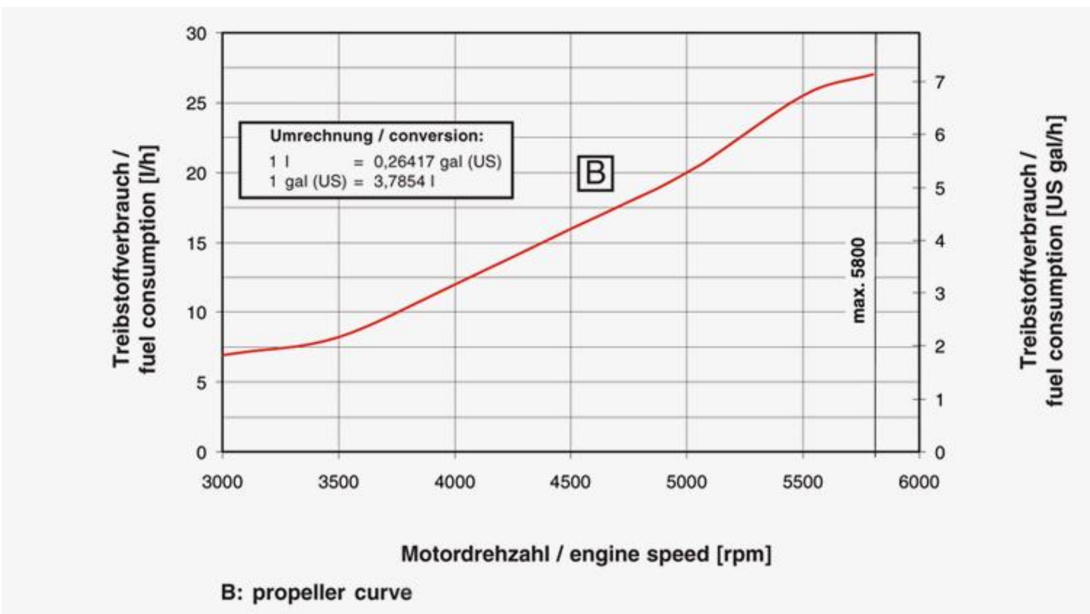


Fig 9 ROTAX engine fuel consumption for different engine speeds

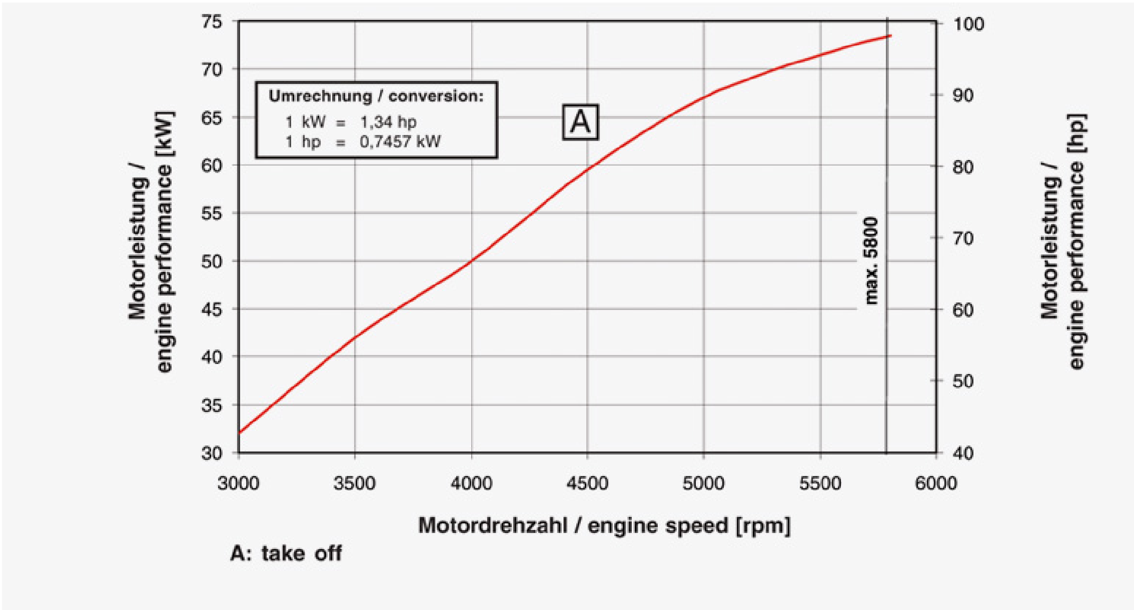


Fig 10 ROTAX engine performance for different engine speeds

Due to the lack of information on the propeller, for the calculations it was used the characteristics for propeller of similar category,it is Hoffmann HO-V62R. Propeller factor reduction in efficiency was set at 0.9058. The effectiveness of the propeller is shown in the Fig 11.

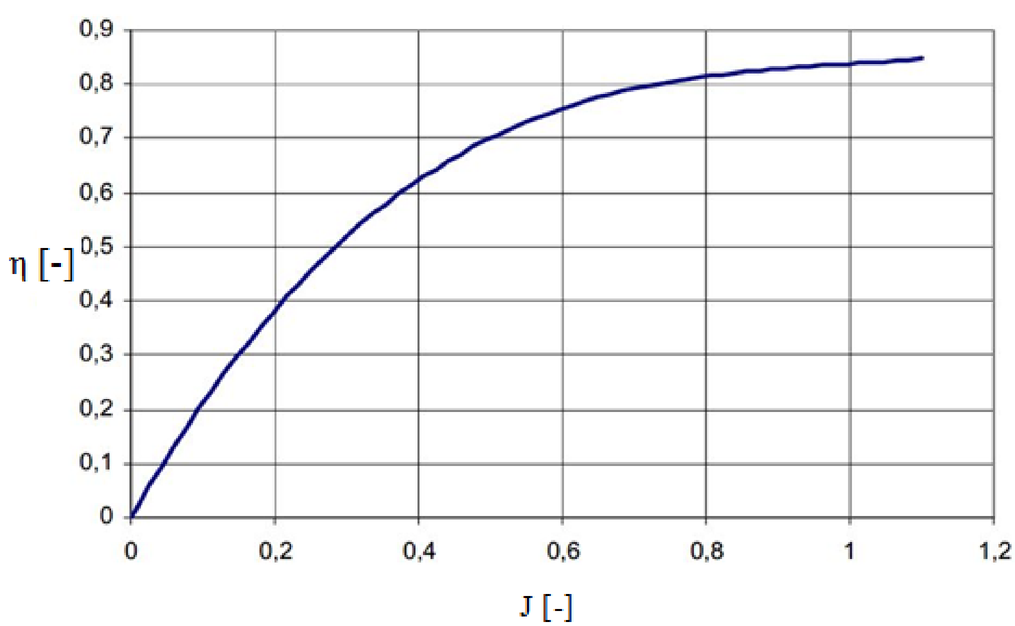


Fig 11 Propeller efficiency

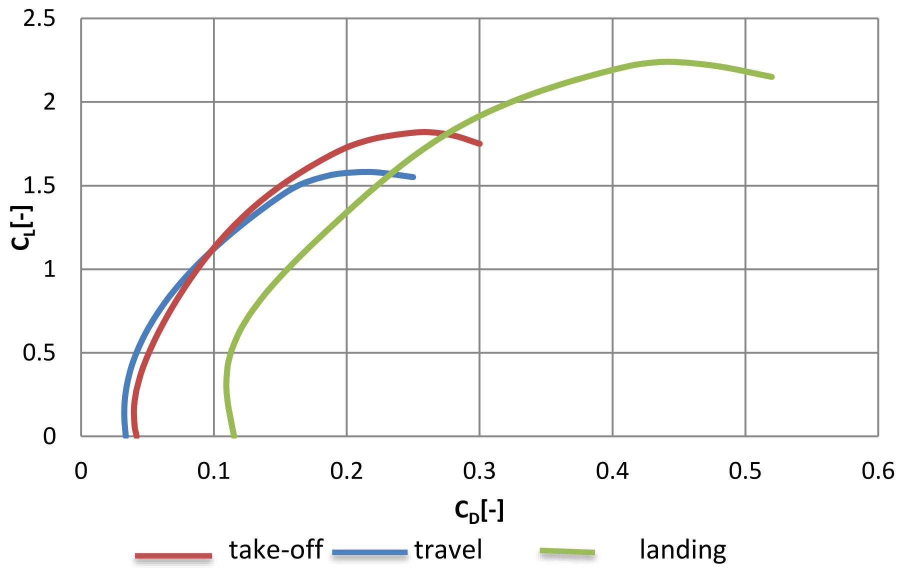


Fig 12 Airplane polar for different configurations

Table 9 Max. Lift coefficient

Configuration	Max. Lift coefficient
Cruise	1.58
Take off	1.81
Landing	2.24

9.2. Stalling speed

Stalling speed is the lowest speed at which the airplane is able to keep in a steady flight and is calculated according to the equation (9.1)

Stalling speeds were calculated for the max. take-off weight 600 kg, at maximum lift coefficient and different configurations and altitude range from 0 to 8000 ft MSA (step 2000 ft). The values of max. lift coefficient C_{Lmax} are taken from airplane polar Fig 12 and are listed in Table 9.

$$V_s = \sqrt{\frac{2G}{C_{Lmax} \rho S}} \quad (9.1)$$

Table 10 Stalling speed for different configurations and different flight altitudes (Lpg)

Configuration	Stalling speed [km/h]				
	Flight altitude [ft]				
	0	2000	4000	6000	8000
Cruise	82.34	84.79	87.37	90.15	92.92
Take off	76.9	79.225	81.63	84.23	86.81
Landing	69.15	71.216	73.38	75.715	78.04

Table 11 Stalling speed for different configurations and different flight altitudes (cats)

Configuration	Stalling speed [km/h]				
	Flight altitude [ft]				
	0	2000	4000	6000	8000
Cruise	82.34	84.8	87.3	90.1	92.9
Take off	76.93	79.22	81.6	84.23	86.8
Landing	69.1	71.2	73.38	75.7	78.04

Table 12 Stalling speed for different configurations and different flight altitudes (electric motor)

Configuration	Stalling speed [km/h]				
	Flight altitude [ft]				
	0	2000	4000	6000	8000
Cruise	77.4	79.7	82.1	84.7	87.33
Take off	72.3	74.4	76.7	79.1	81.6
Landing	65	67	69	71.1	73.4

According to ELSA-A legislation, maximum stalling speed in landing configuration must not exceed 75 km/h. The landing configuration stallinging speed is 69.1 km/h, this speed is lower than required speed as shown in Table 10, Table 11 and Table 12.

9.3. Horizontal flight

Maximum speed in horizontal flight for travel configuration was determined as a steady mode, wherein required thrust and available thrust are equal - for different engine regime.

Speed at horizontal flight is calculated according to the equation (9.2)

Table 13 shows the maximum speed in horizontal flight for different modes of engine operation and at 0 ft altitude.

$$V=\sqrt{\frac{2gm}{C_L\,\rho\,S}} \tag{9.2}$$

$$F_V = \frac{\eta P_M}{V} \tag{9.3}$$

$$F_P = \frac{C_D}{C_L} G \tag{9.4}$$

Table 13 Maximum speed for different cinfigurations and flight altitude 0ft (Lpg)

Configuration	Max.speed [km/h] Altitude [ft] 0
Take off	222
Permanent	220
75%	205

Table 14 Maximum speed for different cinfigurations and flight altitude 0ft (cat's)

Regym	Max.speed [km/h] Altitude [ft] 0
Take off	220
Permanent	215
75%	202

Table 15 Maximum speed for different cinfigurations and flight altitude 0ft (electric motor)

Configuration	Max.speed [km/h] Altitude [ft] 0
Take off	185
Permanent	215

9.4. Climbing flight

Angle of climbing is calculated from equation (9.10), where V in the first step is calculated from equation (9.2), then reapeating the calculation considering V resulting from equation (9.9) until reaching a stable value of flight speed.

Required and available thrust in climbing flight are calculated according to equations (9.8) and (9.3).

Climbing speeds are caculated for different operation modes and diffirent altitudes according to the equation (9.5).

Table16, Table 17 and Table 18 show max. climbing speeds and corresponding flight speeds at different altitudes (0-8000) ft.

Engine power changes depending on flight altitude according to equation (9.11).

$$U = \frac{\Delta P}{G} \qquad (9.5)$$

$$\Delta P = P_V - P_P \qquad (9.6)$$

$$P_P = F_P V \qquad (9.7)$$

$$F_p = C_D \frac{1}{2} \rho S V^2 \qquad (9.8)$$

$$V = \sqrt{\frac{2G \cos\gamma}{C_L \rho S}} \qquad (9.9)$$

$$\gamma = arc \sin\frac{U}{V} \qquad (9.10)$$

$$\Delta P_M = \left(1.11 * \left(\frac{\rho}{\rho_0}\right) * \sqrt{\left(\frac{T_0}{T}\right)}\right) - 0.11 \qquad (9.11)$$

Following are calculation for take-off configuration and 0ft altitude, at C_L = 0.617, C_D = 0.0486.

Table 16 Climbing speed and corresponding flight speeds at different altitude and different configuration (Lpg)

Engine mode	Climbing speed [m/s]/flight speed [km/h]				
	Flight altitude [ft]				
	0	2000	4000	6000	8000
Take-off	5.99	5.51	5.08	4.5	4.11
	129.5	133.5	137.8	139	142
Permanent	5.6	5.2	4.75	4.21	3.77
	129.6	133.6	137.9	142.4	145
75%	4.89	4.44	4.02	3.5	3.2
	129.9	133.8	112	116	120

Table 17 Climbing speed and corresponding flight speeds at different altitude and different configuration (cat's)

Engine mode	Climbing speed [m/s]/flight speed [km/h]				
	Flight altitude [ft]				
	0	2000	4000	6000	8000
Take-off	5.63	5.2	4.55	3.8	3.18
	129	133	137	139	140
Permanent	5.79	5.2	4.55	3.81	3.18
	125	127	129	130	135
75%	5.79	5.2	4.55	3.81	3.14
	129	128	127	131	136

Table 18 Climbing speed and corresponding flight speeds at different altitude and different configuration (electric motor)

Engine mode	Climbing speed [m/s]/flight speed [km/h]				
	Flight altitude [ft]				
	0	2000	4000	6000	8000
Take-off	4.64	4.24	3.88	3.44	3.09
	122	125.78	120	124	128
Permanent	3.2	2.88	2.57	2.21	1.92
	113.35	166.8	112.7	116.3	119.98

According to ASTM Norm F2245-12D climbing speed must be more than 1.6 m/s, the aircraft fullfil the riquirement of climbing speed at all operation mode.

9.5. Ceilling

Theoretical ceilling is the altitude at which the climbing speed is zero, practical ceilign is the altitude at which the climbing speed is 0,5 m/s. Theoretical and practical ceilling for each handled case (Lpg system, cats, electric motor) is listed in Table 19, Table 20 and Table 21.

Table 19 Theoretical and practical ceilling for different engine modes (Lpg)

Engine mode	Ceilling[ft]	
	Theoretical	Practical
Take-off	29941.5	27441.5
Permanent	28406.5	25906.5
75%	24685.5	22185.5

Table 20 Theoretical and practical ceilling for different engine modes (cats)

Engine mode	Ceilling[ft]	
	Theoretical	Practical
Take-off	19386	17719
Permanent	18392	16725
75%	15792	14126

Table 21 Theoretical and practical ceilling for different engine modes (electric motor)

Engine mode	Ceilling[ft]	
	Theoretical	Practical
Take-off	23150	20650
Permanent	16000	13500

9.6. Range and endurance

For the case of airplane with Lpg fuel, range and endurance were calculated for motor speed 4600 rpm at this speed can be obtained at equivalent between required and available power. At flight speed = 210 km/h, engine fuel consumption is determined based on engine speed from Fig 13.

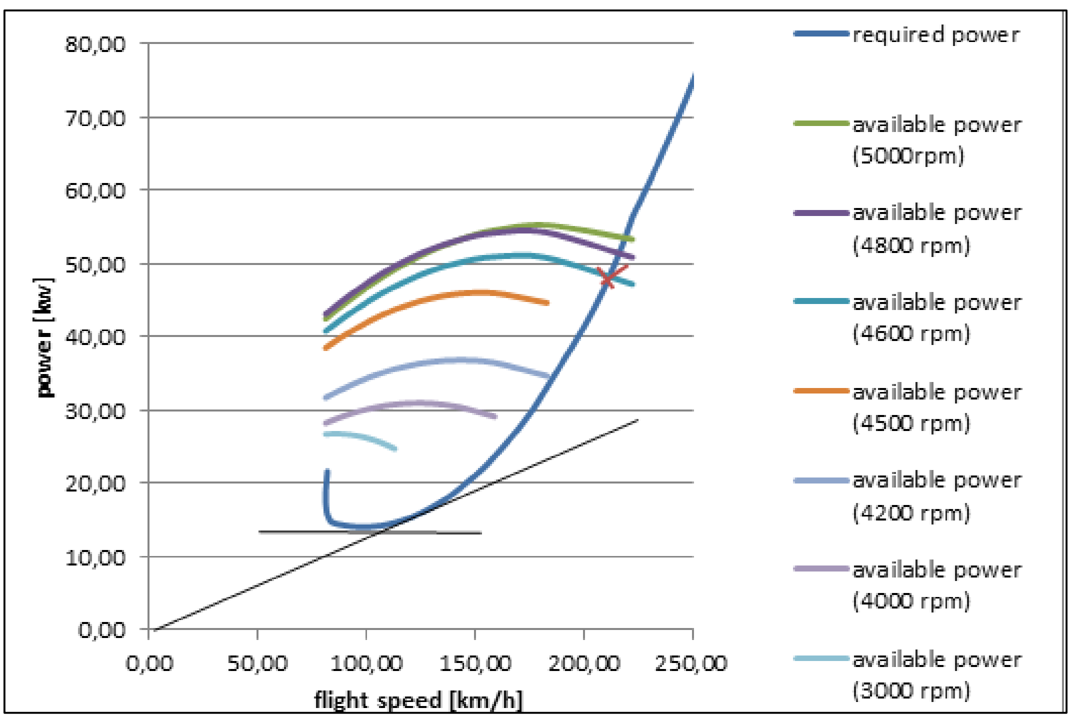


Fig 13 Available and required power for different flight speeds and different engine speeds

Fuel consumption = 14 l/h

$$Endurance = \frac{\max fuel}{fuel\ consumption} = \frac{81}{14} = 5.8 \text{ h}$$

$$Range\ = endurance \times speed = 5{,}8 \times 210 =\ 1215\ km$$

For the case of exhaust system equipped with catalytic converter, range and endurance were calculated motor speed 4500 rpm, Fig 14. At this speed, flight speed will be 202 km/h, and engine fuel consumption will be 11 l/h. Endurance= 10.9 h, Range = 2203 km

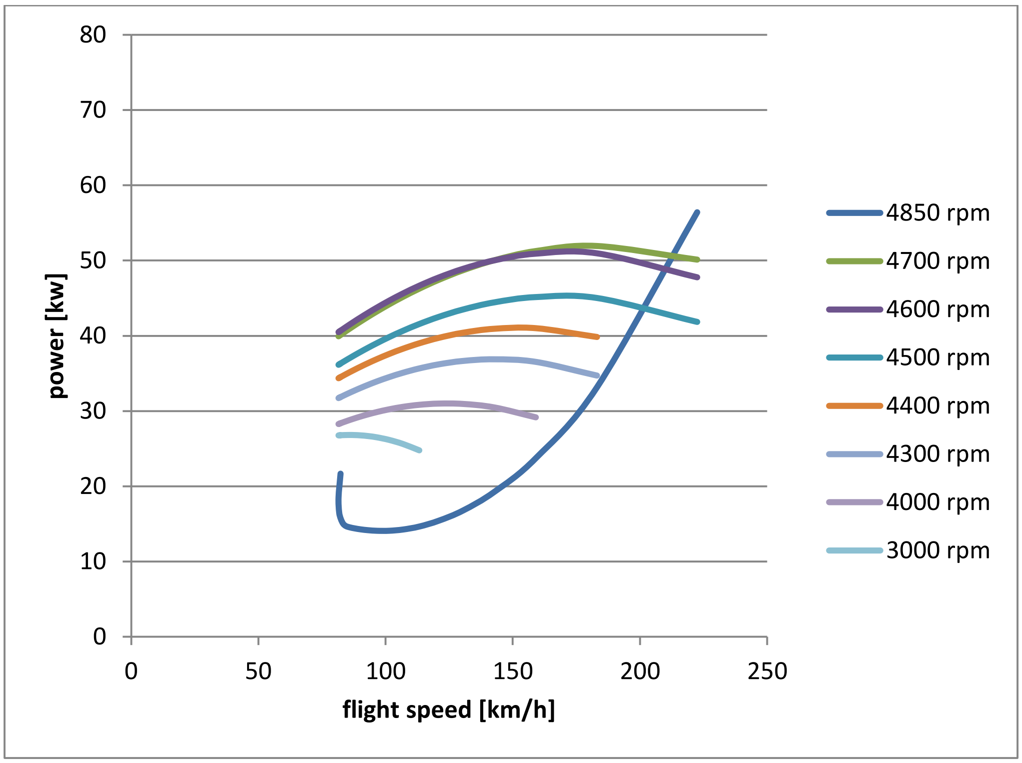


Fig 14 Required and available power for different flight speeds and different engine speeds

9.7. Take off

Ground segment of Take-off starts at speed V= 0 untill V_{LOF}, then starts airborne phase until V_2. At this speed airplane climbs to the height of obstacle 15m. Speeds for take-off segments are calculated according to equations (9.12), (9.13).

The calculation was made considering max.take off weight 600 kg, take off at altitude 0 ft MSA, friction coeficient f= 0.04, hight of obstacle h_P is 50 ft (15m).

Throughout take off flaps are set for take off mode, and engine operates at take off mode, pich angle is 0^o, at this angle C_L=0.539.

Length of take off segments are calculated according to equations (9.14), (97.15), (9.16).

$$V_{LOF} = 1.1\, V_{S1} \tag{9.12}$$

$$V_{LOF} = 1.1 \times 76{,}93 = \frac{84{,}6km}{h} = 23{,}5m/s$$

$$V_2 = 1.3V_{S1} \tag{9.13}$$

$$S_{G,TOF} = \frac{1}{\rho g}\frac{G/_S}{C_D - fC_L}\ln\left|\frac{\left(\frac{F_{mid}}{G} - f\right)}{\left(\frac{F_{mid}}{G} - f\right) - \frac{C_D - fC_L}{C_{L,LOF}}}\right| \tag{9.14}$$

$$S_{A,TOF} = \frac{G}{(F-D)_{mid}}\left(\frac{V_2^2 - V_{LOF}^2}{2g} + h_p\right) \tag{9.15}$$

$$S_{TOF} = S_{G,TOF} + S_{A,TOF} \tag{9.16}$$

Table 22 length of take-off path (Lpg)

Segment	Segment length [m]
$S_{G,TOF}$	116
$S_{A,TOF}$	105
S_{TOF}	221

Table 23 Length of take-off path (cat's)

Segment	Segment length [m]
$S_{G,TOF}$	118
$S_{A,TOF}$	107
S_{TOF}	226

Table 24 Length of take-off path (electric motor)

Segment	Segment length [m]
$S_{G,TOF}$	122
$S_{A,TOF}$	118
S_{TOF}	240

9.8. Landing

Airborne phase of landing starts at altitude h_P=15m and reference speed V_{REF} untill V_P approach speed then starts ground phase till speed V=0. Speeds at landing segment are calculated according to equations (9.17) and (9.18)

Pitch angle is 0°, therefore lift coefficient C_L=1.066, drag coefficient C_D=0.1635, and friction coefficient will be cosidered 0.4.

Length of landing segments are calculated according to equations (9.19), (9.20), (9.21).

$$V_{ref} = 1.3\ V_{s0} \tag{9.17}$$

$$V_P = 1.15\ V_{S0} \tag{9.18}$$

$$S_{A,L} = \frac{G}{D_{mid}}\left(\frac{V_{ref}^2 - V_P^2}{2g} + h_p\right) \tag{9.19}$$

$$S_{G,L} = \frac{1}{g}\int_0^{V_P} \frac{V dV}{f + (C_D - f C_L)\frac{\rho V^2 S}{2\,G}} \tag{9.20}$$

$$S_L = S_{G,L} + S_{A,L} \tag{9.21}$$

Table 25 Length of landing path (Lpg)

Segment	Segment length [m]
$S_{A,L}$	229
$S_{G,L}$	71
S_L	300

Table 26 Length of landing path (cat's)

Segment	Segment length [m]
$S_{A,L}$	224
$S_{G,L}$	71
S_L	295

Table 27 Length of landing path (electric motor)

Segment	Segment length [m]
$S_{A,L}$	218
$S_{G,L}$	63
S_L	281

10. Conclusion

In this thesis there are ten chapters. The first chapter, after the introduction, contains an overview about aviation traffic and aircraft emissions. It also contains information about EU aviation's contribution to climate change and different EU and ICAO Initiatives to reduce greenhouse gas emissions.

This is followed by the measurements made at Medlanky airport and the Institute of Automotive Engineering laboratory, for Rotax engine without catalytic converter and engine, type Skoda 1.0 MPI which is equipped with catalytic converter. These measurements revealed the clear effect of using catalytic converter in exhaust system.

In the fifth chapter were presented daily flight plan for aircraft of categories LSA, ULA, during a year. The analysis of the most frequent flight times of aircraft and the determination of maximum probable one, allows the flexibility to change the maximum fuel amount in the airplane, or suggest another alternative motor which may be more suitable.

Further in the following chapter, I made a statistic study for the experts‘ opinion about their opinions on the development of new engine or modification to drive two-seat sport aircraft category CS VLA. Also about development new engine or modifications to drive four seat sport aircraft (category CS23-N). This study gave an idea about the alternative propulsion option which can be considered the closest to optimal from the viewpoint of experts working in this field.

In the last three chapters, three options among all options presented as alternative propulsion or alternative solution to reduce aircraft emissions were examined. These options are, using Lpg fuel, replacing the traditional engine with electric one, and adding catalytic converter to the aircraft exhaust system.

These options were examined individually, taking into account the advantages and disadvantages of each of them, choosing the component of fuel system or all propulsion system. Finally, there was presented the effect of using each one on aircraft performance by calculating aircraft speeds, ceiling, endurance, range and take-off and landing path.

After reviewing the emission rates from air traffic and the programs of EU in collaboration with ICAO to limit the emissions, I found that it is worthwhile to search in the field of new solutions which will support the process of reducing emission and at the same time it can be economically viable and doable.

In order to support the research with practical and realistic views, I made the statistical study on the use of all possible solutions in this area. The results of this study was, that 61.6% of experts thinks that using current types of engines working on gasoline stays the most effective propulsion for two seats aircraft. However, the solution can be in focusing on increasing their efficiency, reliability, durability, weight reduction, emission and noise.

Whilst, 25 % of them thought that adding catalytic converter to the exhaust system is the better solution. I can expect that this option is relatively good at first from ecological point of view. Whereas, as shown in chapter 7, engine for airplane equipped with catalytic converter produces significantly less hydrocarbons and carbon monoxide emissions. It must be taken into account a very important factor which is, adding catalytic converter to exhaust system reduces the engine power of about 11 % . So that I calculated all aircraft performance for airplane VUT-081 Kondor for which was applied catalytic converter.

A slight decrease in max. speed at horizontal flight was recognized. Climbing speeds at different altitudes also changed, but all performance details still fulfill the corresponding norms. A comparison between all calculated performance is listed in table 54.

Returning to the expert's opinions 28% said that using Lpg is in the third place and 21% gave it the fourth place. It seems, at the first glance, that engine which burns liquefied petroleum, produces significantly less emissions. This idea appears from the facts that visible emission (soots) does not exist in products of Lpg combustions.

In fact, Lpg emits all greenhouse gases producing by traditional fuel, but this rate is a little less for carbon dioxides. Here it should be noted that Lpg has less heat content/ dm3 than jet fuel and avgas, which means increasing in fuel consumption about 10%, and this is its main disadvantage.

Using Lpg as fuel causes also reducing of engine power about 5%. Moreover, Lpg fuel system is have a greater weight that the other of Avgas for the same airplane. That's because this fuel needs a pressure tank to save it is a liquid form.

After applying Lpg on Kondor airplane again, the calculated amount of fuel is significant so that will be no enough place for the pressure tank to be equipped. Based on this, and on the information provided by flight plan for some similar airplanes in chapter 6, I decided to decrease the fuel amount carried by aircraft and calculated performance changes according to the new criteria's. A slight decrease in max. speed at horizontal flight was recognized. Climbing speeds at different altitudes also changed, but all performance details still fulfill the corresponding legislation.

Table 28 Camparing of flight performance for all proposed systems [1]

Dicreption	Traditional motor	LPG system	+ cat's	Electric motor
Stalling speed [km/h] at 0 [ft] altitude and cruise configuration	82.34	82.34	82.34	77.4
Max. speed at horizontal flight [km/h] at 0 [ft] altitude and take-off configuration	228.16	222	220	185
Climbing speeds [m/s] / flight speed [km/h] at 0 altitude and take- off configuration	6.07/127	5.99/129.5	5.63/129	4.64/11
Theoretical/ practical ceiling [ft] at take- off configuration	25675/ 23556	29941/ 27441.5	19386/ 17719	23150/ 20650
Length of take-off path [m]	197	221	226	240
Length of landing path	276	300	295	281

[1] Flight performance for airplane Kondor equipped with traditional motor is taken from reference [15]

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