Numerical calculation of gas exchange in two-stroke engine for aircraft

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Abstract. General aviation light aircrafts and unmanned aerial vehicles are equipped mainly with internal combustion piston four-stroke and two-stroke engines. Despite of the significant amount of research and development works, the ways of the further performance improving for such engines are nearly exhausted. However, there are fundamentally new developments, which combine the advantages of four-stroke valvetrains with the two-stroke cycle, which provides significant increasing of the engine performance. This article presents the results of computational studies of a Rotax 914 four-stroke aircraft engine, modified to the two-stroke cycle. The calculations were carried out with the software named Diesel-RK, which made it possible to select the optimal engine settings, mostly timing, and software AVL FIRE for 3D numerical simulation of cylinder scavenging through valves to confirm the residual gas amount in cylinder with such type of gas exchange. The calculations confirmed the possibility of increasing performance of the engine almost in 1.5 - 2 times for the entire operating speed speed, which is confirmed by experimental results published in the known open articles.

1. Introduction

On the general aviation light aircrafts and unmanned aerial vehicles usually are installed internal combustion piston engines. They are distinguished by design simplicity, reliability, lower fuel consumption and lower cost in comparison to the gas turbine powertrains. Piston engines usually have two-stroke and four-stroke cycles. Many scientific papers have been devoted to improving designs and improving the characteristics of both two-stroke [1] and four-stroke [2,3] engines used in aviation. Two-stroke engines of the simplest design with a crank-case scavenging and a loop scavenging of the cylinder through intake ports and exhaust ports have a power up to 80 kW. They are characterized by the best ratio of power and weight, and are used on ultralight class aircrafts. Four-stroke engines have a more efficient valve gas exchange system; to improve technical and economic parameters, they can be equipped with turbochargers [4-6], inertial superchargers [7-9], have a power up to 400 kW and are widely used on the light-engines for larger dimensioned aircrafts. The effective power $N_e$ of piston engines is expressed by the formula:

$$N_e = \frac{i \cdot V_h \cdot P_e \cdot n}{k \cdot \tau}$$

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where \(i\) – the number of cylinders, \(V_h\) – engine displacement, \(P_e\) – the effective pressure of the operation cycle, \(n\) – the crankshaft speed, \(r\) – number of strokes in cycle (2 for two-stroke, 4 for four-stroke), \(k\) – the proportionality coefficient (depends on the units of measurement).

This formula shows power advantage up to two times for two-stroke engines compared to four-stroke ones with the same values of \(V_h\) and \(n\). However, in reality this advantage is in general not so big. This happens due to the insufficient scavenging of the cylinders with the loop scavenging through the ports, symmetric timing of gas exchange and, as a consequence, low effective pressure \(P_e\). In addition, two-stroke engines are characterized by high toxicity of the exhaust and, most importantly, increased fuel consumption due to the high amount of unburned fuel – up to 25-40% [10, 11].

However, the fundamental possibilities of increasing of power performance and other characteristics by account of the two-stroke cycle, force the engines' developer to find a new ways of the further improvement. The most important is the combination of the usage of the general valvetrain mechanisms with a two-stroke cycle. Some results of such developments have already been patented in USA, Australia, Japan, and France [12-14]. For example - prototype engines Orbital ES, GM CDS2, IAPAC with a crank-case cylinder scavenging. Here the fresh charge is pathed not by the inlet ports, but through special valves in the cylinder head, fuel (gasoline) is fed to manifold before the valves with the special nozzles. These nozzles are using the pneumatic spray made by compressed in the crankcase gas. In other engines, for example, Subaru, Toyota S 23L, a direct injection system of gasoline into the cylinder is implemented, the engines are mechanically supercharged. It is important to note that Toyota engine has neither inlet nor outlet ports, whole gas exchange is carried out with the typical valves like in four-valve cylinder heads.

Tests results showed that for such engines the main disadvantages of traditional two-stroke engines are completely eliminated: high fuel consumption, lean combustion (especially at low loads). It is noted [12-14], that for such engines the fuel consumption is reduced two times compared to traditional two-stroke engines, in the load ranges up to 50%, fuel consumption is even 20% lower than in high-performance four-stroke engines.

The most important factors for aviation application is the weight to power ratio. For such engines it is 30 to 40% less than for similar in power range four-stroke engines. The volumetric power for such engines almost two times higher than the typical values for general four stroke engines and reaches power values of 80 - 90 kW per litter.

It is also important to note the possibility of modifying already set in serial production and well accepted by market designs of four-stroke engines to a two-stroke cycle after the appropriate refinement of the control systems and valvetrain.

However, a number of problems still require further research. Among them are the optimization of the timing, fuel injection and ignition, the adjustment of the boost systems, and most important, it is necessary to verify the feasibility of the residual gas scavenging from cylinder through the valves in a short period of time, typical for the two-stroke engine. Without these researches, a two-stroke engine with a valve gas distribution system is simply unable for operation.

The purpose of this work was the numerical calculation study, feasibility study of modification for the real four-stroke engine to the two-stroke cycle with an assessment of the main technical and economic characteristics.

2. Materials and research methods
The four-stroke four-cylinder Rotax 914 [15] horizontally opposed (boxer) aviation spark ignited engine was chosen as an object for study. Fuel - RON 98 gasoline, compression ratio \(\varepsilon = 9:1\), \(V_h = 1211.2\) cc, bore 79.5 cm, stroke 61 cm, boost pressure - up to 2 bar. The numerical calculation studies were carried out in two stages.

2.1. Work process in Diesel-RK
At the first stage, using the thermodynamic simulation software Diesel-RK [16], the numerical calculation and optimization of the working process for Rotax 914 engine were executed. This engine
was modified to two-stroke cycle, with assumption that existing two intake and two exhaust valves provide enough scavenging and admission. After simulation work with this software it was possible to compare the engine parameters both for the basic four-stroke cycle and for the two-stroke cycle after the engine parameters modification and optimization for such two-stroke cycle.

2.2. Gas exchange simulation in AVL FIRE

At the second stage, in order to confirm the possibility of the required scavenging of the cylinder and admission by the charge through two exhaust and two intake valves, it was necessary to use 3D numerical simulation of the flow in the following simulation system - “inlet valve port - cylinder - exhaust valve port”.

There are many published papers with description of different gas dynamics numerical methods, that could be potentially applied for such task [17, 18]. However, it appears that the most suitable software here is AVL FIRE ™ [19]. This software was developed by the well-known company AVL List specifically for such numerical 3D simulation of gas exchange and in-cylinder processes for piston engines. This software allows to simulate 3D fields for gas velocity and other parameters, as well as the final parameters of the engine cylinder scavenging and admission in the real time conditions for intake and exhaust valves with the optimized for combustion of the piston engines turbulence simulation model.

3. Results and discussion

Figure 1 and figure 2 represent plots of calculated characteristics comparison for the Rotax 914 engine for ground test conditions with the basic four-stroke and two-stroke modes. Figure 1 shows a significant advantage in $N_e$ of the two-stroke operating cycle to the four-stroke operating cycle on the entire speed range. Particularly, at speed $n = 3000$ rpm, an increase $N_e$ by 88% was obtained, for $n = 6000$ by 71%.

The dependence of the torque $M_e$ from the engine's speed in the two-stroke cycle also significantly exceeds the torque values obtained for the engine with the original four-stroke cycle. The increase of $M_e$ at the maximum speed points is 89%.

![Figure 1. 2-stroke engine’s power in comparison with common engines (kW at speed).](image-url)
Figure 2. 2-stroke engine’s torque in comparison with common engines (Nm at speed).

In order to perform the numerical 3D calculations of the engine's scavenging-admission in two-stroke cycle, at first was created a 3D numerical mesh (regular grid) consisting of cells with edges not exceeding 1 mm size. This mesh is necessary for finite-different gas dynamic calculations, it fits into the complex geometry of the computational domain of the system “inlet valve ports - cylinder - outlet valve ports”. The mesh is adaptive and provides calculations in the conditions of movable valves and piston.

The resulting mesh is presented on figure 3.

Figure 3. 2-stroke engine’s mesh boundary conditions.

Numerical calculations were performed with the initial conditions and boundary conditions, previously obtained at the first calculation stage in the Diesel-RK software. Among them were the changing temperature distribution over the hot surfaces inside the cylinder; variable pressure and mass air flow at the inlet and outlet, consistent with the characteristics from the compressor map and turbine
map; variable valve timing, timing of ignition and fuel injection. The whole process was carried out in stages, based on the set of the main influencing factor - the valve timing parameters combination. The change in the corresponding angles was carried out in increments of 1 degree separately for each step of changing valve timing (for opening and closing, intake and exhaust - all separate). It was obtained a table of results, and the best combination of parameters was chosen after this. The crankshaft rotation angle at the time of opening the exhaust valve is 66º before bottom dead center (BDC), the inlet opening angle is 44º before BDC, the closing angles coincide and are 25º after BDC. The ignition timing and fuel injection angles vary widely and are selected using the optimization module integrated in the Diesel-RK software. In real engine, this task is performed by electronic control system.

According to numerical calculation, as a result of an integrated assessment of the scavenging and admission of the cylinders for each of the modes, the value of gas residual coefficient $\gamma$ was obtained. It varies depending on the crankshaft speed in the range from 11% to 18%. These values are higher than in an engine operating on a four-stroke cycle, but are sufficient for the stable operation of a two-stroke engine. It should be noted here that an increased amount of exhausted gases provides the effect of internal recirculating (the EGR system's effect without system itself), which significantly improves engine emissions.

The calculation results are also presented on figure 4 and figure 5 in a form of the streamlines at the time of the most intensified scavenging. It can be seen that there are no zones of local stagnation in the entire volume of the cylinder, air displaces exhaust gases from all zones, and reliable scavenging is provided.

![Figure 4. 2-stroke engine’s gas exchange (small streamlines).](image)

4. Conclusion
This paper represents the results of a numerical calculation study of the possibility of modifying the four-stroke piston aircraft engine Rotax 914 to a two-stroke operation cycle. It is shown that, with a relevant setting of the valvetrain and setting of the well-optimised phases of the intake and exhaust valves, ignition and fuel injection timing, it is possible to receive a significant increase of the engine's power and torque.

The calculations showed that with a dry engine's weight of 64 kg at a nominal mode matching to a speed $n = 6000$ rpm, weight to power ratio of the engine decreases from 0.83 to 0.48 kg / kW, i.e. by 42%, the volume power $N_V$ increases from 63.6 to 109.0 kW per litter, by 71%. These results are fully coincide to the data given in [12-14], which presents the results of practical work with similar piston engines.
Figure 5. 2-stroke engine’s gas exchange (large streamlines).

It should also be noted that the part of exhausted gases in the cylinder by the time of ignition is 11-18%, which ensures normal mixing of the fuel and air as well as the combustion for such two-stroke engine, it creates the effect of internal exhaust gas recirculation (the EGR system's effect without system itself). The experiments showed [12-14] that this effect, in addition to the fact that the valve gas exchange in a two-stroke engine prevents the emission of 20–40% of unburned hydrocarbons and reduces nitrogen oxides, the exhaust toxicity of such engines is reduced to 80%.

It is obvious that the continuation of numerical calculations and practical researches on the modify of four-stroke engines to a two-stroke cycle with the usual valvetrain system seems to be very actual.

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