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COMBUSTION ANALYSIS OF A NEW CONCEPT UNIFLOW TWO STROKE ENGINE FOR EXPERIMENTAL AIRCRAFT APPLICATION

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Abstract. Experimental aviation has been growing in several countries and the engines to equip these aircraft are in constant advances and modifications, aiming to increase power and reduce fuel consumption. In this context, the objective of this study is to present the performance characteristics of a new concept of two-stroke engine with Uniflow gas scavenging system, which has a much lower specific fuel consumption (BSFC) when compared to two-stroke engines with Cross or Loop Scavenging system, commonly used in this category of aircraft. Therefore, a one-dimensional simulation was performed in the GT-Power© software of the proposed arrangement operating in conditions similar to an aircraft operation, with 2 bar of supercharging boost and maximum engine speed of 3000rpm, evaluating combustion and performance parameters. In addition to the standard aviation gasoline (AvGas) with 100 octane fuel, the use of ethanol was also simulated, which, due to its low lower heating value, showed high specific fuel consumption. Using AvGas as fuel, the power achieved at this engine speed is very close to 23kW@3000rpm, generating maximum torque of 71,5N.m@2700 rpm. At cruising speed (between 2400 and 2700rpm) the BSFC varies between 255 to 277 g/kW.h, lower than two-stroke engines currently used for this purpose, which present values between 420 to 480 g/kW.h, also in the cruising operation range (between 5000 and 6000 rpm for standards two stroke engines). Being supercharged, its efficiency is also higher, reaching more than 30%. Due to its two-stroke cycle, the power density is high, with specific power of approximately 90kW/l. According to the simulations performed at this point, the engine proposal is suitable to equip an experimental aircraft, as the engine is physically compact, with low fuel consumption and with specific power higher than its direct competitors.

Keywords: two stroke engine, experimental aviation, 1D simulation, uniflow scavenge, boosted.

1. INTRODUCTION

Much progress has been made in internal combustion engines aimed increasingly at reducing their size versus an increase in power and efficiency (can be expressed as a decrease in consumption).

In the aviation industry it is no different, and, although more conservative than the automotive industry, has been searching for more efficient, more powerful and smaller engines, since mass is one of the primary factors in this line of application.

Engine alternatives range from new concepts in terms of combustion and operation with different fuels in the same engine to the adaptation of automotive engines for aeronautical use. This last option has been growing lately due to the technology employed in such engines, the high durability and reliability during use. Engines for light experimental aviation (in the 40kW range) have 3 basic suppliers worldwide: Rotax (Austria), the market leader, Hirth Motoren (Germany) and Limbach Flugmotoren (Germany), the latter more directed to UAV's, (Kitplanes, 2022), (Limbach, 2022).

Recently the Austrian Rotax has stopped production of two-stroke engines on the reason that ultralight aircraft are migrating to four-stroke engines, as (KG, 2021), With this, only 2 or 3 suppliers worldwide are still producing engines in this power range (up to 40kW): Hirth Motoren and Limbach Flugmotoren, both on Germany.

Below, Table 1 presents the complete data for both manufactures of those engines:

Table 1- Two stroke engines for experimental and UAV application power up to 50kW- basic data.

Company name	Model	Configuration	Displacement [cm ³]	Power [kW]	Max. speed [rpm]	Weight [kg]	HP/kg
BRP Rotax**	582UL	2 cils - in line	580.1	48.5	6800	50.6	1.28
Hirth	F-23	2 cils cils - h. oposed	521.1	37.3	6500	22.0	2.28
Hirth	3202	2 cils - in line	624.3	41.0	5500	26.5	2.08
Hirth	3503	2 cils - in line	624.3	44.7	5200	35.8	1.67
Limbach Flugmotoren	L 275 E	2 cils cils - h. oposed	274.0	14.9	7200	7.2	2.78
Limbach Flugmotoren	L 275 EF	2 cils cils - h. oposed	274.0	17.9	7500	7.2	3.33
Limbach Flugmotoren	L 550 EF	4 cils - h. oposed	548.0	37.3	7500	15.0	3.34
Limbach Flugmotoren	L 550 E	4 cils - h. oposed	548.0	37.3	7500	16.0	3.12

** BRP Rotax is out of market, listened here only for comparison.

From the engines presented up to 50kW, only the manufacturer Hirth presents electronic management as optional items, the others only have carburetors and electronic ignition. All of them operate with lubricating oil mixed with the fuel, another fact that contributes to the increase of pollutant gases, emission of particulate material, and higher fuel consumption. Specific power values, according to (Heywood and Sher, 2017), for ultralight aircraft engines are in the range of 50 to 60MW/m³ and usually use intake port with reed or disk valves, which is exactly the case with the engines shown. Some alternatives to minimize the impacts of this type of engine regarding the emission of pollutant gases are the inclusion of an ECU and the elimination of lubricant oil mixed with the fuel, introduction of intake and/or exhaust valves and combustion operations in HCCI or CAI (CAI - controlled Auto Ignition or HCCI -Homogeneous Charge Compression Ignition). Two-stroke engines with intake and exhaust valves in the cylinder head, according to (Y. Zhang et al., 2012), have a high potential for reducing pollutant gases, especially when operating with the CAI system, and also covers an operating range similar to that of 4-stroke engines.

Typical BSFC data for two-stroke engines, presented by (Blair, 1996), for an Yamaha DT 250 (250cc) engine with different cylinder modifications are compared with those of the Rotax engine model 582 UL, and are shown in Figure 1. The cilinders has identical geometric dimentions, the difference is in transfer ports and shape (or profile) of the transfer ducts. The scavenging ratio and area of ports are identical for all five cilinders evaluated.

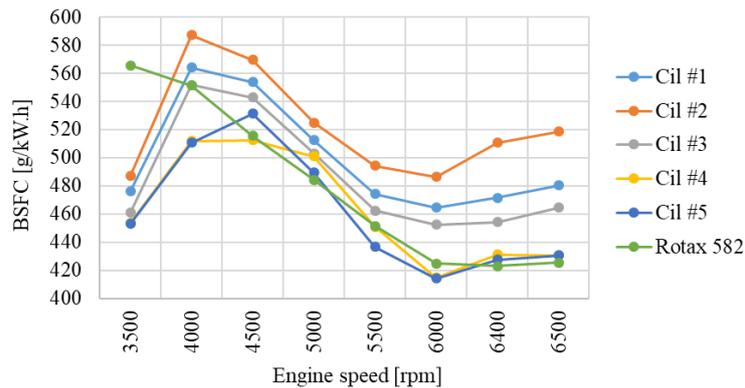


Figure 1 - Typical BSFC for two stroke engines with cylinder modifications compared to Rotax model 582 UL
Adapted from Blair (1994)

In Figure 2, Blair presents a study comparing these modified cylinders (using loop scavenge) with the cross scavenge and uniflow systems. The scavenge efficiency is similar for all of them, but the gas retention efficiency is higher for the uniflow system, certainly because it has a valve that allows better control of the gases inside the cylinder.

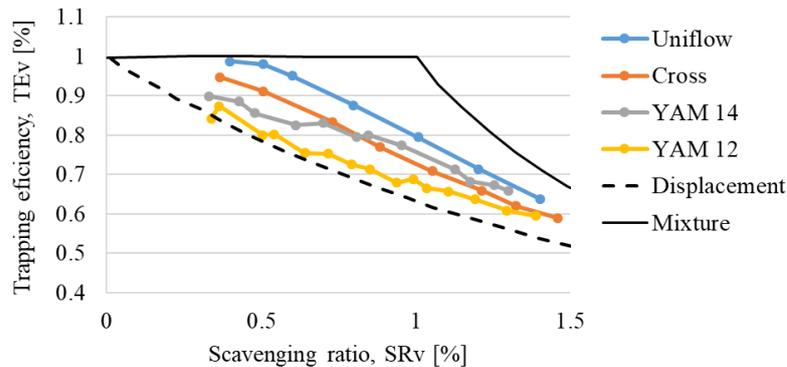


Figure 2 - Trapping efficiency characteristics for different scavenging systems.
Adapted from Blair (1994)

Data from two-stroke engines with uniflow system operating at altitude were evaluated by (Mattarelli, Cantore, and Alberto 2013) and the results presented show an advantage of this system over the other systems evaluated (loop scavenge, Loop Scavenge with compressor, as well as a 4-stroke engine converted to a two-stroke - poppet valve). The uniflow system showed significantly better data in terms of charge retention inside the cylinder but slightly less efficient scavenging, Loop scavenging close to 90% scavenging while uniflow presents data close to 80%.

(Laget et al., 2013) compares and claims that the uniflow scavenging system is the most efficient used in two-stroke engines because it is close to the case where there is ideal displacement, where the air flow inside the cylinder allows an almost perfect flushing as well as limits the short circuit between intake and exhaust.

Combustion chamber geometry interferes directly in the combustion process, where (S. Zhang et al., 2019) presents a study of different chamber shapes and their influence on the combustion process. Depending on the chamber geometry the swirl and tumble rates are intensified, accelerating the flame front propagation and increasing the combustion rate. (Jajcevic et al., 2010) states that the high performance (high power and low weight) two-stroke engine has the disadvantage of high fuel consumption and high emissions as a result of the cylinder scavenging problem. Three different configurations of direct fuel injection were evaluated and it can be seen that the quality of the mixture of injected fuel and air is directly dependent on the cylinder scavenging process and the flow situation inside the cylinder. A change in injection strategy, injection time, duration and position of the injector(s), may be more effective for mixture quality than changes in the type of injector flow, as found by the author.

In terms of reducing fuel consumption, (Bascunana, 2012) states that if an internal combustion engine has been modified not to work stoichiometrically and not to restrict air intake, while keeping the combustion rate within appropriate limits, the efficiency increases as a function of the flame front temperature reduction by dilution of the mixture in a larger amount of air. The specific heat ratio increases with decreasing temperature (as dissociation declines), and the elimination of air throttling reduces pumping losses. The result of the study showed that split combustion chambers showed very

significant fuel consumption reduction and very low pollutant emissions. (Alvarez et al., 2018) has made a compilation of the background, designs, and test results with pre-chambers and the results for emissions, overall combustion efficiency, and thus increased engine efficiency are promising. Possibilities of operation with lean or ultra-lean mixture also aiming at fuel consumption reduction is what the world seeks today. In aviation this reduction in fuel consumption is fundamental, as it translates into increased range and aircraft weight reduction. (Anderson et al., 2013) studied a Rotax 914 engine (114HP with turbo compressor and PFI- Port Fuel Injection) with a jet ignition device fitted to one of the two spark plugs in the engine cylinder head. The pre-chamber used was of the passive type. The fuel used was gasoline with 87AKI and 10% ethanol in the natural aspirated and turbo engine tests, while AvGas was used only in the turbo engine tests. Two evaluations were carried out, with the normally aspirated engine and the original turbo engine. A slight increase of the indicated power (around 2HP) is noticed when the ignitor is used on the engine, as well as IMEP (around 0.2bar). Another important data presented by the author is the mass fraction burned from 0 to 10%. The system with ignitor presented 7° of crankshaft angle less to reach the same MFB (0-10%) when compared to the spark plug ignition system. This is due to the jet that is fired inside the chamber accelerating the combustion process, which leads to the increase of IMEP.

Considering the previous, it was decided to start the project of an aeronautical engine to be used in experimental aviation, in order to add technology as a way to increase operational safety and reliability. Mass reduction and power increase were also sought, making the engine more compact compared to competitors of the same power range.

Based on this, the design of a new concept of a two-stroke engine with uniflow scavenging is being evaluated and is the focus of this paper, where 1D simulation data of the proposed design is presented, hereby named Uniflow New Concept - UNC. Benefits of this new configuration are being verified when comparing it to existing engines on the market for the same application, i.e. Experimental Aviation. Positive aspects such as significant reduction of fuel consumption, higher efficiency, and even geometric issues such as total engine size and reduction of moving parts (gearbox) have been verified for this new concept.

2. METHODOLOGY

The proposed engine was modeled in 1D simulation software in order to study the behavior of an engine with the proposed characteristics. The software used is the GTPower® V. 2021 available in the Engine Laboratory of the Federal University of Santa Maria. The computational model presents an exhaust valve with 48mm diameter, equivalent to two 35mm² valves, PFI injection configuration, 14 air intake ports at the base of the cylinder (BDC) totaling 1990mm² of flow area.

The engine displacement is 254cm³ with an effective compression ratio of 8:1, stroke 66.2mm and bore 70mm. The supercharger has been set up with a maximum pressure of 2bar absolute at maximum engine speed. This setup is due to the operation of an aero engine, where the maximum load is obtained at maximum engine speed, normally used for a defined period of time (like during the take-off). After that, a cruise speed is established and both speed and load are decreased.

The Uniflow scavenging system with two valves was adopted for better retention of the mixture and better scavenging of the cylinder.

The 1D simulation was developed from the architectural configuration of the engine, maintaining the highest possible fidelity to lengths and diameters of ducts, position of the PFI type injector and other data initially created for the prototype. The simulation is being improved and the modeling in CAD software is also being fed back by the results. For the sake of simplicity, the combustion model adopted in the simulation was the non-predictive Wiebe combustion model, thus reducing processing time and still providing consistent data. The equations used as follows:

$$WC = \left[\frac{D}{BEC \left(\frac{1}{E+1}\right) - BSC \left(\frac{1}{E+1}\right)} \right]^{-(E+1)} \quad (1)$$

$$SOC = AA - \frac{D \cdot BMC \left(\frac{1}{E+1}\right)}{BEC \left(\frac{1}{E+1}\right) - BSC \left(\frac{1}{E+1}\right)} \quad (2)$$

$$Combustion(\theta) = CE \left[1 - e^{-(WC)(\theta - SOC)^{E+1}} \right] \quad (3)$$

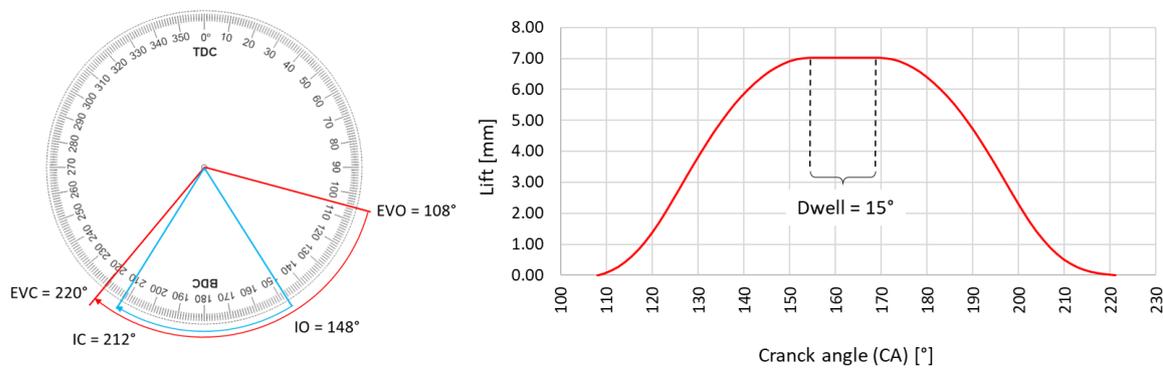
where AA is the anchor angle varied to reach the minimum advance point for best torque (MBT); D is the combustion duration from 10% to 90% mass burned, this value was adopted as 18° CA. E is the exponent of the Wiebe function (used value of 2.0); CE the combustion efficiency (used value of 1. 0); BMS, BMC and BME are the burning constants of the start (Bs=0,1), middle (Bm=0,5) and end (Be=0,9) points of combustion with BMi=-ln(1-Bi); SOC is the combustion start (moment of spark that varied in order to find the MBT or even limitation by detonation); WC is the Wiebe constant calculated for each case of combustion; θ is the instantaneous angle of the crankshaft.

The intake pressure (MAP) was generated by a simple compressor model added to the intake with the drive power deducted from the engine crankshaft. Consequently, this already provided net power and torque data. The manifold absolute pressure (MAP) adopted is presented in Table 2 and was chosen so as to provide the necessary power at each engine speed point:

Table 2 – Manifold Air Pressure for model 1D

Cases of simulation	Case 01	Case 02	Case 03	Case 04	Case 05	Case 07	Case 08
Engine speed [rpm]	1200	1500	1800	2100	2400	2700	3000
MAP [bar]	1.17	1.25	1.40	1.51	1.60	1.85	2.00

The intake port and exhaust valve setup was optimized between 2400 and 2700 rpm, which is the indicated cruising speed for the engine. A cam profile with dwell was adopted in order to obtain a better cylinder scavenging. The best configuration found was with a dwell of 15°. Figure 3 shows the timing of opening and closing of doors and valves and the cam profile adopted.



* EVO = Exhaust Valve Open, IO = Intake Open (port), IC = Intake Close (port), EVC = Exhaust Valve Close

Figure 3- Opening and closing diagram for intake ports and valves

The knock model in use was Douaud and Eyzat, according to (Ra and Reitz, 2011), and is based on the calculation of the integral of the induction time which is calculated taking into account the fuel's anti-knock index AKI (average between MON and RON), the fractions of fuel, oxygen and diluents, the activation energy of the fuel in a reference state and the instantaneous temperature at each time step during combustion. When the induction time integral reaches the value of 1.0, any mass fraction of fuel remaining in the unburned gases is released at constant volume in order to simulate fuel detonation. A monitor has been added in order to visualize the knock index in real time in the simulation, enabling the correction of the CA-50 point to avoid knock.

A plenum was also verified and incorporated into the model. Through an optimization made in the software itself, a volume of 3.1 liters was reached, and the lengths of the inlet and outlet ducts in this plenum were also optimized.

The effective compression ratio was initially assumed to be 9:1 and corrected through a preliminary simulation performed in CFD, where it was verified to be exactly 7.9. Injection time, injection duration, ignition time, etc, were initially imposed and corrected as needed, targeting for the desired operating range.

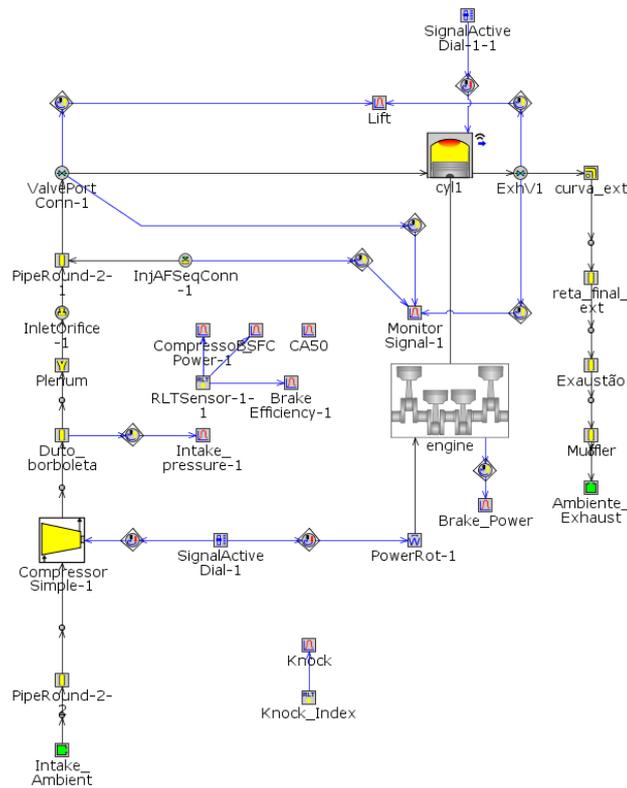


Figure 4 – UNC engine 1D simulation model

In parallel to the simulation, data from the engine used in the benchmark, Rotax 582 UL, was obtained from the engine's operation and installation manuals (Rotax Aircraft Engines, 1999) , Comparisons in terms of torque, power, and efficiency have been made.

3. RESULTS

The simulation was carried out based on idle speed (1200rpm) to maximum speed (3000rpm) in 300 rpm increments.

Next is the LogP_xLogV diagram for the engine cruise speed (2700rpm), where it can be seen the combustion pressure being transformed into useful work by the piston, without presenting pressure peaks (knock) or losses in pumping without the effective transformation into work. The sparking time is set at 9° CA BTDC, allowing the engine to operate at maximum brake torque (MBT) point, with cylinder peak pressure reaching 88,5 bar, well, withing the range of comparable engines and suitable for normal and stable combustion (Figure 5).

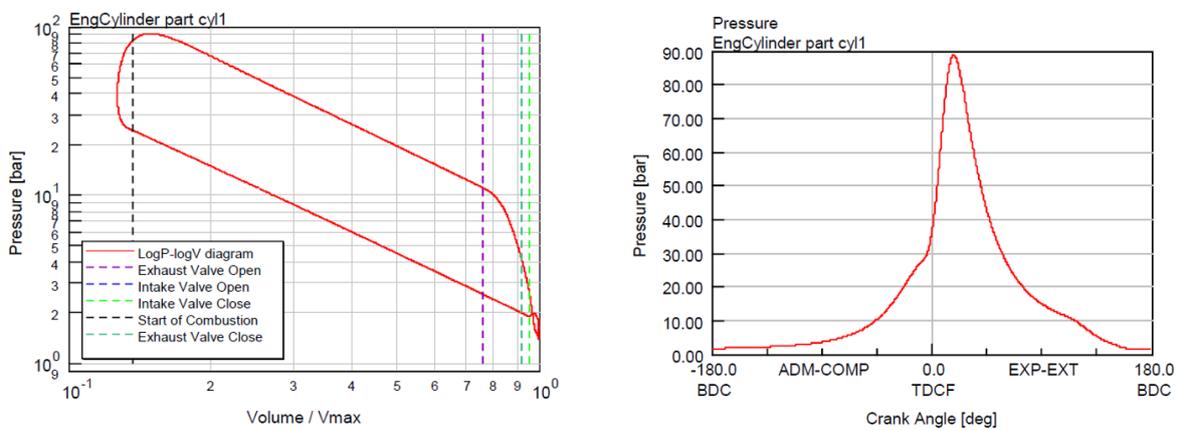


Figure 5 - LogP x LogV diagram and cylinder pressure @ 2700rpm

Figure 6 shows the engine flow timing diagram, with opening and closing of valves and ports according to the crank rotation (CA°), as it was the input for the simulation. The opening and closing configuration of intake ports and exhaust valves was a specific point of evaluation and some configurations were made, combining opening and closing times for both, in order to obtain a better scavenging and trapping ratio, as well as an optimization of torque and power at cruising engine speed.

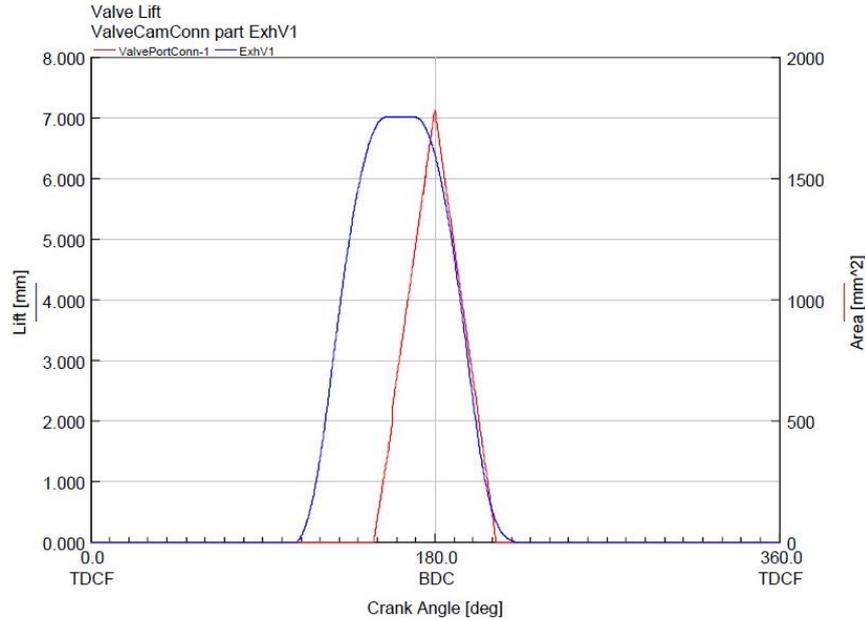


Figure 6 – Intake port and exhaust valve diagram.

The engine speed should be a maximum of 3000 rpm for engines without a reduction gearbox, with propellers fitted directly to the crankshaft (direct drive). The propeller tip speed should reach a maximum of 0.85 mach, thus avoiding propeller tip stall, vibrations, and structural damage. Based on this, the highest power achieved by the engine in the simulation was around 23kW at 3000 rpm (Figure 7), with maximum torque at 2700 rpm. The torque values at 2400 and 2700 rpm are very similar, making it possible to use different propellers with still adequate thrust at the same speed.

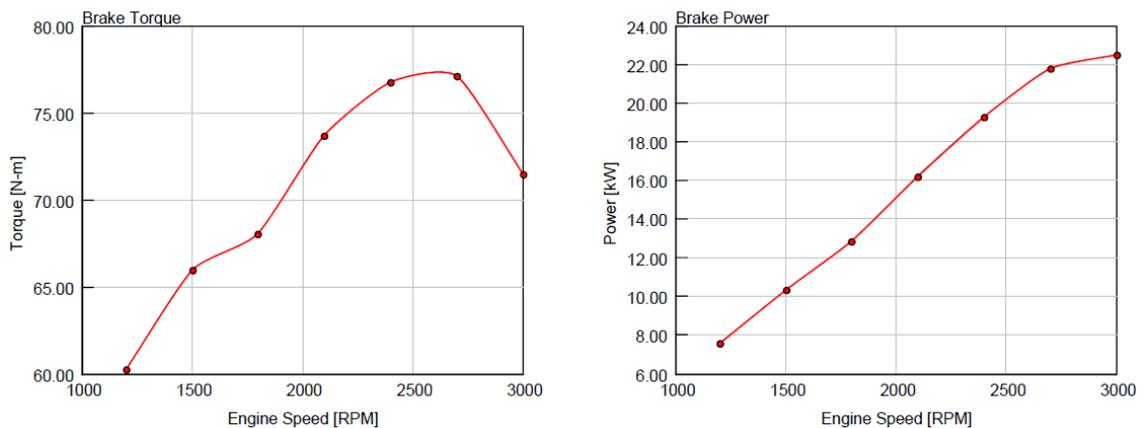


Figure 7 – Power and torque for UNC 1D simulation

It is estimated that a two-cylinder engine, in-line or horizontally opposed, depending on the future design, should generate around 46kW of power, something very close to what the Rotax 582 produces, but with a much higher efficiency, close to 33% compared to the approximate 19% of the Rotax, both at maximum power, as shown in Figure 8.

The brake efficiency data of the proposed engine was collected from the simulation and, for comparison purposes with the benchmarked engine, Rotax 582, the brake efficiency of the Rotax engine had to be calculated, because no data regarding this information was released. To calculate the BEFF, equation 4 was used:

$$BEFF = 3600 / (BSFC \cdot PCI_{AvGas}) \quad (4)$$

Where BEFF is the Brake Efficiency, given in %, BSFC is the Brake Specific Fuel Consumption for the given engine speed, given in g/kWh and LHV is the Lower Heating Value of the fuel, in this case Brazilian with 43.5 MJ/kg, as (Petrobras, 2002).

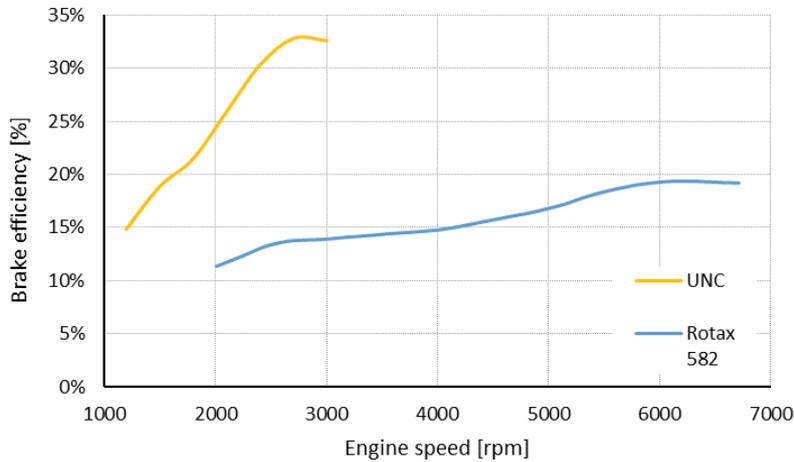


Figure 8 – Brake efficiency comparison: Rotax 582 x Uniflow New Concept (UNC)

Another interesting data to be compared is power, since it is one of the first characteristics to be explored by a potential customer. The engine tested presents data for a single cylinder and the comparison was made taking into account the same configuration for the Rotax, that is, the power of only one cylinder. The power outputs are close, this fact due to one of the boundary conditions imposed in the project, that the "commercial" engine should provide a power output close to 48kW. An important detail in this data is the specific power presented by the two engines. The UNC has 254cm³ and provides maximum power of 23kW@3000rpm while the Rotax 582 has a volume of 580.1cm³ and provides 48kW, resulting in specific powers of 90kW/l for the UNC and 82.7kW/l for the Rotax.

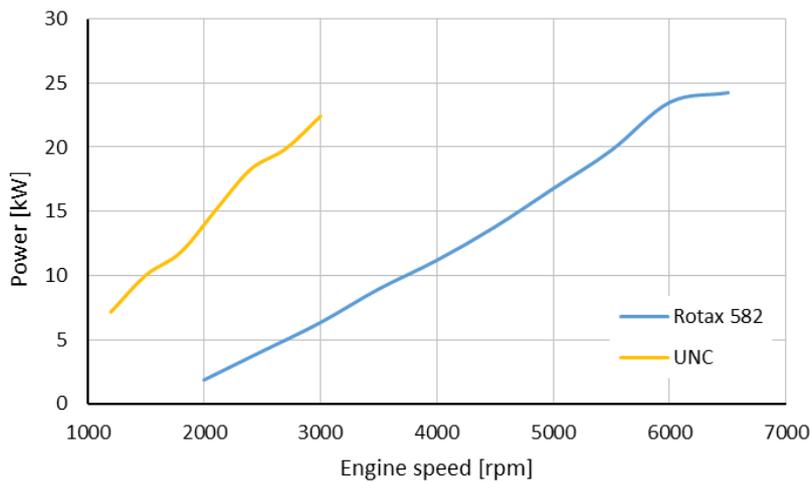


Figure 9 – Power comparison: Rotax 582 x Uniflow New Concept

Another important point is fuel consumption, which is also checked when a customer purchases an engine. The BSFC is provided by Rotax in its engine operation and maintenance manuals. From the simulation, BSFC of the UNC was obtained and compared with the value from the Rotax engine, as show Figure 10.

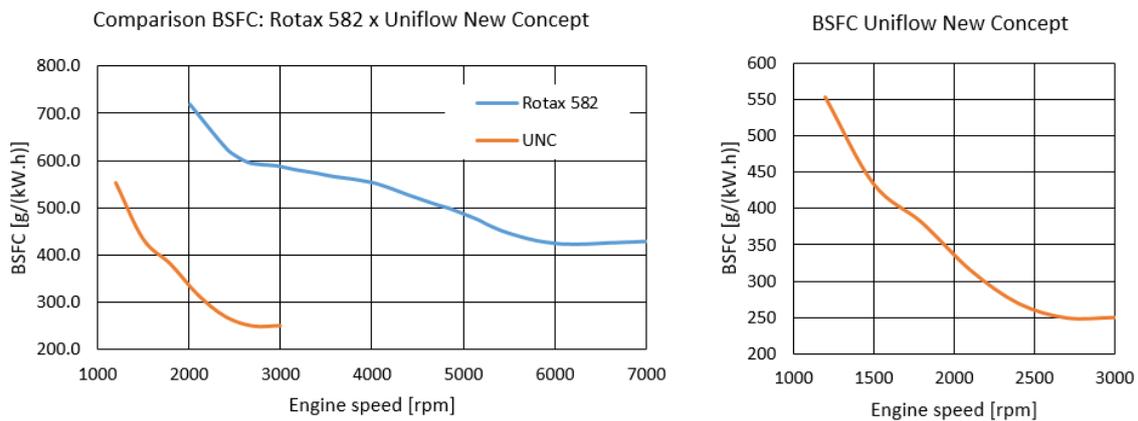


Figure 10 – BSFC comparison: Rotax 582 x Uniflow New Concept and BSFC UNC detailed

A significant reduction in BSFC is observed for the UNC, which translates directly into reduced operational cost and increased range for the same amount of fuel in the aircraft tank. At cruise speed a BSFC of 424g/kW.h is observed for the Rotax 582 against 249g/kW.h for the UNC, a 42% reduction in specific fuel consumption. The comparison between the two engines was made because they are engines for the same application, although with different gas exchange systems. The intention was to show the advantages that the proposed system has over the conventional engine. These are due to the nature of intake ports, using the uniflow system of inclined ports generating swirl, which benefits combustion and mixture preparation, and exhaust valves that better control the cylinder scavenging and filling.

The model proposed has a maximum speed of 3000 rpm, directly related to the propeller drive. At this speed there is no need for a gearbox, which yields less mass and fewer components to maintain.

The concept engine was evaluated using AvGas as fuel, but the model is already being prepared for use with compression-ignition fuels, such as Diesel, Bio-Diesel and Aviation Kerosene. Significant adjustments in terms of geometry would be needed in this case. The use of Ethanol is also being verified for future tests, but there is a logistical barrier, already thinking in terms of engine production, that at airports and runways, whether private or public, do not have widespread supply of this fuel. It would be possibly found where there is operation of agricultural aircraft that already use this biofuel.

4. CONCLUSION

This study showed the beginning of the development of a new concept of two-stroke engine with uniflow system, which already presents significant and consistent data that will serve as a basis for the continuity of the project. The efficiency of the proposed engine is 43% higher than the Rotax 582 and a consequently lower specific consumption that is directly related to greater savings in terms of operational cost and flight range.

The 1D computational model was adjusted to the real conditions of flight, both in engine speed and manifold pressure, returning torque and power values very close to what was being expected in the study. The fuel consumption values for an aero engine operating under these conditions were very favourable. The validation of the data obtained or even a comparison with existing systems or engines cannot be made because no similar engine was found, i.e., two-stroke uniflow system operating with AvGas. Studies of engines operating with compression ignition, two-stroke uniflow were found and cited in the text, but not compared because they deal with combustion, injection system, intake pressures and CR very different from the proposed here.

Computational Fluid Dynamics - CFD studies has been prepared also to increase this research as a prototype is in workshop for assembly at the moment. With the engine assembled, real data from tests in the test cell at GPMot - UFMSM can be verified and the simulations validated. There is already a sketch for the complete engine and a possible architecture to be assembled on an experimental aircraft where it has been shown to be geometrically smaller than the engines currently used. The fact that it operates at lower speeds than two-stroke engines with cross scavenging or loop scavenging also eliminates the reduction gearbox, making it possible to mount the propeller directly on the shaft, called direct drive. The results presented so far are promising and the studies are advancing towards consolidating the project and producing the prototype.

5. ACKNOWLEDGEMENTS

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