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A new design concept for 2-Stroke aircraft Diesel engines

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Abstract

High power density, low weight, compact dimensions, high efficiency as well as reliability are the key factors in designing and dimensioning piston engines for General Aviation and Unmanned Aerial Vehicle (UAV) power plants. Despite of new available technologies, conventional solutions are still struggling to fulfill simultaneously all those requirements.

The paper explores the application of a new design of 2-Stroke externally scavenged engines to aircraft. The new concept basically consists in the use of a patented rotary valve for controlling the flow through a set of inlet ports, enabling supercharging and the achievement of extremely high power densities compared to conventional solutions. The scavenging is realized by using an external pump, made up of a further cylinder, whose piston is connected to the same crankshaft. The piston pump allows the crankcase to be used as a conventional oil sump, and greatly improves the crankshaft balance. No poppet valves or camshafts need to be installed, since the flow is driven by piston-controlled ports and by two sets of reed valves.

The engine can adopt two types of combustion system: Gasoline Direct Injection (GDI) for SI operations, and Direct Injection Common Rail for Diesel cycle. The paper is focused on the last version, since it can run on standard aircraft fuel.

The Diesel engine has three cylinders and three piston pumps, for a total displacement of 1.5 liter The engine is turbocharged and inter-cooled, in order to reach a power target, at sea level, of 150 kW@4000 rpm. Another fundamental target is the minimum power of 100 kW, at the altitude of 20,000 feet.

The paper reviews the design of the engine and presents the numerical prediction of the key performance parameters.

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Keywords: 2-Stroke-Engines, Diesel, Aircraft, CFD-simulation

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1. Introduction

The application of the 2-Stroke Diesel concept to aircraft engines is everything but a novelty: as just one example, Junkers built a very successful series of these engines in the late 19-'30's, named "JUMO". The main advantage offered by such an engine is fuel efficiency; even in 1938, the JUMO engine was capable of a Brake Specific Fuel Consumption of 213 g/kWh [1], an impressive figure even by modern standards. It should be noticed that fuel consumption is very important for aircraft performance, since a relevant portion of the aircraft total weight (sometimes up to 50%) is due to fuel storage. The main reason of the outstanding fuel economy of 2-Stroke Diesel engines is the high mechanical efficiency ensuing from the 2-Stroke cycle; besides the possibility of having no poppet valves and the associated driving system, mechanical friction losses over the cycle are about halved, in comparison to a four-stroke engine having the same crank and piston and crankcase design, thanks to the double cycle frequency. A further interesting feature of the two-stroke cycle is the high power density at low crankshaft speed, allowing the designer to connect the engine to the propeller without a reduction drive (which is heavy and expensive, and it penalizes fuel economy).

Supercharging further improves power density and fuel efficiency, as well as enhancing altitude performance. Diesel combustion allows a higher boosting level, in comparison to Spark Ignited engines, limited by knocking. In addition, high octane aviation gasoline may be not always available, while a Diesel engine can burn a variety of fuels: besides automotive Diesels, also turbine fuels such as JP4 and JP5, and Jet A. Further advantages in comparison to gasoline power-plants are: reduced fire and explosion hazard and better in-flight reliability (no mixture control problems).

The recent development of Diesel technology, along with the above mentioned series of advantages, has made the 2-stroke, compression ignition engine an interesting option for light aircraft manufacturers, seeking power unit of 100-300 HP, preferably not heavier than existing SI powerplants. Conversion of automotive four stroke units is generally not attractive, since they are relatively heavy. Thus, design must be carried out from scratch, in order to achieve an acceptable power to weight target. The mission is far from impossible: as an example, already in the second half of the '90's, AVL developed a 1-liter 2-Stroke turbocharged Diesel engine, with uni-flow scavenging, achieving a brake power of 50 kW, and a weight less than 80 kg [2], and Wilksch Airmotive brought to the experimental aircraft market a 90kW three cylinder two-stroke unit using IDI combustion and weighting only 100kg [3-6].

Passing from General Aviation to Unmanned Aerial Vehicles (UAV), the above mentioned advantages of 2-Stroke Diesel engines still remain. The constraints on cost and safety are generally less stringent, while other specifications may arise, such as low acoustic and infra-red signatures, ability to resist at extreme operating conditions, et cetera.

Recently, some hybrid powerplants, based on efficient Diesel engines coupled to electric motors, have been proposed for aircraft [16]. In this field, one of the most interesting advantages of hybridization is the possibility to boost the power output of the propulsion system, exploiting the capability of the electric motor to be loaded over its maximum nominal limits for a short time. The extra power provided by the electric machine may be used during the take-off phase, while for continuous operation it is sufficient a lower power output, typically one third of the take-off one. This technique allows the designer to reduce the dimensions and the weight of the powertrain, as well as to improve the overall system efficiency. An additional benefit of a hybrid powerplant is the limited heat and noise signature. As well known, in comparison to internal combustion engines, electric machines work at much lower temperatures and they are almost noise-less and vibration-less. Therefore, a UAV flying in electric mode is less easily detectable than an aircraft powered by an internal combustion engine.

The two typical options for hybrid architectures are series or parallel. Both configurations allow the aircraft to fly in pure electric mode. The most important benefit of the serial configuration is its lower impact on an existing electric powerplant, which can be easily integrated with an APU (Auxiliary Power Unit) with only minor adjustments. Furthermore, series hybrids enable the size reduction of the battery pack, which can be designed to provide energy only for the pure electric range. At the same time, the overall range can be dramatically extended, in comparison to pure electric aircraft, allowing also long range flights (therefore addressing the biggest issue of current electric aircraft).

On the other hand, the main benefits of a parallel hybrid configuration are the multiplicity of the operating modes, the need of one electric machine instead of two units, and the propulsion redundancy, which improves drastically the system safety.

For both designs, the most important challenge for the hybridization is the necessity to have a compact and light internal combustion engine, in order to compensate the room and weight of the additional components. A 2-Stroke

Diesel engine may be an interesting solution to address this issue, for the reasons already discussed in the previous sections.

This paper presents the result of a theoretical study, supported by some experiments, on a new design of 2-Stroke engine, which can feature either a Spark Ignition or a Diesel combustion system. In a couple of previous technical reports [7, 8], the new design concept was explored with reference to Range-Extender automotive applications. Now, the attention is shifted to the aircraft field. For exploring an application range as wide as possible, the engine specifications are set in order to meet the requirements of both a typical light passenger aircraft, and of a big UAV.

In particular, the power rate is set at 150 kW at sea level, with a maximum speed of the propeller equal to 2000 rpm. As a further constraint, the minimum power at 20,000 feet must be at least 100 kW. Finally, the engine must be able to run on several types of fuel: automotive Diesel oil, kerosene, JP4, JP5, Jet A.

A further analysis of the proposed engine included in a hybrid system is outside the scope of this paper, although the authors intend to carry it out in the near future.

2. The new engine concept

The application of the 2-Stroke cycle to aircraft engines has to face some important challenges, mainly related to high fuel consumption and low durability in the standard realizations. However, the progress of the available technologies (i.e. fuel injection systems), combined with an innovative architecture and the particular operating needs of an aircraft, makes this solution really promising for such a kind of systems.

For obvious reasons, the main issue that must be addressed on a 2-Stroke engine is the scavenging process. Crankcase and piston controlled ports - the solution universally adopted for small bore petrol engines – seems not suitable for aircraft applications, because of the poor lubrication at high load. Conversely, an external compressor enables the use of a traditional and efficient oil sump, leaving a lot of freedom in the choice of the induction and exhaust systems. Most of externally scavenged engines have Roots-type blowers, but other solutions are possible. As in the Ricardo Dolphin engine [9], or in the more recent ALCOR [10], an additional cylinder can be adopted for scavenging purpose, and also be used to achieve an excellent balance of the crankshaft (the power cylinder and the pump cylinder are disposed at 90°, the two rods connected to the same crank). It is observed that adopting a piston pump is like to split the four-stroke cycle between two cylinders, the former getting the compression and expansion strokes, the latter the intake and exhaust ones. However, instead of cam-driven poppet valves, simple reed packs can be installed on the pump head, maintaining a very compact and cost-effective design, in comparison to a 4-Stroke conventional engine. From the point of view of efficiency, a piston pump is certainly better than a rotary blower. Furthermore, the displacement of the pump can be set in a quite free manner, just varying the piston bore. As a result, the supercharging degree of the engine can be chosen according to the project targets: small pumps are suitable for fuel efficient engines, while large pumps can be adopted to increase brake performance.

The capability of a 2-Stroke engine to run with only piston controlled ports is another significant advantage, even in front of some downsides. On the one hand, an engine without camshafts and poppet valves is more compact and efficient (less friction losses, more freedom in the design of the combustion chamber). On the other hand, it is difficult to get a good scavenging quality, and a number of minor issues arise when designing the piston-rings-liner assembly. According to the authors' experience, the arguments in favor of the piston controlled ports are stronger than those supporting the so called "Uniflow" scavenging (that is a set of induction ports in the liner, controlled by the piston, and some exhaust poppet valves in the engine head). A recent paper [6] demonstrated that on Diesel aircraft engines a proper ports and combustion system design can cancel all the downsides of Loop scavenging in comparison to "Uniflow", while keeping the original advantages. A further help to Loop scavenging can be obtained from a patented rotary valve called "Charge Control Device" [11], visible in figure 1.

The valve is made up of a rotor, mounted on roller bearings and revving at the same speed of the engine, controlling the flow upstream of a specific set of transfer ports, called "supercharging ports". The shape of the valve rotor's cross section allows the designer to define the time-area diagram of the supercharging ports in an almost free manner, enabling the adoption of effective scavenging strategies. In particular, the supercharging ports can remain fully open when the piston is closing the exhaust port (compression stroke), taking the maximum advantage from the action of the piston pump, that is pushing fresh charge toward the engine at the same time. Moreover, the supercharging ports are slightly higher than the exhaust port, in order to provide an additional amount of fresh charge after the exhaust closing. In figure 1 it can be also observed that, besides the supercharging ports, there is a set of conventional transfer ports, quite small in comparison to the standard design. The installation of the CCD device does not generate significant additional constraints on ports design, that can follow the guidelines provided by the well-established engineering practice on 2-S engines.

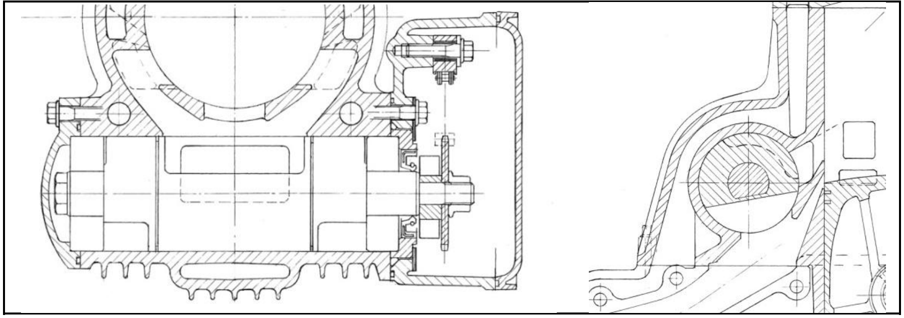

Figure 1: View of the rotary induction valve

3. Engine Design

The development of the aircraft engine is based on the experience of the turbocharged CI Range Extender reviewed in [7]: in particular, the combustion and scavenging systems are almost identical, while the attention is focused on the air metering system and on the timing of the CCD valve. In comparison to the single-cylinder turbocharged Range Extender engine, delivering a maximum power of 36 kW at 4000 rpm, the aircraft application has a much higher target: 150 kW. This goal is even more challenging considering that the engine must provide a power of 100 kW at 20,000 feet of altitude, where the air density may be almost one half of the sea level standard value. Therefore, the aircraft engine must have at least 3 cylinders, along with an increased boosting level. As a result, the structural design of the engine is to be completely revised, in order to comply with much higher levels of thermal and mechanical stress. This fundamental issue is not discussed in the paper, however the current automotive practice suggests that, limiting the in-cylinder peak pressure at 150 bar, it is possible to design a reliable Diesel engine.

In the aircraft application, the turbocharger must include a reliable control system, preventing over-speeding at high altitudes. A waste-gate valve appears as the most suitable solution; the valve can also be used to limit boosting at sea level, enabling a freer and more effective selection of the turbocharger itself. A high technical sophistication is required for both the turbocharger and the intercooler: each component must have a top-class efficiency, in order to guarantee excellent performances and a compact design.

Boosting is provided by the combined action of the piston pump and the dynamic compressor. Since a good fuel efficiency is highly desirable, it is convenient to limit the compression work done by the piston pump. This result can be easily achieved by reducing the pump bore. On the one hand, with a proper displacement it is possible to cancel almost completely the contribution of the volumetric pump (the piston is simply moving the compressed charge from the intake plenum to the power cylinders, without changing its pressure); on the other hand, the piston pumps help the engine to start. This function is fundamental on an aircraft, since engine starting must be guaranteed also at high altitudes, where temperature may drop as low as -30 °C and the turbocharger is not providing any type of support. In these critical conditions, a further help can come from a valve installed at the exhaust port, controlling the cross section area of the duct near the port. Reducing this section, it is possible to increase both in-cylinder pressure and temperature during the compression stroke, improving ignition.

The injection system is a critical component, since it has to deal with different types of fuel. However, the operating range of major interest is quite limited, since the engine is generally running at mid-high speeds, high load (top speed and load during take-off, medium speed and load for cruising). In these conditions, combustion efficiency requires high injection pressures, and a limited number of pulses (one or two). Therefore, a first or second generation of Common Rail systems should be sufficient to meet the aircraft standards. Also a mechanical system could be considered, trading performance with reliability and cost.

Pollutant emissions are not expected to be an issue, with the current aircraft legislation; however, the 2-Stroke engine can be as clean as the last generation of automotive Diesel engines, adopting a Diesel Oxidation Catalyst (DOC), along with a Diesel particulate filter. Since the engine is always operated at medium-high load, in a quite steady way, the filter regeneration is of little concern. NOx emissions can be controlled by a low pressure EGR circuit, in addition to the internal EGR, typical of 2-Stroke engines.

Finally, the maximum rotational speed of the engine must be at least 4000 rpm, in order to achieve the power target. Since the speed of the propeller cannot exceed 2000 rpm, a reduction drive is mandatory. Also this component must be light, efficient and reliable.

A suitable lay-out of the aircraft engine is presented in figure 2, while figure 3 shows the design of a single cylinder.

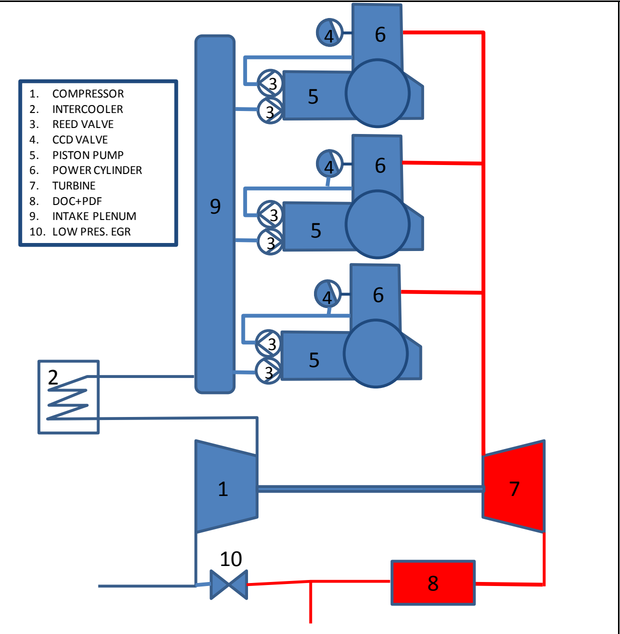

Figure 2: lay-out of the aircraft engine, including an after-treatment system and a low pressure EGR circuit

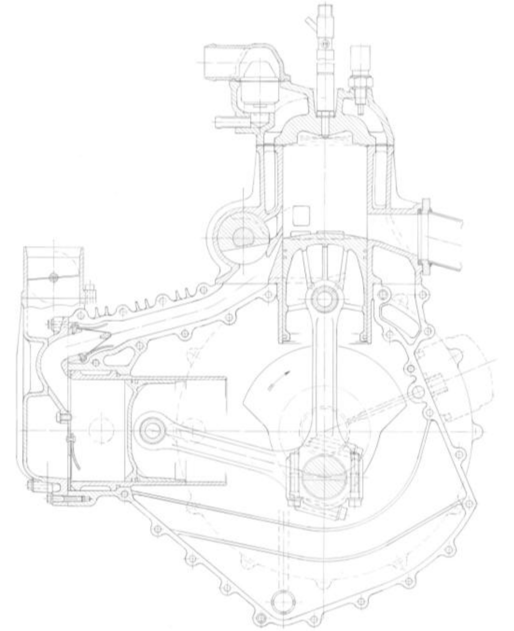

Figure 3: view of the single cylinder-pump assembly.

4. Numerical Modeling and Optimization

As already done in the study reviewed in [7], the GT-Power initial model derives from the one experimentally calibrated for an exemplar of an old 2-S loop-scavenged Diesel engine produced by Detroit Diesel – General Motors and fully restored at the UniMoRe laboratories. Specific information on the plow patterns through the ports (discharge coefficients as a function of port opening), on scavenging (percent of residuals in the exhaust flow as a function of in-cylinder charge composition), on combustion (burn rates and combustion efficiency calculated for a few different engine speeds and relative air-fuel ratios) and in-cylinder heat transfer is provided by the specific CFD-3D analyses, described in [7]. These simulations have not been repeated, since the cylinder geometry is almost identical, except for a few details.

A quite critical issue is the definition of the mechanical friction losses, required as input data by 1D simulations. Since at this stage of the study a physical prototype for measurements is not available, some empirical hypotheses are made.

First, it is assumed that the work spent to drive the induction rotary valve is negligible in comparison to the work lost for the actuation of a conventional valve-train. In fact, the rotary valve does not induce the typical losses of a conventional valve-train: no friction between cams and tappets, no springs, no relevant load applied to the shaft journals .

Second, it is postulated that the friction work spent in the 2-Stroke cycle by both the power cylinder and the piston pump is equivalent to the work spent during two complete crankshaft revolutions by a single cylinder of a 4-Stroke engine, having a comparable design and similar unit displacement. The work dissipated by the valve-train is not included. Furthermore, for the sake of simplicity, the energy lost by the 4-Stroke engine is considered as evenly distributed over the piston strokes (in other words, half of the friction work is lost in the intake-exhaust strokes and the other half in the compression-expansion strokes)

The influence of the valve-train on the total friction losses is very hard to determine, without experimental evidence. According to some textbooks [12-13], at full load this figure generally varies between 20 and 40%. Waiting for some experimental evidence, the authors arbitrarily decided to consider the energy lost in the valve-train by a 4-Stroke engine equal to 30%, at any speed.

As a result of the previously discussed hypotheses, the following equation is used to calculate the Friction Mean Effective Pressure of the 2-Stroke engine ($fmep_{2S}$), starting from the knowledge of the values of a similar 4-Stroke unit ($fmep_{4S}$)

$$fmep_{2S} = 0.35 fmep_{4S} \left(\frac{D_{2S,p} + D_{2S}}{D_{2S}} \right)$$

where D_{2S} is the displacement of the 2-Stroke power cylinder, while $D_{2S,p}$ is the displacement of the piston pump.

As visible, the higher is the piston pump displacement, the higher is fmep. If cylinder and pump have the same capacity, then the friction mean effective pressure of the 2-Stroke engine corresponds to the value of the 4-Stroke, except for the valve-train.

A numerical optimization has been carried out , starting from the geometry devised for the automotive application described in [7]. The most important parameters to be set are: exhaust and transfer ports height; the actuation law and timing of the Charge Control Device; the bore of the piston pump; the geometry of the exhaust manifold connecting the cylinders to the turbine inlet; the geometry of the manifold between the piston pump and the cylinder; the features of the reed valves, installed at both the pump inlet and delivery ports; the size of both compressor and turbine; the waste-gate valve opening degree.

It is observed that the size of the turbocharger is a trade-off between conflicting issues: as the turbine (or the compressor) nozzle area decreases, higher boosting can be achieved, but also the exhaust back-pressure increases, along with the specific fuel consumption. Furthermore, as the aircraft is climbing, a small turbocharger tends to choke at a lower altitude. The inertia of the turbocharger is not a critical issue, since the engine operates at almost constant speed and load.

The criterion followed in the choice of the turbocharger has been to find the minimum size of the compressor able to guarantee a proper airflow rate in any condition. The maximum airflow rate requirement for the turbocharger occurs when the engine is revving at its maximum speed and the aircraft is flying at 20,000 feet above the sea, in a hot day. Even in these extreme conditions, the engine must be able to provide a brake power of 100 kW, so that this requirement defines, from a practical point of view, the maximum flow rate delivered by the turbocharger.

The scavenging process at maximum power can be analyzed on the basis of the pressure traces and the mass flow rates through the cylinder ports. In figure 4, the values calculated at sea level, standard conditions, are plotted, along with the effective areas of the ports. It is observed that the inlet ports controlled by the CCD valve (called Supercharging ports and referred to as “Super”) are closed by the piston: this is the reason for the abrupt change in the effective area plot.

Some comments are listed below.

1. The patented CCD valve allows the designer to define a non-symmetric opening for the inlet ports, with strong advantages in terms of scavenging effectiveness. As visible, a high pressure differential across the cylinder occurs after BDC (180°), due to the suction generated in the exhaust manifold; furthermore, in the same moment, the piston pump is pushing fresh charge toward the cylinder. Therefore, it is highly convenient to have large inlet port areas after BDC, while a late opening of the same ports helps to reduce the loss of fresh charge through the exhaust. As visible, the fresh charge enters the cylinder from -25° to 75° after BDC
2. The exhaust port opening occurs very close to BDC (70°), in comparison to most high power 2-Stroke engines, with ensuing advantages in terms of fuel efficiency (more work during the expansion). This port setting is possible because of the piston pump action, pushing the charge across the cylinder after BDC. Such an effect is quite evident in the shape of the exhaust mass flow rate, presenting a secondary peak 30° after BDC.

The engine main geometrical features resulting from the optimization are reviewed in Table 1. Table 1 also shows the main constraints placed upon engine design: maximum speed (4000 rpm), maximum in-cylinder pressure (120 bar)and maximum turbine inlet temperature (1000 K).

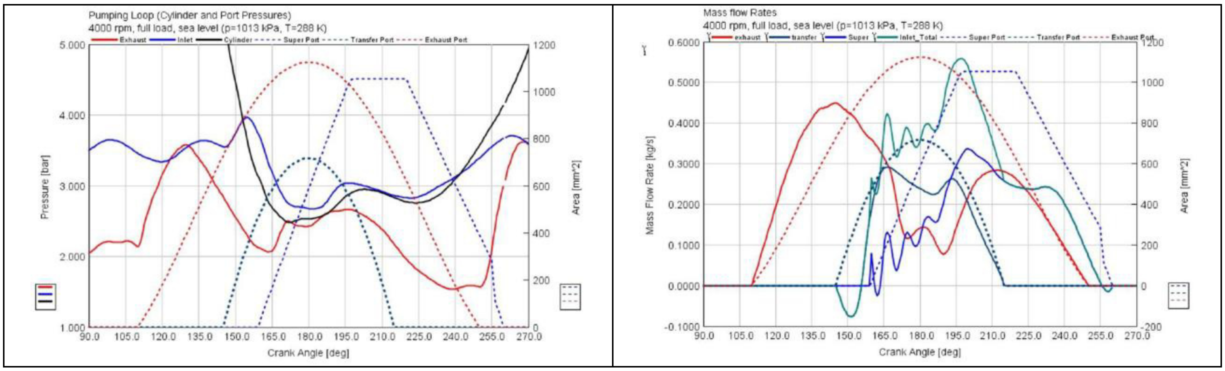

Figure 4: Pressure traces and mass flow rates through the cylinder ports, calculated at 4000 rpm, full load, sea level (p=1013 kPa, T=288 K). The effective areas of the ports are also reported.

Table 1: main geometric parameters and constraints of the optimized aircraft engine. Overall dimensions calculated on the basis of a single-cylinder prototype, under construction at the BRC laboratories in Cherasco (Italy)

# power cylinders	3
# pump cylinders	3
Power cylinder bore x stroke (mm)	83x 90
Power cylinder compression ratio (*)	14
Pump cylinder bore x stroke (mm)	55 x 90
Pump Cylinder compression ratio	3
Total Engine Displacement (cc)	1461
Total Cylinder pumps displacement (cc)	641
Engine lay-out	V6-90°
Interval between firings (CA °)	120
Engine maximum speed (rpm)	4000
Max. in-cylinder peak pressure (bar)	120
Max. turbine inlet average temperature (K)	1000
Length x Width x Height (mm) (**)	490x530x580
(*) Volume@EPC/Volume@TDC (**) Intake/Exhaust systems NOT included	

The weight of the engine has been estimated on the basis of the CAD drawings. Intake and exhaust pipes, the turbocharger, the intercooler, the fuel pumps and the electronic control units are not considered, since they depend on the specific installation features. It is found that the engine core weights 94.8 kg, about one half of a modern V6 4-Stroke turbocharged Diesel engine delivering a comparable power [14]. This lightness is due to both the compact dimensions of the assembly (see table 1) and the absence of the valvetrain.

5. Engine Performance

An aircraft engine generally operates at full load during take-off, and at constant speed, partial load when cruising. Therefore, one of the most interesting performance parameter is the maximum brake power as a function of altitude. Since ambient conditions have a strong influence, the most critical condition (i.e. the highest possible temperature at sea level, 30° C) should be always considered .

Figure 5 shows the correlation between maximum brake power and altitude, at both standard and hot sea level conditions, referred to as “std” and “hot”, respectively. The maximum brake power is obtained at the maximum engine speed (4000 rpm) and for a specific setting of trapped air-fuel ratio. The last parameter is directly related to combustion efficiency and smoke: on the basis of previous CFD-3D calculations, presented in [7], it is assumed that the engine can operate at 4000 rpm with a minimum AFR=18 (Lambda= 1.24), yielding an acceptable level of smoke (Smoke Number about 2.0) and burning at least 98% of the injected fuel. This value drops to 85% as the trapped AFR approaches the stoichiometric threshold. However, this limit is never reached, since the minimum AFR is set at 18, except over 19,000 feet of altitude, where the value is lowered to 16.8 (Lambda=1.15), in order to meet the minimum power target (100 kW at 20,000 ft).

As the aircraft climbs, the air density decreases: this negative effect can be compensated by increasing the boost pressure, obviously complying with the constraints enforced by the turbocharger. In particular, boosting is limited by compressor stalling and over-speeding, as visible in figure 8. Another “trick” is to slightly increase the injection advance, since the value at sea level is set in order to limit in-cylinder peak pressure, and this requirement becomes less and less pressing as the ambient pressure decreases, as visible in figure 6. This figure shows that, despite the high power density (110 kW/l), the 2-Stroke engine presents very low values of combustion peak pressures, in comparison to modern automotive 4-Stroke Diesel engines (typically 160-180 bar) . This issue is fundamental advantage to achieve a light design of the powerplant, as well as to meet more easily the reliability targets.

Turbine inlet temperature is high (figure 7), but it always remains below the limit of 750 °C.

Figure 8 shows two sets of operating points plotted on the compressor map: both sets of data refer to the maximum power rate at different altitudes (from 0 to 20,000 ft), one is for standard ambient conditions at sea level, the other is for hot atmosphere. The map demonstrates how critical is the choice of a single-stage turbocharger for the engine: smaller compressors would yield a lower choking limit, bigger ones would not allow the engine to reach sufficient boost pressures.

As far as the brake specific fuel consumption is concerned, see figure 9, four levels of brake power have been assumed for the calculation of fuel consumption as a function of altitude: 100-75-65-55% of the maximum rate (150 kW), corresponding to an engine speed of 4000,3650, 3450 and 3280 rpm, respectively. Ambient conditions are the standard ones. Looking at the values, it should be considered that the maximum fuel efficiency has been traded for a lighter design and more compact dimensions. Under this point of view, a bsfc of 235 g/kWh is an excellent result for a Diesel engine weighting less than 100 kg and delivering a brake power in excess of 150 kW at 4000 rpm. As a term of comparison, in [15] it is reported of a very light 3-cylinder 4-Stroke Diesel engine designed for a motorcycle, weighting 80 kg, delivering a brake power of 75 kW at3500-4500 rpm, and with a minimum bsfc of 230 g/kWh at 4000 rpm.

Figure 10 presents the values of trapped air-fuel ratio at the previously considered power rates, the altitude varying from 0 to 20,000 ft. The only slightly critical condition is at maximum power, over 19,000 ft, where the trapped air-fuel ratio drops below 18 (Lambda=1.24), making combustion completion more difficult, with ensuing rise of the smoke level. This is the reason also for the abrupt rise of fuel consumption, visible in figure 9.

A fundamental design parameter for an aircraft engine is the amount of heat power rejected by the engine through the heat exchangers, directly affecting the air scoops dimensions, thus the aircraft drag. The analyzed 2-Stroke engine has been compared to a similar 4-S V6 turbocharged Diesel unit, having an almost identical brake power output (165 kW), same maximum speed (4000 rpm), very close bore (82 mm) and stroke (90.4 mm). The reference 4-Stroke engine is a typical modern automotive engine, and it has been numerically analyzed by means of GT-Power, with a model as close as possible to the one employed for the 2-Stroke engine. The comparison is made considering each contribution to the global heat power rejected by the engine, divided by the correspondent brake power output. It is found that the analyzed 2-Stroke engine rejects about 15% of heat less than the 4-Stroke unit. This result is mainly explained by the lower power lost for mechanical friction, and also by the more compact combustion chamber and the absence of swirl during combustion, that improves combustion but it also increases heat transfer. Finally, the instantaneous torque generated by the gas expanding within the cylinders and by the inertia forces has been calculated at rated power. In comparison to the V6 4-Stroke engine mentioned above, the 2-Stroke curve presents the same number of peaks during a whole crankshaft revolution, but the amplitude is at least halved because of the lower weight of the pistons and the action of the in-cylinder gas pressure, always balancing the inertia force around top dead center.

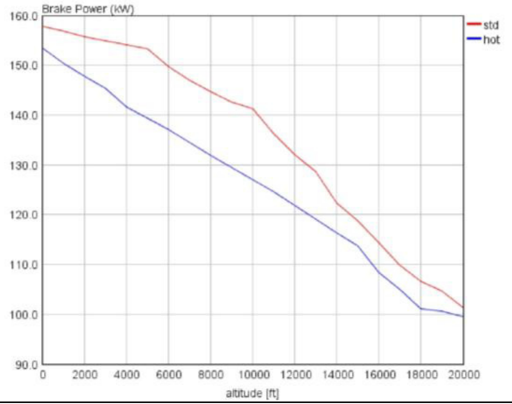

Figure 5: maximum brake power of the engine plotted as a function of altitude at standard and hot sea level conditions

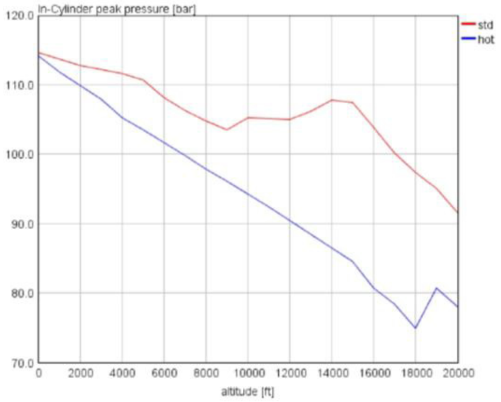

Figure 6: Peak in-cylinder pressure plotted as a function of altitude at standard and hot sea level conditions

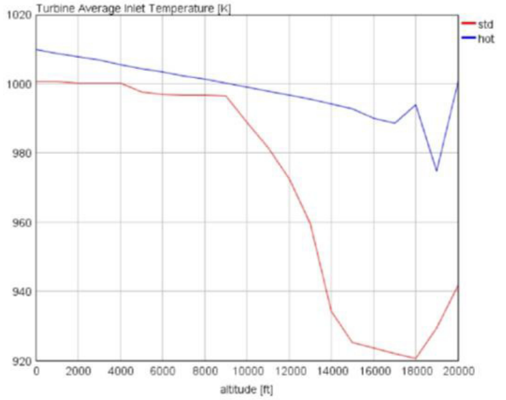

Figure 7: Inlet turbine temperature plotted as a function of altitude at standard and hot sea level conditions

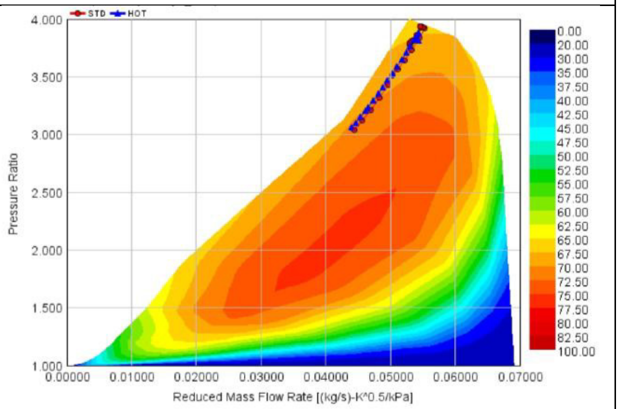

Figure 8: operating points at maximum power rate plotted on the compressor efficiency map. Standard and hot sea level conditions, altitude 0-20,000 ft

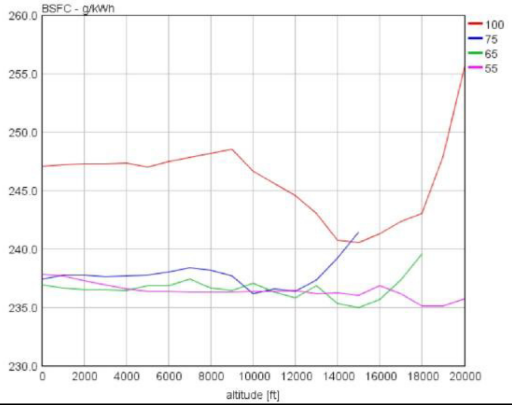

Figure 9: brake specific fuel consumption at different power rates (100-75-65-55%), plotted as a function of altitude.

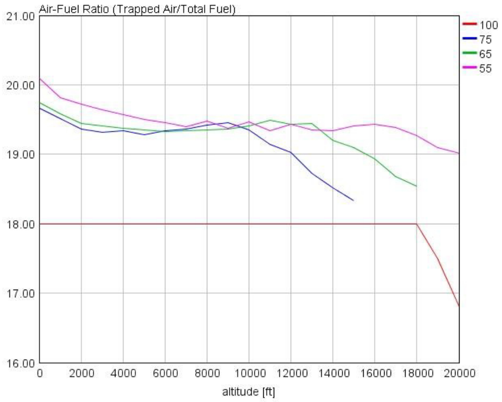

Figure 10: trapped air-fuel ratio at different power rates (100-75-65-55%), plotted as a function of altitude.

6. Conclusion

The paper reviews the numerical optimization of the fundamental parameters of a 2-Stroke aircraft Diesel engine, featuring a patented valve for improving the loop-type scavenging, and a combustion system specifically developed for valve-less cylinders.

The engine is made up of three cylinders and three piston pumps, arranged as in a conventional V6, with an angle between the two banks of 90°. The total displacement is 1460 cc for the power cylinders, 641 cc for the piston pumps . The engine is turbocharged and inter-cooled, in order to reach a power target, at sea level, of 150 kW@4000 rpm. Another fundamental goal is the minimum power of 100 kW, at the altitude of 20,000 feet.

The CFD analyses have been performed by using GT-Power; the models are calibrated on the basis of experiments carried out on similar engines, and on extensive CFD-3D simulations (not shown in the paper)

The main results of the study can be summarized as follows:

- The 2-S engine is able to meet all the performance aircraft targets, with acceptable levels of smoke
- Overall dimensions and weight of the 2-S engine are strongly reduced (in some cases halved), in comparison to a typical 4-S automotive Diesel engine delivering the same brake power
- The best specific fuel consumption of the 2-S engine, among the operating conditions of practical interest, is 235 g/kWh, a value very close to the best in class 4-S automotive powerplants
- In cylinder peak pressures in the 2-S engine are considerably lower than in typical 4-S automotive Diesel units (110 bar, against 150-180 bar)
- The heat rejected by the 2-S engine through the exchangers is 15% less than that calculated on a V6 Diesel automotive engine, delivering the same brake power at the same speed.
- From the point of view of the instantaneous torque transmitted to the propeller, the 2-S 3-cylinder engine output is smoother than the one of a corresponding V6 automotive Diesel engine.

The work presented in the paper is just a preliminary investigation, the further step will be to build and test a single cylinder prototype.

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