VOL. 13, NO. 13, JULY 2018 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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THE DECISIVE ADVANTAGE OF CRDID ON SPARK-IGNITION PISTON ENGINES FOR GENERAL AVIATION: PROPELLER AND ENGINE MATCHING FOR A SPECIFIC AIRCRAFT

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ABSTRACT

Aircraft fuel consumption depends on engine, engine installation, propeller and aircraft efficiency. The matching of the installed propeller is optimized for a design point and it is a compromise for the other working points. The matching of aircraft optimum lift/drag, the minimum engine fuel consumption and the maximum propeller efficiency is rarely achieved. The hyper simplified model on books does not reach the result. Practically very few aircrafts truly match the three conditions The champion of matching are current airliners that, at least in cruise and with half the fuel, reach the optimum at least at the nominal density altitude. In addition, a few fighters and record aircrafts also achieve the maximum possible speed at the nominal conditions. The large majority of the general aviation aircrafts are far from the optimum matching. Even Unmanned Aerial Vehicles are not champions of propulsion efficiency. Ultralight and sport aircraft are the worst. Turbines are very difficult for matching since their optimum efficiency is reached in a very limited working area. Even spark ignition engines are not efficient in off-design conditions. In fact, the spark ignition engine works with an air to fuel ratio by mass that can ran from 16:1 (lean mixture) down to 12:1 (rich mixture). Even spark ignition direct injection engines the combustion takes place within this range. At the relatively high torque settings typical of aircraft engines, the air inside the combustion chamber is burnt entirely and the power output depends on the engine volumetric efficiency. In diesel engines, the air inside the combustion chamber is never burnt entirely. The minimum air to fuel ratio is around 17:1, but the engine works well with any air to fuel ratio below this value. This means that CRDID (Common Rail Direct Injection Diesel) efficiency or BSFC (Brake Specific Fuel Consumption) curve is flatter than the spark ignition engine one. This fact gives a decisive advantage in the propeller matching and in the fuel consumption. In fact, off-design performance is the strongest point in favour of CRDIDs in general aviation. Therefore, the fuel consumption of CRDID takes advantage not only from the extremely high efficiency of the engine, but also from the better matching. In fact, it is possible to map the CRDID FADEC (Full Authority Digital Electronic Control) to optimize SFC (Specific Fuel Consumption). In the example shown in this paper, a CRDID needs nearly half the fuel necessary to a very good spark ignition engine.

Keywords: spark ignition engine, diesel engine, propeller efficiency, power plant installation efficiency, propeller, aircraft matching.

INTRODUCTION

Fuel consumption of piston engines has been considered for long time a solved problem. The fuel consumption is measured with several methods during flight tests with acceptable accuracy. However, when a new power plant should be evaluated, the calculated values may differ significantly from experimental results. Fuel consumption data are often shown in lt/hour. This is a practical way for flight manuals but not for powerplant comparison. First, the engine and the propeller compose a powerplant. The propeller and the engine should be suited to the aircraft. In fact, the engine powers the propeller with a defined efficiency. The propeller transforms the power (torque) into thrust with another value of efficiency. Even the very best variable pitch propeller are never champions of efficiency. There are always regions of altitude and speed were propeller efficiency is less than 40%. The maximum best region is limited to a small area of 80% efficiency. The map of Figure-1 represents a very successful variable pitch propeller. The development of these blades can be traced down to WWI and it has been continuously improved up to now. Figure-1 shows how small the area of maximum efficiency is. In aircrafts, the thrust is balanced by drag, gravity and acceleration. While gravity and acceleration are not specific to the aircraft, type the drag is. In fact, at a defined rpm, with a defined fuel consumption the maximum engine output torque is known. However, the amount of the torque that the propeller is capable to convert into thrust and the efficiency of this transformation depends also on the aerial vehicle.

Propeller efficiency depends on aircraft CAS (Corrected Air Speed). The total efficiency of the propulsion system (powerplant) depends also on the installation efficiency. Every hole, bump and obstruction before and after the propeller reduce net thrust. In the typical side-by-side trainer, the optimized installation of the air-cooled engine reduces the propulsion efficiency by 20%. Air intakes and bulky fuselages take a huge energetic toll. On the Cessna 337 push pull SAR (Search and Rescue) aircraft, the thrust is given 75% by the rear engine and 25% by the fore one. The two engine-propeller(s) are the same. The propeller efficiency is so important that the Rolls-Royce Merlin installed on the Spitfire had a very different propeller from the same engine installed on the Lancaster Bomber. The speed

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reduction was different and the diameter was larger for the Bomber. The Lancaster was optimized for high altitude cruise at full load, while the Spitfire was optimized for maximum speed with half the maximum fuel load. In the De Havilland Mosquito, the nacelles were so streamlined that the manufacturer dealt with Rolls Royce to move the engine accessories in position that is more favourable (from the aerodynamic point of view). In addition, the gap between the propeller hub and the cowling was reduced to a minimum. On the German side, Hoerner and other smart engineers worked full time during WWII to improve propulsion efficiency of the Bf109 alone.

General remarks on spark ignition engines

Spark ignition engines ignite the air-fuel mixture with an extremely high temperature spark. The combustion then proceeds with a front surface of flame and completes inside the volume. If the fuel is directly injected inside the combustion chamber the flame volume finishes where the mixture is too lean for combustion. In this boundary, unburned and partially burnt mixtures are present. In automotive engines, they are digested by the catalytic converter. It is possible to burnt extremely lean mixtures by increasing turbulence. Engines for extremely lean mixtures have been designed from WWI up to the eighties. Good examples of these studies are the RR Merlin and the Fiat Fire. The emission requirements have partially stopped this work in favour of “clean engines”. In the aircraft field there are no requirements for emissions at the moment. Therefore, the spark ignition aircraft engines are more similar to old pre-emissions engines and to racing engines used in Formula 1. Naturally aspirated Formula 1 (up to 2013) and MotoGP engines are the champions of BSFC with the lowest absolute values. The maximum pressure in the combustion chamber is directly linked to efficiency and BSFC. With automotive and aviation gas it is usually limited in the range of 80 to 100 bar. Over this value, detonation takes place with degradation in efficiency and damage to the engine. It is possible to arrive over 140bar with the special fuels used in racing engines and in WWII both by the Allied and the Germans. The Allied fuel was designed for high performance at lean and rich mixtures, while the German fuel was designed only for rich mixtures. Continuous fuel improvement took place during WWII. Special fuels were then reintroduced in the Formula 1 racing by BMW during the turbo era. Also air temperature and humidity reduce efficiency and power output. Usually the air intake and exhaust system is designed to work at a well defined Reynolds. Design Reynolds number defines the maximum torque point where volumetric efficiency is at its top. In aircraft engines, the altitude moves this best point and remapping should be made at different altitudes. The introduction of a turbocharger reduces the BSFC. This is true in the case of boosting for power and also in boosting for altitude (critical altitude improvement only). In boosting for power, boosting is used to compensate the volumetric efficiency reduction and to improve maximum power. In boosted engines, the geometric compression ratio is reduced to allow the expansion of an increased mass of air-fuel mixture. In fact, maximum combustion chamber pressure is almost the same for naturally aspirated and turbo engines. The turbocharger requires an intercooler to reduce the intake temperature. However, this temperature is always higher than the ambient one. For this reason, boosted engine efficiency is reduced. The BSFC map of figure 3 is the one of an extremely efficient naturally aspirated spark ignition engine. Due to the room available on the head, the diameter of intake and exhaust ducts is limited. In Formula 1 engines, cooling ducts are so small that it was necessary to use coolant pressure up to 10bar to obtain the required fuel flow. Spark plug, ducts and valves occupy most of the volume available in the overcrowded head of most engines. For this reason, the maximum volumetric efficiency is usually in the first half of the rpm range, even when higher positions are required.

Maximum volumetric efficiency corresponds to maximum torque and maximum efficiency. Even if accessories like pumps and alternators may move slightly this best point. The engine of figure 3 has an efficiency of 0.33 that is a very best of modern technology. The best efficiency of spark ignition engines is obtained with the throttle almost fully open. In fact, regulation in most of these engines is obtained by a butterfly valve that cuts the fuel flow of the homogenous mixture that is predefined in the intake duct by injecting the required amount of fuel. In most indirect-injection engines the fuel charge depends on the air mass and on the lambda signal in the exhaust. In addition, humidity is important for optimum performance. The carburetted engine uses a Venturi to measure the air volume. For this reason, the altitude compensation is made elsewhere by regulating the fuel flow into the nozzle. Direct injection engines directly inject the fuel in the combustion chamber with limited improvements in efficiency at very low loads. Another regulation system is valve opening. The most known of these systems are made by Honda and FIAT that operate on maximum intake valve travel. It is also common to change cam phase on both intake and exhaust. The FIAT system is particularly efficient at low loads with a continuous regulation of the valve travel. However, maximum efficiency always takes place at almost 100% load at every rpm (see Figure-3).

General remarks on diesel engines

Diesel engines dose the fuel inside the hot air. The fuel droplet heats up to the combustion point and complete the combustion before meeting the cylinder, head or piston wall. The combustion then proceeds with a front surface of flame and completes before meeting the cold surfaces of piston, head and liner. For this reason, the combustion takes place inside a “thick” surface in place of the volume of spark ignition engine. Inside the volume enclosed in this surface a “cold” area is present where the fuel heats up to required temperature. When the injection stops, this thick surface retracts toward the injector. Direct injection engines, that are the most efficient, are divided in three main technologies. In mechanical injection, the injection takes place within two crank angles. This means that it will work optimally only at a certain rpm. Out of this optimum, you will have a too long or too short injection. Due to a not upgraded technology, the maximum injection pressure is limited to about 600bar. When compared with the common-rail 2000bar maximum-pressure you have about 15% reduction in efficiency. Electronically-assisted pump systems conjugate an electronic system to adapt the high pressure pump pressure and phase to the load and the rpm. This highly successful system is popular in heavy truck engines. It is more flexible than mechanical direct injection, but does not reach the of Common Rail (CR) systems. In CR you can define injection pressure and injection (or multi-injection) timing almost freely. The most important advantage of common rail system is not merely the better efficiency, but also the flexibility of ECU (Electronic Control Unit) mapping. Therefore, it is possible to map for emissions, for torque or, as in the aircraft case, for high efficiency. The result is engines with almost flat BSFC surface (Figure-9). This is the best choice for aircraft engines, as we will see in the following paragraphs. In addition, the maximum rpm is increased up to 6,000rpm. The limit is given by the dynamic of the injectors. The diesel engines are always turbocharged to meet the desired power to weight ratio and to optimize the amount of air charge. The increase of temperature given by boosting is welcome in diesel combustion. However, in order to avoid thermal overload, the intercooler is usually adopted [1-3].

Matching the propeller with a spark ignition engine

Figure-1 shows a commercial propeller performance map.

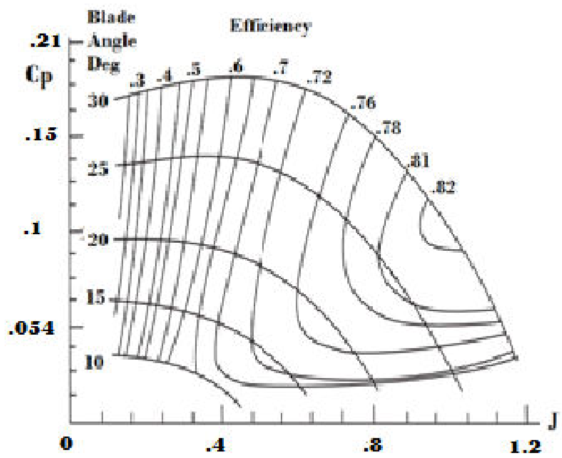

Figure-1. Propeller performance map.

Propeller performance is well described in these propeller maps where the efficiency is a function of advance ratio J (l) and power coefficient C_p (2).

$$J = \frac{v_0}{nD} \tag{1}$$

$$C_p = \frac{P}{\rho n^3 D^5} \tag{2}$$

For power plant matching it is of interest to evaluate the minimal fuel consumption for a certain engine on a certain aerial vehicle.

The propeller efficiency (3) captures how much of the shaft power that is turned into useful thrust. This means that the propulsive efficiency, swirl losses as well as profile losses are included in the number. Unfortunately, the powerplant installation is not included.

$$\eta = \frac{Tv_0}{P} = \frac{C_t}{C_p} J \tag{3}$$

Where C_t is given by equation (4).

$$C_t = \frac{T}{\rho n^2 D^4} \tag{4}$$

Propeller blade tip speed v_{tip} and disc loading D_L (5) are the two parameters most often used to find the optimum design compromise.

$$D_L = \frac{P}{D^2} \tag{5}$$

To reduce fuel consumption, the design points should be tuned to the maximum aerodynamic efficiency, engine best (minimum) BSFC and maximum propeller efficiency. This choice includes density altitude, CAS, disc loading and tip speed. In this condition, the advance ratio and the power coefficient are found using the following relations (6) (7):

$$J = \frac{v_0 \pi}{v_{tip}} \tag{6}$$

$$C_p = D_L \frac{J^3}{v_0^3 \rho} \tag{7}$$

Given a blade angle (fixed pitch propeller) Ct/J^2 and Cp/J^2 are linearly dependent (8).

$$\frac{C_p}{J^2} = m \frac{C_t}{J^2} + n \tag{8}$$

Therefore, it is relatively easy to draw the performance map of Figure-1. This performance map depends on propeller and air density. The map of Figure-1 should be evaluated in wind tunnel tests or CFD numerical simulation. Drag of Figure-2 is referred to a general aviation small aircraft similar to the Cessna 152 with a 110 HP engine. Figure-2 shows the drag at 8000ft with a mass of 750kg.

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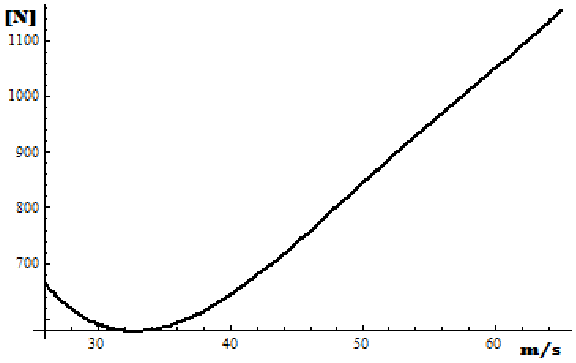

Figure-2. Drag [N] vs. CAS [m/s] of a general aviation trainer (750kg/8000ft).

The correspondent required power curve is shown in Figure-6. Therefore, the velocities of maximum range (35m/s) and of maximum endurance (26m/s) can be evaluated. Theoretically, with a propulsion system of unitary efficiency it is possible to obtain the required power at 1,700 rpm and 1,500 rpm for maximum range and maximum endurance respectively (at 8000ft). However the propeller has a maximum efficiency of η_{prop}=0.82 for J=1. With installation efficiency like the classical side by side cockpit of many trainers, it is possible to have an overall propulsion efficiency of η_{prop_inst}=0.66. Therefore, the installation efficiency is η_{inst}=0.66/0.82=0.8. The performance curves of the engine were obtained at 20°C s.l. (50% humidity) with an air density of 1.2 kg/m^3 (figures 3, 4 and 5). At 8000ft ISA+0 the air density is 0.96 kg/m^3. Engine power and torque curves (figures 4 and 5) are reduced approximately in proportion with air density. For these reasons, the required minimum crankshaft speeds for maximum range and endurance are 3,100rpm and 2,700rpm respectively (see Figures 4 and 5).

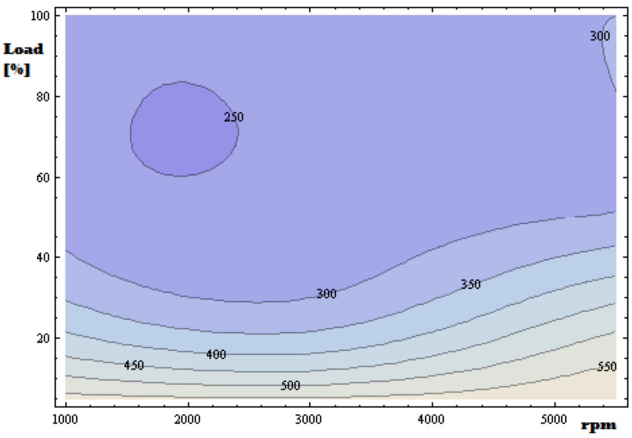

Figure-3. SFC [g/kWh]-Load [%]-rpm of an n.a. spark ignition engine (ISA+0 s.l.).

The Brake Specific Fuel Consumption (BSFC) surface of this extremely efficient naturally aspirated spark ignition engine is show in Figure-3.

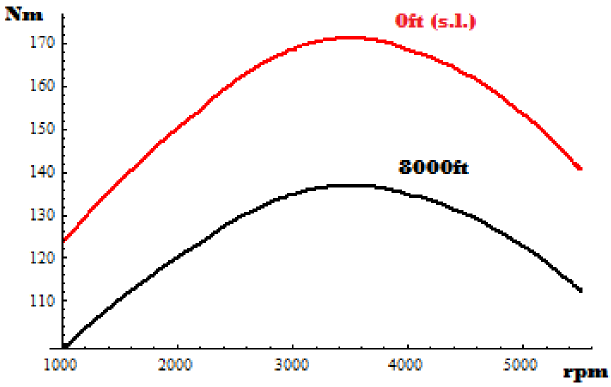

Figure-4. Torque [Nm] vs. rpm for the engine of Figure-3.

From Figure-3 the optimum area of BSFC is between 1520rpm and 2410rpm at 70% of the load (70% of the power). Figure-7 shows the power curve at 70% load. It is then possible to calculate the optimum propeller for maximum range and endurance.

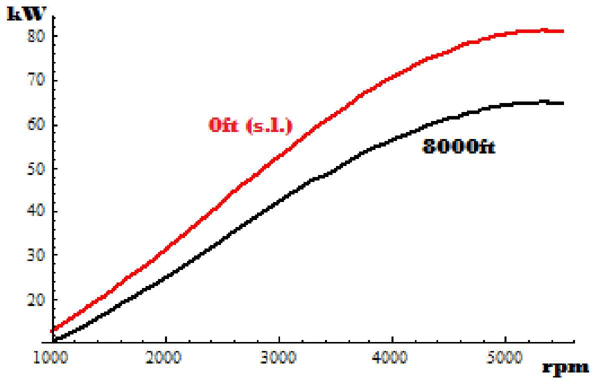

Figure-5. Power [kW] vs. rpm for the engine of Figure-3.

As explained before, the overall propulsion efficiency of 66%, the power required is $P_{endurance}$=17.3/0.66=26kW and P_{range}=20.3/0.66=31kW (Figure-7). Therefore, it is not possible to match the maximum range with the maximum engine efficiency. Luckily, the SFC curves are continuous (see Figure-8). The efficiency loss is then acceptable (260g/kWh). For this power level, commercial propeller blades of diameters from 1500mm to 1800mm are available. For maximum endurance, the engine should run at 2,700rpm.

For maximum range, the optimum rpm is 3,100 rpm (see Figures 6 and 7). Possible speed reduction ratios for ordinary gearing are from r=1.6 up to r=3. From the definition of advance ratio, it is possible to write the following equation system (9).

$$\left.\begin{cases} D-\dfrac{v_{endurance}}{\frac{rps_{endurance}}{r}J}=err_1 \\ D-\dfrac{v_{range}}{\frac{rps_{range}}{r}J}=err_2 \end{cases}\right\} Min(|err_1+err_2|) \tag{9}$$

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The minimization of the sum of errors brings an acceptable condition. This minimum is found for r=2.23 and D=1.75. In this optimum point, we have (10) and (11)

$$J_{range} = \frac{v_{range}}{\frac{rps_{range}}{r} D} == 0.86 \quad (10)$$

$$J_{endurance} = \frac{v_{endurance}}{\frac{rps_{endurance}}{r} D} == 0.74 \quad (11)$$

The C_p will be 0.12 for the velocity of maximum range and 0.17 for the maximum endurance one. Therefore, the propeller efficiency for maximum endurance is only 0.76 (Figure-1). The propeller efficiency for maximum range is a better 0.81. The installation efficiency of 0.8 should be multiplied to these values to obtain the overall propulsion efficiency. Unfortunately, the power necessary for maximum endurance is 28 kW that corresponds to 100% load. This would imply low engine efficiency. To avoid this condition the engine rpm should be increased to 2,900rpm. The new values for the advance ratio and power coefficient at max endurance are then 0.68 and 0.14. The efficiency remains 0.76. The condition of maximum speed is met when the engine runs at maximum power. The usually assumption of 0.66 propulsive efficiency corresponds to a maximum velocity of $v_{tmaxspeed}$=53 m/s (see figure 6). After various iterations, it is possible to obtain the maximum aircraft speed (12) (13).

$$J_{\max speed} = \frac{v_{t \max speed}}{\frac{rps_{\max}}{r} D} == 0.8 \quad (12)$$

The Cp is (13):

$$C_p = \frac{P_{\max}}{\left(\frac{rps_{\max}}{r}\right)^3 D^5 \rho} = 0.54 \quad (13)$$

In this point, the propeller efficiency is 76% and the aircraft will not exceed 51 knots. This means that outside the very slow speeds for maximum range, the aircraft will have high fuel consumptions. Fuel consumption depends on engine, propeller and aircraft. Engine, propeller and PSRU ratio should be chosen for a specific purpose, fuel economy, cruise or speed. In engines where the PSRU is absent, the matching is even more critical. A specific blade should be designed for best matching.

The situation worsens as the aircraft has lower wing loadings to improve range and endurance as in most MALE (Medium Altitude Long Endurance) UAVs (Unmanned Aerial Vehicles). In this case, fast cruise pays huge penalties in terms of fuel consumption.

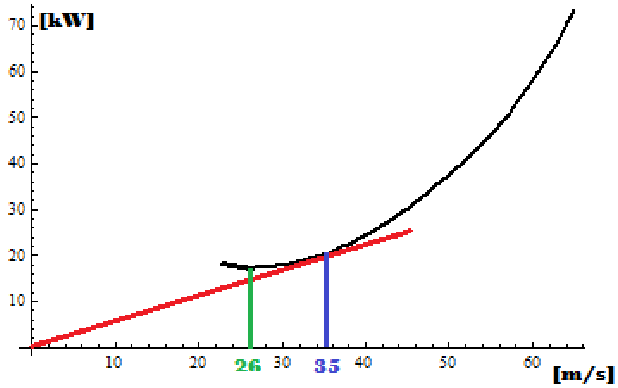

Figure-6. Power required [kW] vs. speed [m/s].

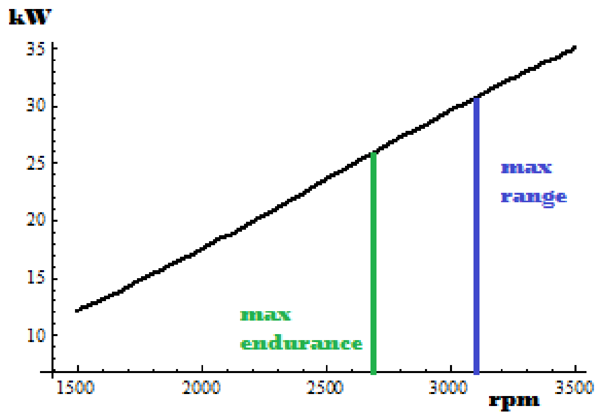

Figure-7. Engine power curve at 8000ft ISA+0 and 70% load.

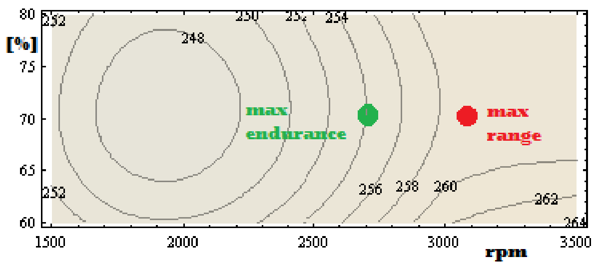

Figure-8. Enlargement of figure 3.

Table-1. Fuel consumption the aircraft with a very good spark ignition engine.

	Speed m/s	Power kW	Fuel Cons. kg/h
Endurance	26	28	7.2
Range	35	31	8
Cruise	51	63.3	19

The CRDID advantage

The spark ignition engine works with an air to fuel ratio by mass that can ran from 16:1 (lean mixture) down to 12:1 (rich mixture). Even in direct injection

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engines, the combustion takes place within this range. At the relatively high power settings typical of aircraft engines, the air inside the combustion chamber is burnt entirely and the power output depends on the engine volumetric efficiency. In diesel engines, the air inside the combustion chamber is never burnt entirely. The minimum air to fuel ratio is around 17:1, but the engine works well with any air to fuel ratio below this value. This means that its efficiency or BSFC curve is flatter than spark ignition engine one. This fact gives a decisive advantage in the propeller matching and in the fuel consumption. In fact, off-design performance is the strongest point in favour of CRDIDs in general aviation (Figure-9).

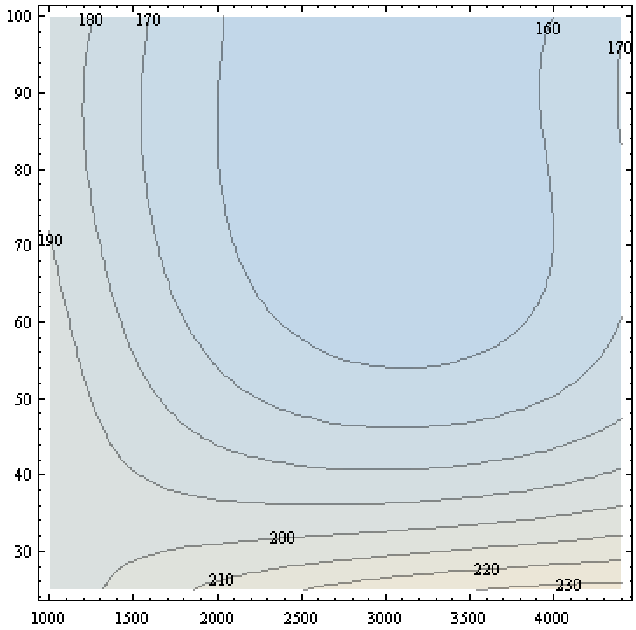

Figure-9. BSFC [g/kWh] of an automotive derived CRDID [4].

In the case of the diesel, it is possible to choose the most convenient rpm for every aircraft speed to meet the best propulsion efficiency. For example, in order to optimize the range, propeller efficiency the speed reduction should be 1.54. Table-2 shows the fuel consumption of the diesel powered aircraft.

Table-2. Fuel consumption of the aircraft with a CRDID.

	Speed m/s	Power kW	Fuel Cons. kg/h	Engine rpm
Endurance	26	28	4.8	2000
Range	35	31.3	5	2150
Cruise	51	60	9.1	3000

The diesel engine can easily reach a maximum speed of 60 m/s with and engine power output 89kW. This power output is the maximum possible for the propeller. At this speed the fuel consumption is only 14.5 kg/h. This result is possible due to the better matching of the engine with the propeller and the aircraft. This is the strongest point of modern CRDIDs.

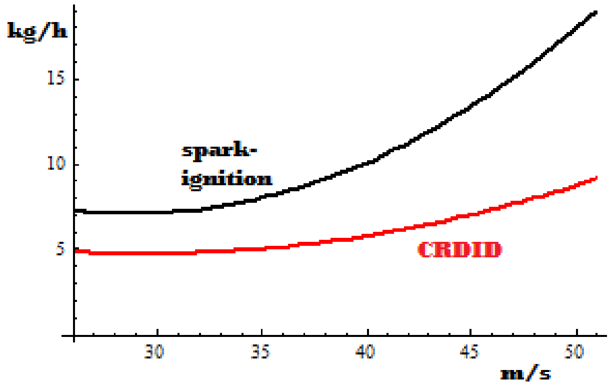

Figure-10. Fuel consumption for diesel (red) and for spark ignition engine (black).

CONCLUSIONS

Aircraft fuel consumption depends on engine, propeller engine installation and aircraft efficiency. The optimum matching of the installed propeller for a design point becomes a compromise for the other working points. The spark ignition engine works with an air to fuel ratio by mass that can ran from 16:1 (lean mixture) down to 12:1 (rich mixture). Even in direct injection engines, the combustion takes place within this range. At the relatively high power settings typical of aircraft engines, the air inside the combustion chamber is burnt entirely and the power output depends on the engine volumetric efficiency. In diesel engines, the air inside the combustion chamber is never burnt entirely. The minimum air to fuel ratio is around 17:1, but the engine works well with any air to fuel ratio below this value. This means that CRDID (Common Rail Direct Injection Diesel) efficiency or BSFC (Brake Specific Fuel Consumption) curve is flatter than spark ignition engine one [4-27]. This fact gives a decisive advantage in the propeller matching and in the fuel consumption. In fact, off-design performance is the strongest point in favour of CRDIDs in general aviation. Therefore, the fuel consumption of CRDID takes advantage not only from the general efficiency of the engine, but also from the better matching. In fact, in the emission-free aircraft world it is possible to map the CRDID FADEC (Full Authority Digital Electronic Control) to optimize SFC (Specific Fuel Consumption). On most aircrafts, the CRDID halves the fuel consumption of the spark ignition engine.

Symbols

Symbol	Description	Unit
J	Advance ratio	-
C_p	Power coefficient	-
ρ	Air density	kg/m^3
n	Propeller velocity	1/s
D	Propeller diameter	m
η, η_{prop}	Propeller efficiency	-
P	Power absorbed by the propeller	W
T	Thrust	N
C_t	Thrust coefficient	-
D_L	Disk loading	W/m^2
v_0	Aircraft CAS	m/s
V_{tip}	Propeller tip velocity	m/s
η_{prop_inst}	Powerplant efficiency	-
η_{inst}	Installation efficiency	-
P_{range}	Engine power necessary for maximum range velocity	W
$P_{endurance}$	Engine power necessary for maximum endurance velocity	W
v_{range}	maximum range velocity	m/2
$v_{endurance}$	maximum endurance velocity	m/s
r	Power Speed Reduction Unit ratio	-
$err_{1,2}$	error	-
rps_{range}	Engine rps for max range	1/s
$rps_{endurance}$	Engine rps for max endurance	1/s
$P_{endurance}$	Engine power absorbed by propeller max velocity	W
V_{tmax}	Maximum theoretical CAS	m/s
rps_{max}	Max engine rps	1/s

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