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MAPPING OPTIMIZATION FOR COMMON RAIL DIESEL CONVERSIONS FROM THE AUTOMOTIVE TO THE FLYING APPLICATIONS

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ABSTRACT

Performance of electronic controlled diesel engine is depended on quality of the map(s). In this paper, the implementation of an electronic-control map in common rail diesel engine is made, the character of operational profile in diesel engine and rule of typical profile data obtained from experiment is analyzed, a method of developing these surfaces from very few data point is applied. The particular application of aircraft and elicopter common rail direct injection diesel engines is considered. The steps of this experimental optimization activity is presented in order to test to operational profile demand. This demand is very different from the automotive to the aircraft/helicopter application. The preparation of the test engine(s) and of the test electronics for brake tests is completely different. Also the mapping technique differs substantially being the primary objectives widely different.

Keywords: common rail, fitting surface, mapping, electronic control, diesel engine, aircraft, helicopter.

INTRODUCTION

In the automotive field, emission regulations for Common Rail Direct Injection Diesel(s) (CRDID) are becoming increasingly stringent. The main trend of Electronic Control Unit (ECU) programming and mapping is aimed to effectively decrease diesel engine emission to make the marketing of the vehicle possible. ECU control parameter, such as injection timing, injection quantity and injection pressure is looked in tables obtained from experimental parameter mappings, in fact, the so-called MAP is a chart of three dimensions. The ECU fulfils looking-up table calculation and sends the Boolean control signals to its Electronic Power Module that controls the injection actuators. Maps quality directly affects the operational performance of CRDID. Control parameter maps include rail pressure, injection(s), quantities (injection(s) time), injection(s) timing, EGR (Exhaust Gas recirculation), VGT (Variable Geometry Turbine)...with increasing dimension and number, experiment quantity and difficulty for match calibration has increased dramatically. Maps are basic data to ensure control system formal work for mechanic engine to electronic control engine. Generally, maps are obtained by experiment and simulation. Experimental brake results make it possible to refine the engine and vehicle mathematical models, in order to reduce the number of expensive and time consuming tests necessary to reach the emissions and marketing requirements like power, torque, drivability, shifting and durability.

The impressive efficiency of CRDIDs that, in many cases, surpasses the 50% value, has attracted the aircraft and helicopter market, where turbines, that have dominated the market in the last 60 years have only partially corrected their main shortcomings: poor efficiency and very poor off-design performance.

However, CRDIDs still pay for inferior power to weight ratio and reliability. For example the best automotive engine we developed has a power to weight ratio of 600/255=2.35 [HP/kg]; the turbine to be replaced by this engine has 600/113=5.3[HP/kg]. The main advantages of CRDIDs are: fuel consumption, safety and manutability. The CRDID consumes from 1/3 to 1/4 the equivalent up-to-date turbine, it can use the much less flammable diesel fuel and it does not require inspections throughout its life.

The non-explosive characteristics of diesel make the installation of the Diesel simpler. The size of the fuel tanks is less and they can be placed nearer to the center of gravity and the longitudinal axis of the airplane thereby improving its aerodynamic qualities. Installation of the fuel lines is simpler as there are no explosive fumes from fuel oil at ordinary atmospheric temperatures. The advantage of being able to carry a greater payload and/or fly a longer distance with the same weight of fuel which a Diesel-engined aerial vehicle has over a kerosene-engined airplane is due to the lower fuel consumption of the Diesel and better off–design performance. As teached to the B29 WWII crews by Charles Lindberg in his famous conferences, as fuel is consumed it is possible to reduce throttle level to keep the aircraft in the maximum efficiency point. Not so for turbines, since off-design performance is not so brilliant. Diesel fuel also occupies less space than gasoline due to its higher specific gravity and so more room is available for payload in the aerial vehicle.

In addition to the savings in fuel operating cost and the increase in payload capacity, there is also the advantage of reduction of fire hazard which accrues with the use of this type of power plant. Thousands of valuable lives and many millions of dollars worth of equipment have been lost in fires involving kerosene or gasoline. Private fliers and their passengers have been trapped in their planes and burned alive. Airliners have caught fire in the air or on the ground and have become fiery tombs for their inmates and for people on the ground below. The non-explosive character of diesel used in CRDIDs eliminates practically all danger of fire on airplanes in which these engines are used. True, some fires originate with the lubricating oil but they are of a local nature and can be extinguished quickly provided there is no highly explosive fuel to add to the flames. Diesel fuel actually will extinguish a rag dipped in gasoline and ignited, so its adoption for aviation where fire now constitutes one of the greatest hazards is justifiable on humanitarian grounds alone. Owners of helicopters that has a private landing field can avoid the time consuming and expensive travels to the airports for refueling. In addition to the outstanding advantage of reduced fire hazard the difficulty of transporting fuel to remote out-of-the-way places will be reduced due to the commonality of fuel with trucks and cars and to the smaller amount of fuel required. The fact that diesel fuel has a limited evaporation rate at atmospheric temperatures makes fuel storage easier. The ability of the CRDIDs to run also on Jet (A1) in an is also important. Increased flight range and ability to carry a greater military load are two of the outstanding advantages which the CRDIDs makes possible for military vehicles. The single fuel supply line with the other Army vehicles reduces enormously the logistic costs increasing the momentum.

CRDIs from 100 up to 800HP are available from almost inexpensive automotive conversions. Another advantage of the CRDIDs is the efficiency at altitude. 6,000m (20,000ft) recovery altitude is obtained with ordinary turbo charging. With specially equipped engines it is easy to reach 10,000 m (32,000ft) with a limit up to 18,000m (60,000ft). The advantage in this case is that SFC (Specific Fuel Consumption) and power curve remain identical from ground to the recovery altitude. However 10,000m (20,000m) turbo charging equipment adds 10% (30%) of additional weight. Restarting up to 6,000m is readily obtained, while additional equipment is required for 10,000m hot starting.

Hardware for aircraft/helicopter conversion

The automotive engine is stripped from all the accessories unnecessary for aerial vehicles, a new wiring and a FADEC (Full Authority Digital Electronic Control) are installed in place of the original wiring and ECU. A new manifold and exhaust and a new turbo charging unit are also often installed. The FADEC may be derived from the sporting automotive field or specifically conceived for aircraft/helicopter application. In both cases it comes with a cable to a Personal Computer (PC) and specific programming software for engine tuning or mapping. Sensors and actuators are changed or updated in order to have the necessary reliability. Generally the rail pressure sensor(s) and the pressure actuator(s) on the rail are kept. However for this later it is necessary to check if, in case of failure, it remains closed. An additional pressure limiter valve may be added to the rail.

For the other sensors, it depends on many factors and choices, however a duplicated rpm sensor on the crankshaft is mandatory. The sensors should have an on-line diagnostic system in order to check whether it works properly. Another sensor that should be duplicated is the throttle, since it is not easy to land with "full throttle" and this is the "recovery option" for throttle sensor failure.

Engine selection

When taking off with a helicopter, the net thrust with full throttle is 1.05 times the weight. If the pilot makes a mistake in the calculation the helicopter does not take off. It may seem safe, but accidents at take off are common. Aerial vehicles should clear the ground as soon as possible for safety reasons. For this reason the engine should deliver the take off output power at the end of the useful life, in the worst environmental condition and with the worst fuel available. This condition is completely different for the automotive field, in which certification requirement are tested on new or very moderately worn equipment. For ground vehicles a certain degradation of performance is accepted during use, the occurrences that should be avoided are a full stop and a sudden increase in fuel consumption. When used car are tested, relevant differences in performances are common. A good tuner may simply put the car at its best, this result in many cases is sufficient to satisfy the user. In fact, automotive sensors are usually very cheap, mass produced units. They are automatically calibrated during the manufacturing process and never controlled again, if the diagnostic system does not signal an error. In this case the sensor is replaced without any further tuning or control. At most the code of the new sensor is inserted in the system for calibration. A few of these sensors are particularly important for performance. A typical "faulty" sensor is the air mass one that is present also in the CRDIDs for EGR (Exhaust Gas Recirculation) and other compensations for emissions. Air mass sensors come for the same car from different manufacturers or special units are available on the market. The replacement of this sensor with a more efficient one is a common operation to tune up the engine. Much more difficult is the tuning of the high pressure sensors on the rail and in many systems also on the pump. In the automotive field it is difficult to generalize, since each engine type has its own sensor set and its wiring. The automotive CRDIDs are produced in several millions in a few years and customized components are common. The high pressure sensor has its own tolerance. If the rail has a maximum pressure of 2000bar a +/-5% tolerance, it means a 200 bar variation range. The true pressure may arrive at 2000+100=2100bar when the sensor reads 2000bar, the maximum pressure in the rail may be larger since the ECU control overshoot should be calculated. A possible overshoot is around 5%. This means that the rail may reach 2200 bar true value. The first problem is that the rail is an autofrettaged unit with a safety margin that cannot be too high (usually 1.5, with the weak point in a “safe” position), the other one is that performance between a 2200bar unit and a 1800bar are different. In fact a common rail system is practically a pressure reservoir with an On/Off tap that is electrically opened. The longer the opening time and the higher the pressure the larger the Fuel Charge (FC). In fact:

$$\Delta p = \xi \left(\frac{Q}{A} \right)^2 \tag{1}$$

$$FC = t\sqrt{\frac{\Delta p}{\xi A}} \tag{2}$$

$$\frac{FC_{2200}}{FC_{1800}} = \sqrt{\frac{2200}{1800}} = 1.1 \tag{3}$$

So the 2200bar engine will have an increase in FC and output power of 10%. In general the sensor manufacturer keep the tolerance fully in the inferior part, so, sensors for 2000 bar will give the maximum electric output value in a range from 2000bar to 1800bar. In this case, if our hypothesis on pressure sensor tolerance holds, the difference in FC and output power would be even higher: 11%.

Another important point is that the ignition delay is given by Wolfer (1938) [1] equation (4):

$$\tau_{ign} = 0.44 P_o^{-1.19} \exp\left[\frac{4650}{T_o}\right] \tag{4}$$

For ignition delay blow-by is influent both for P_0 and T_0. In old diesel engine if the blow-by was excessive the engine would not start. In modern CRDIDs the ceramic glow plugs are so hot that fuel is ignited anyway. So the engine will start and run.

However the worn engine will ignite with more delay and this will reduce the maximum pressure and its position ATDC (After Top Dead Centre). Since the engine efficiency depends on maximum temperature, the power output will be reduced (5). Also the blow-by will directly affect power along with lubricant consumption. So a worn engine will output less power and will consume more fuel. Both these factors are critical for aerial vehicles applications. A typical SFC value for a worn out automotive CRDID is 150 gr/HPh. CRDIDs have a SFC that is almost constant from 25% to 95% of the output power. Normally, but not always, there is a slight increase of 5-20% of SFC in the 95%-100% power range:

$$\eta_{tot} = \eta_{Carnot}\eta_{mec} = \frac{T_1 - T_2}{T_1}\eta_{therm}\eta_{mec} = \frac{3500 - 288.15}{3500}\eta_{therm}\eta_{mec} = 150 \tag{5}$$

For this reason cylinder cold pressure measurements are necessary periodically to verify the piston rings wear.

Aircraft CRDID s that comes from the automotive conversions has the advantage that "used" engine are available o the market. For various reasons engines tend to survive to the car. Modern CRDIDs are normally conceived for a useful life of 250,000 km (155,000 mi), this usually means approximately 3500h. If your target endurance is 3,000h a used car with about 200,000km should be chosen. It is true that car use is very different from aircraft use, but a worn engine is better than a new one in any case. This engine can be tested as it is, but normally it is better to change the injectors, since their replacements should be done every 150,000km for optimum performance. The original electronic can be installed and the engine can be tested on the brake, a slight reduction of maximum output power is normal (about 10%). Many data can be retrieved from this tests that can be then used for the aircraft conversion. The worn engine is the best choice for the mapping process, since it is close to our worst "aircraft condition". During the certification process a first reduced life is initially assigned in the "type certificate". A typical initial "certified" life is 500h. As flight experience is done this limit is progressively extended to the design target that, in our case, should be 1500h for helicopters and 3000h for aircrafts. It is also possible to implement an algorithm in the FADEC that calculates the residual life depending on the load history, since the hours/cycles approach is obsolete.

The engine is then "dressed" for aircraft use. This means, first of all, a choice on sensors and actuators.

For the sensors the racing field proposes several solutions with extremely high reliability. Do not forget that a faulty sensor means, in many cases, a lost race. The sensor takes with it a diagnostic system that can be actuated by the FADEC. In any case the sensor should be tested and calibrated before installation to be sure to individuate the worst case from the power output point of view. To achieve this result it is possible to introduce additional ad-hoc calibration maps into the FADEC software. For the actuators the same can be done, especially for injectors. An old injector tends to open in more time and inject less quantity in a less efficient way. For opening time and injection quantity it is possible to introduce calibration maps. For injector nozzle efficiency it is more critical, but something can be done working on the fuel as it can be seen in the following paragraph.

For the wiring it is highly advisable to use "racing type" wirings that are both high quality and tested for electronic interference.

Many automotive engines have flaps that regulate the air flux through the valve ducts. It is common that, in worn engines, these flaps are locked into a random position. It is important to repair them and to find the position for maximum power defined by the manufacturer. Then the flap system can be removed and replaced by a more reliable fixed unit.

Fuel tayloring

An extremely critical issue is given by fuel quality. The costumer, even the aircraft one, buys the fuel at the pump. Fuel quality cannot be checked by the user, even if the most critical factors, cetane and density can be measured by sensors. However, sensors in aeronautics means additional costs, maintenance and reduced availability of the aerial vehicle. For this reason it is better to purchase the "worst case fuel" for your tests. For diesel fuel the most important parameters are summarized in Table-1.

Table-1. Worst fuel data.

Parameter	Advised value	
Cetane number ASTM D-976	40	Inferior than
Density ASTM D-975 [kg/lt]	0.83	Inferior than
Lubricity (60°) HFRR D-975 [µm]	520	Superior than
Viscosity (40°) ASTM D445 [mm^2/s]	3.6	Superior than
Sulfur content [mass%	0.09	Inferior than

Fuel supply temperature should be measured and should be from 15°C to 25°C, this value guarantees high viscosity that is detrimental to FC. The low sulphur content is not for emissions, but to reduce the lubricant properties of the fuel, that are kept very low.

After the tuning two other extreme tests can be carried out. The first is by using a premium quality fuel. The power output should be increased. This should not damage the engine. The other test is to blend the "tailored fuel" with 50% jet (A1). Most jet (A1) have a cetane index superior than 40, so cetane should not be affected. What happens is a reduction in density. This fact is balanced by the reduction in viscosity so the power should be kept. This blending practice may happen to convert "summer" fuel to "invernal" one.

If required, the CRDID can work also with Jet (A1) or JP4, but, in this case an alternative map should be used. A common mapping for jet fuel and diesel can be obtained, but in this case, the SFC would be slightly increased.

Fortunately, during the first years of the CRDIDs introduction on the market, several cases of seizure due to high water content in the fuel were detected. For this reason almost every injector and HPP (High Pressure Pump) available on the market have an anti-seizure treatment. This treatment makes it possible to use Jet fuel without lubricant, however and addition of 0.1% in volume of 2 stroke oil is advisable as common practice to reduce common rail system wear.

The mapping: initial remarks

Differently from an automotive engine, the aircraft engine carries a fan or a propeller. In both cases, even with variable pitch unit, the torque at low rpm is not relevant. This is exactly the opposite of automotive application where torque at low rpm is highly desired, since it is the torque that is felt by the driver and gives the sensation of "power". High torque also increases performance when it is most needed. Other issues common to automotive applications are fast starting, high regularity at low rpm and low noise at low rpm. In aerial vehicle applications, started is delayed by propeller/fan inertia or, in case of helicopters, by the habit of the pilots that the turbine takes a while to start-up. Regularity and low noise at low rpm are not so important, since, in aircraft applications, the propellers are a primary sound generator. On the contrary, power at high rpm, which, in automotive field is more or less a number written in marketing leaflets, is of primary importance. At every single flight the pilot takes the engine to max rpm and to max power to take off. During flight throttle may be kept at 30% to 75% depending on the type of aircraft. For helicopter maximum rpm are always kept. In this case the engine is usually derated and TBO (Time Between Overhaul) is reduced. The flight is governed by throttle, pitch and rpm. Constant rpm, fixed point flight is common. In case of a variation in air density the propeller tends to accelerate, this can be controlled manually by the pilot. In case of helicopters the propeller and engine speed are normally kept constant by an automatic system, that acts on the pitch of the blades. Automotive software for FADECs and sporting ECUs differ greatly from one another, due to their implementation history. In some cases they derive from the beginning of the CR history, in other they are derived from spark ignition engine software. In many cases the implementation is FC dependent. The more the pilot press the throttle the more fuel is injected into the engine. It is a torque control, since rpm depends on load, current engine speed and turbocharger speed... This torque control may work also for aircraft applications, even if it is far from ideal. In these applications however, care should be taken to the overspeed control strategy, that as many other parameters, depends on the software implementation. In a few of this controller also the injection model and correction maps are hidden into the system. It is then advisable to install the engine on the brake and then ask for the assistance of a specific software specialist that will assist the engineer in proper engine tuning. This will avoid time and cost waste and also surprises during the flight. When possible the automotive FC control should be avoided and a speed control should be adopted. This later one may come from the maritime racing field. In this case the rpm are fixed and the load depends from the propeller. A software PID controls the FC at the inputted rpm. The throttle controls the rpm value. This is exactly the case of aircrafts and helicopters and it is the best solution. Pitch may be automatically controlled by the FADEC (from the airspeed sensor) or by the pilot. By the way, pitch, air density and maximum-rpm limit the maximum power required to the engine.

The mapping: optimization criteria

The aim of the correct mapping is to obtain the maximum power and then the maximum efficiency. Both these results are obtained by controlling the indicator diagram and putting the peak pressure between 10-14 CAD (Crank Angle Degree) ATDC (After Top Dead Center). The more interesting rpm that has to be mapped first are the maximum one for aircraft applications (5 to 10 min duration depending on FAA or EASA rules) and the maximum continuous power. In this latter case efficiency is to be preferred. Then the rpm for helicopter use should be tested, both for power and efficiency. In this area accurate mapping can be performed avoiding interpolation in order to obtain optimum efficiency from 100% down to 75%. The peak pressure attained should be the maximum allowed by the engine design. This can be seen for equation (5) and (6) (Ideal gas equation). At 10 CAD the volume is approximately the combustion chamber volume V_{cc}. The obtainment of the peak pressure corresponds to an higher T_1, hence a higher efficiency.

$$p_{peak}V_{cc} = RT_1 \tag{6}$$

Also temperature should be kept at the engine design limit, since temperature increases combustion efficiency. For this reason a FADEC controlled bypass of the after cooler is advisable for altitude operations.

For practical and economic reason it is not feasible to optimize every single point of the map. A few very important point are experimentally optimized. Some others may be found by a mono dimensional engine model or/and by interpolation. It should be taken into account that the worst fuel is used, so the ignition and combustion are slightly restarted. A pressure peak in the area of 15 CAD ATDP (After Top Dead Point) is optimum.

The mapping: maximum power

This point is of outmost importance, since it is the Take Off (TO) point. The engine should be in "warm" condition, this is obtained by measuring air manifold, coolant and oil temperature. The VGT is progressively opened and maximum pressure is obtained in the manifold. FC is augmented up to the peak pressure obtainment. CAD timing advance is then varied to optimize this parameter. This seems to be obvious and straightforward. However, several factors are to be taken into account. First, a few software do not allow to introduce explicitly the timing advance but you have to introduce a minimum timing advance common to the whole map, then you have to input additional maps for coolant temperature compensation and rpm. Other software require to introduce your own maps starting from a draft "engine model". Every case differs from the other. However, it should be kept in mind that maximum allowed rpm is always higher than the red line on the car (up to 15% or even more). It is convenient to run at the higher rpm possible, in order to elaborate the maximum volume of air and to keep the cooling of the pistons, that are mostly air cooled, at the maximum level possible. At increasing rpm the heat transfer is more limited, since there is less time. This means that the exhaust will be hotter. The pilot injection cannot be made over a certain rpm depending on injectors and FADEC and the post injection is senseless since emission requirements are absent and the partially burnt post-injection FC will only dilute the lubricant. Single main ignition is used. If the desired power cannot be obtained, the software implementation should be controlled first, then a larger compressor can be tried, then injectors with increased permeability can be tested. Coolant inlet temperature should be 80°C, the exit one (more important) should be around 90°C. In case of overheating, an additional electric pump can be added to the circuit to substitute the original unit. Normally the coolant centrifugal pump cavitates at high rpm to reduce pressure and flow, while keeping sufficient pressure at low rpm. This is due to the fact that centrifugal pumps are highly non linear. In many cases it is sufficient to correct the inlet of this pump to obtain more flow. Lubricant temperature should not exceed 140°C in the wet sump and 110° after the cooler. Air manifold temperature should not exceed 50°C. Since aircraft engine use the maximum power at relatively high speed, cooling is not a problem with a proper radiator position. In any case, it should be kept in mind that engine failure is not a tragedy and it is a good rule to avoid to dismantle a "new" engine from the brake to send it to the disposal. Since it is not important to obtain the maximum efficiency, peak pressure and peak pressure position may be not important.

The mapping: throttle control at maximum power rpm

In order to define the FC interval it is necessary to assess the FC interval, the idling condition at max rpm should be then found. This is not relevant for the user since throttle reduction always corresponds to rpm reduction. You will never idle at high rpm during flight, except during descent when the fuel will be cut by the pilot to avoid propeller over speed. However you must have this data for FADEC programming. On your worn out engine you will underestimate this value since the engine, but it is not important. Many FADEC software already have a preset idling curve that is automatically calculated and, in many cases, has only to be validated.

The mapping: maximum continuous power

This point is of less important than the previous and it can be obtained by using the maximum rpm of the car application and by using the same FC. This means an increased timing advance of the previous step in terms of CADG. Oil and coolant maximum temperatures should be monitored. Peak pressure should be attained in the right CADG range. Cylinder exhaust gas temperature and pressure before the turbocharger should be monitored, being differences greater than 15% index of unstable working condition.

The mapping: throttle control at maximum continuous power rpm

Again, in order to define the FC interval it is necessary to assess the FC interval, the idling condition at max rpm should be then found. This is not relevant but you must have it for FADEC programming. On your worn out engine you will underestimate this value since the engine, but, again, it is not important for the engine itself.

The mapping: 75%, 50% and 35% rpm

These points are important because they are typical of normal flying operations. Propeller and fan output a thrust proportional to the square root of speed, so under 35% the speed is very low and it is used only on ground (taxiing). The engine should be in "warm" condition. The VGT is progressively opened and required pressure is obtained in the manifold. FC is augmented up to the peak pressure obtainment. CAD timing advance is then varied to optimize this parameter. Air flow can be measured by the debimeter that is not necessary for flying but it is useful for tuning. The point should be controlled in the compressor map. If the turbocharger has been correctly chosen it should be in area of maximum efficiency, possibly in the lower part, since with altitude pressure ratio should be increased. These points are of outmost importance for efficiency. From throttle position (75% and 50% rpm) and manifold pressure the correct FC and timing advance point should be optimized. If a VGT is present the correct air mass can be adjusted to the required ratio, usually 20:1. For these throttle positions is of outmost importance to have also a map at partial loads, both for intake manifold (VGT) and for FC. These points are relevant to obtain good fuel consumption figures. In altitude VGT will be opened to keep the required intake manifold pressure for that load/torque (FC) and that rpm. Software implementation can be a problem because altitude operations are typical of aircraft engine. Normally racing FADECs have some additional maps usually to avoid turbocharger overspeed at altitude. This map can be used for this purpose. Idling FC is important in this case to have a correct interpolation of the value. Again the worn engine figure is acceptable but not ideal.

The mapping: 25% and 10% rpm

This area is useful for taxiing at low altitude, not much power is required but the engine should output acceptable torque. The VGT should generally to be kept closed, since output power is not so important. In this case the idling FC is critical especially for FC automotive derived FADEC software. In this case the minimum idling value read on the worn engine should be increased of 10% to take into account of new or not ideal running conditions. Maximum peak can be kept down to 20 CADG to increase smoothness.

The mapping: warming up

CRDIDs are extremely efficient engines, at low rpm and at low temperatures they tend to overcool even with the thermostatic valve closed. For this reason, but also for emissions and costs, the manifold is often made with reinforced plastic. In case of metallic manifold, it is convenient to insulate it, especially for altitude operations. An additional heat exchanger can be added as in Figure-1. However to heat up the coolant it is advisable to implement a “special” warm-up map that retards the advance as much as reasonable in order to improve the heat transfer rate. It is important that the pilot is instructed to take off with a warm engine, since combustion is not optimal at low temperatures. High rpm idling (usually 1500 rpm) for cold engine can be also adopted. It should kept in mind that an overcooled engine will have an high blow-by with a significant amount of fuel that will dilute the lubricant. This effect is highly undesired and should be avoided.

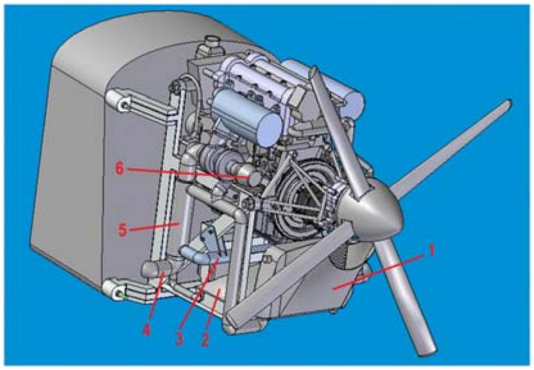

Figure-1. At warm up the aftercooler is bypassed and compressed air is send to a heat-exchanger (5) with the exhaust (4). A bypass (3) sends the air to the air intake that is thermally insulated.

The mapping: starting

CRDID glow plugs are extremely efficient and starting even at temperatures down to ISA-50 is not a problem. However, if a rubber joint is present, prolonged starting should be avoided. Care should be taken not to perform the starting procedure at joint resonant speed. Starting motor usually put the engine at a velocity between 270 and 330 rpm. If this minimum speed cannot be obtained due to low battery or excessive friction, the FADEC should interrupt the starting procedure. After a while restarting can be possible. Starting time should be controlled, since a long procedure is to be avoided due to the risk of flooding the combustion chambers with fuel. The minimum useful pressure of the rail should be used. A small CAD ATDC should be used.

CONCLUSIONS

For the mapping activity, the preparation of the motor in all its components should be accurate and well planned. Care should be taken to test and calibrate the sensors and the actuators, to check the motor and to install it in the exact way it would be on the aerial vehicle. Fuel also should be selected with proper and controlled properties in order to test the worst fuel commercially available. Only a few crucial points have to be experimented and optimized. The other can be easily interpolated. A one dimensional model of the engine can also be used for this purpose. FADEC software internal “secrets” should be fully investigated and understood.

Symbols

Symbol	Description	Unit
τ_{ign}	Ignition delay	ms
p_o	Combustion chamber pressure	MPa
T_o	Combustion chamber temperature	K

Δp	Pressure difference between rail and combustion chamber pressure	bar
ρ	Fuel density	Kg/m^3
ξ	Concentrated loss factor in injector	-
Q	Volumetric flow	m^3/s
A	Injector nozzle area	m^2
FC	Fuel charge for single injection	m^3
η_{Carnot}	Carnot cycle efficiency	-
η_{Carnot}	Thermal efficiency of the true CRDID cycle referred to the Carnot one	-
η_{mech}	Mechanical efficiency of the CRDID	-
η_{engine}	Efficiency of the CRDID	-[gr/HPh]
T_1	Maximum Temperature in CRDID combustion chamber	K
T_2	Outside temperature	K
V_{cc}	Combustion chamber volume	m^3
P_{peak}	Peak chamber pressure	Pa

REFERENCES

[1] Wolfer H. Ignition Lag in DieseI E gines VDI-Forchungsheft 392, 1938, (English Translation, RAE Farnborough, Lib. No 359, UDC 621-436 - 047, Ig5g).

[2] Yahya. 1983. Turbines. Compressors and Fans TATA Mcgraw Hill.

[3] Osnaghi C. 1982. Macchine fluidodinamiche, CLUP.

[4] L. Piancastelli, L. Frizziero, S. Marcoppido, E. Pezzuti. 2012. Methodology to evaluate aircraft piston engine durability. edizioni ETS. International journal of heat and technology. ISSN 0392-8764. 30(1): 89-92.

[5] L. Piancastelli, L. Frizziero, G. Zanuccoli, N.E. Daidzic, I. Rocchi. 2013. A comparison between CFRP and 2195-FSW for aircraft structural designs. International Journal of Heat and Technology. 31(1): 17-24.

[6] L. Piancastelli, L. Frizziero, N.E. Daidzic, I. Rocchi. 2013. Analysis of automotive diesel conversions with KERS for future aerospace applications. International Journal of Heat and Technology. 31(1): 143-154.

[7] L. Piancastelli, L. Frizziero, I. Rocchi. 2012. An innovative method to speed up the finite element analysis of critical engine components. International Journal of Heat and Technology. 30(2): 127-132.

[8] L. Piancastelli, L. Frizziero, I. Rocchi. 2012. Feasible optimum design of a turbocompound Diesel Brayton cycle for diesel-turbo-fan aircraft propulsion. International Journal of Heat and Technology. 30(2): 121-126.

[9] L. Piancastelli, L. Frizziero, S. Marcoppido, A. Donnarumma, E. Pezzuti. 2011. Fuzzy control system for recovering direction after spinning. International Journal of Heat and Technology. 29(2): 87-93.

[10] L. Piancastelli, L. Frizziero, S. Marcoppido, A. Donnarumma, E. Pezzuti. 2011. Active antiskid system for handling improvement in motorbikes controlled by fuzzy logic. International Journal of Heat and Technology. 29(2): 95-101.

[11] L. Piancastelli, L. Frizziero, E. Morganti, E. Pezzuti. 2012. Method for evaluating the durability of aircraft piston engines. Published by Walailak Journal of Science and Technology The Walailak Journal of Science and Technology, Institute of Research and Development, Walailak University, ISSN: 1686-3933, Thasala, Nakhon Si Thammarat 80161. 9(4): 425-431, Thailand.

[12] L. Piancastelli, L. Frizziero, E. Morganti, A. Canaparo. 2012. Embodiment of an innovative system design in a sportscar factory. Published by Pushpa Publishing House. Far East Journal of Electronics and Communications. ISSN: 0973-7006, 9(2): 69-98, Allahabad, India.

[13] L. Piancastelli, L. Frizziero, E. Morganti, A. Canaparo. 2012. The Electronic Stability Program controlled by a Fuzzy Algorithm tuned for tyre burst issues. Published by Pushpa Publishing House. Far East Journal of Electronics and Communications. ISSN: 0973-7006, 9(1): 49-68, Allahabad, India.

[14] L. Piancastelli, L. Frizziero, I. Rocchi, G. Zanuccoli, N.E. Daidzic. 2013. The "C-triplex" approach to design of CFRP transport-category airplane structures. International Journal of Heat and Technology, ISSN 0392-8764, 31(2): 51-59.

[15] L. Frizziero, I. Rocchi. 2013. New finite element analysis approach. Published by Pushpa Publishing House. Far East Journal of Electronics and Communications. ISSN: 0973-7006, 11(2): 85-100, Allahabad, India.

[16] L. Piancastelli, L. Frizziero, E. Pezzuti. 2014. Aircraft diesel engines controlled by fuzzy logic. Asian Research Publishing Network (ARPN). Journal of Engineering and Applied Sciences. ISSN 1819-6608,

9(1); 30-34, EBSCO Publishing, 10 Estes Street, P.O. Box 682, Ipswich, MA 01938, USA.

[17] L. Piancastelli, L. Frizziero, E. Pezzuti. 2014. Kers applications to aerospace diesel propulsion. Asian Research Publishing Network (ARPN). Journal of Engineering and Applied Sciences. ISSN 1819-6608, 9(5): 807-818, EBSCO Publishing, 10 Estes Street, P.O. Box 682, Ipswich, MA 01938, USA.

[18] L. Piancastelli, L. Frizziero, G. Donnici. 2014. A highly constrained geometric problem: The inside-outhuman-based approach for the automotive vehicles design. Asian Research Publishing Network (ARPN). Journal of Engineering and Applied Sciences. ISSN 1819-6608, 9(6): 901-906, EBSCO Publishing, 10 Estes Street, P.O. Box 682, Ipswich, MA 01938, USA.

[19] L. Frizziero, F. R. Curbastro. 2014. Innovative methodologies in mechanical design: QFD vs TRIZ to develop an innovative pressure control system. Asian Research Publishing Network (ARPN). Journal of Engineering and Applied Sciences. ISSN 1819-6608, 9(6): 966-970, 2014, EBSCO Publishing, 10 Estes Street, P.O. Box 682, Ipswich, MA 01938, USA.

[20] L. Piancastelli, L. Frizziero. 2014. How to adopt innovative design in a sportscar factory. Asian Research Publishing Network (ARPN). Journal of Engineering and Applied Sciences. ISSN 1819-6608, 9(6): 859-870, EBSCO Publishing, 10 Estes Street, P.O. Box 682, Ipswich, MA 01938, USA.

[21] L. Piancastelli, L. Frizziero, I. Rocchi. 2014. A low-cost, mass-producible, wheeled wind turbine for easy production of renewable energy. Published by Pushpa Publishing House. Far East Journal of Electronics and Communications. ISSN: 0973-7006, 12(1): 19-37, Allahabad, India.

[22] L. Piancastelli, G. Caligiana, Frizziero Leonardo, S. Marcoppido. 2011. Piston engine cooling: an evergreen problem. 3rd CEAS Air and Space Conference - 21st AIDAA Congress - Venice (Italy), 24th-28th October.

[23] L. Piancastelli, L. Frizziero, E. Morganti, A. Canaparo. 2012. Fuzzy control system for aircraft diesel engines. Edizioni ETS. International journal of heat and technology. ISSN 0392-8764, 30(1): 131-135.

[24] L. Piancastelli, L. Frizziero, 2014. Design, study and optimization of a semiautomatic pasta cooker for coffee shops and the like. Asian Research Publishing Network (ARPN). Journal of Engineering and Applied Sciences. ISSN 1819-6608, 9(12): 2608-2617, EBSCO Publishing, 10 Estes Street, P.O. Box 682, Ipswich, MA 01938, USA.

[25] L. Piancastelli, L. Frizziero, I. Rocchi, 2014. A low-cost, mass-producible, wheeled wind turbine for easy production of renewableenergy. Asian Research Publishing Network (ARPN). Journal of Engineering and Applied Sciences. ISSN 1819-6608, 12(1): 19-37, EBSCO Publishing, 10 Estes Street, P.O. Box 682, Ipswich, MA 01938, USA.

[26] L. Piancastelli, L. Frizziero, G. Donnici, 2014. Learning by failures: The "Astura II" concept car design process. Asian Research Publishing Network (ARPN). Journal of Engineering and Applied Sciences. ISSN 1819-6608, 9(10): 2009-2015, EBSCO Publishing, 10 Estes Street, P.O. Box 682, Ipswich, MA 01938, USA.

[27] L. Piancastelli, L. Frizziero, T. Bombardi, 2014. Bézier based shape parameterization in high speed mandrel design. International Journal of Heat and Technology, ISSN 0392-8764, 32(1-2): 57-63.

[28] L. Piancastelli, L. Frizziero, 2014. Turbocharging and turbocompounding optimization in automotive racing. Asian Research Publishing Network (ARPN). Journal of Engineering and Applied Sciences. ISSN 1819-6608, 9(11): 2192-2199, EBSCO Publishing, 10 Estes Street, P.O. Box 682, Ipswich, MA 01938, USA.

[29] L. Frizziero, A. Freddi, 2014. Methodology for aesthetical design in a citycar. Asian Research Publishing Network (ARPN). Journal of Engineering and Applied Sciences. ISSN 1819-6608, 9(7): 1064-1068, EBSCO Publishing, 10 Estes Street, P.O. Box 682, Ipswich, MA 01938, USA.

[30] E. Pezzuti, P.P. Valentini, L. Piancastelli, L. Frizziero, 2014. Development of a modular system for drilling aid for the installation of dental implants. Asian Research Publishing Network (ARPN). Journal of Engineering and Applied Sciences. ISSN 1819-6608, 9(9): 1527-1534, EBSCO Publishing, 10 Estes Street, P.O. Box 682, Ipswich, MA 01938, USA.

[31] L. Frizziero, 2014. A coffee machine design project through innovative methods: QFD, value analysis and design for assembly. Asian Research Publishing Network (ARPN). Journal of Engineering and Applied Sciences. ISSN 1819-6608, 9(7): 1134-1139, EBSCO Publishing, 10 Estes Street, P.O. Box 682, Ipswich, MA 01938, USA.

[32] L. Piancastelli, L. Frizziero, G. Donnici, 2014. Study and optimization of an innovative CVT concept for bikes. Asian Research Publishing Network (ARPN). Journal of Engineering and Applied Sciences. ISSN 1819-6608, 9(8): 1289-1296, EBSCO Publishing, 10

Estes Street, P.O. Box 682, Ipswich, MA 01938, USA.

[33] L. Piancastelli, L. Frizziero, G. Donnici, 2014. The common-rail fuel injection technique in turbocharged di-diesel-engines for aircraft applications. Asian Research Publishing Network (ARPN). Journal of Engineering and Applied Sciences. ISSN 1819-6608, 9(12): 2493-2499, EBSCO Publishing, 10 Estes Street, P.O. Box 682, Ipswich, MA 01938, USA.

[34] L. Piancastelli, L. Frizziero, 2015. Supercharging systems in small aircraft diesel common rail engines derived from the automotive field. Asian Research Publishing Network (ARPN). Journal of Engineering and Applied Sciences. ISSN 1819-6608, 10(1): 20-26, EBSCO Publishing, 10 Estes Street, P.O. Box 682, Ipswich, MA 01938, USA.

[35] L. Piancastelli, L. Frizziero, 2015. Accelerated FEM analysis for critical engine components. Published by Walailak Journal of Science and Technology The Walailak Journal of Science and Technology, Institute of Research and Development, Walailak University, ISSN: 1686-3933, Thasala, Nakhon Si Thammarat 80161. 12 (2): 151-165, Thailand.

[36] L. Piancastelli, L. Frizziero, G. Donnici, 2015. Turbomatching of small aircraft diesel common rail engines derived from the automotive field. Asian Research Publishing Network (ARPN). Journal of Engineering and Applied Sciences. ISSN 1819-6608, 10(1): 172-178, EBSCO Publishing, 10 Estes Street, P.O. Box 682, Ipswich, MA 01938, USA.

[37] L. Piancastelli, L. Frizziero. 2015. Multistage turbocharging systems for high altitude flight with common rail diesel engines. Asian Research Publishing Network (ARPN). Journal of Engineering and Applied Sciences. ISSN 1819-6608, 10(1): 370-375, EBSCO Publishing, 10 Estes Street, P.O. Box 682, Ipswich, MA 01938, USA.

[38] L. Piancastelli, L. Frizziero. 2015. A new approach for energy recovery and turbocompounding systems for high altitude flight with common rail diesel engines. Asian Research Publishing Network (ARPN). Journal of Engineering and Applied Sciences. ISSN 1819-6608, 10(2): 828-834, EBSCO Publishing, 10 Estes Street, P.O. Box 682, Ipswich, MA 01938, USA.