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High-power and high-rpm two-stroke aircraft engines – applications and prospects

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The article presents the concept of a two-stroke high-power aircraft engine, intended primarily for powering a record-breaking racing aircraft and its version for powering passenger or transport aircraft. Based on the design study and calculated operational indicators, an analysis of its usability in the proposed aircraft will be presented. According to initial assumptions, it should be able to exceed the current speed record for a piston-powered aircraft. Based on the developed design and the tests that were conducted, the engine will also be analyzed as a drive for passenger or transport aircraft. For this purpose, it was compared with a turboprop engine with particular consideration of the generated thrust. In addition, the unused potential of such two-stroke engines as the Rolls-Royce Crecy, Napier Nomad and the high-speed two-stroke engine designs of engineer Tresilian will be analyzed.

Key words: *aircraft engines, two-stroke engines, exhaust gas energy, engine design, Anzani-Argus system*

1. Introduction

The development of two-stroke high-power engines in aviation was interrupted by the appearance of turbine drives. They offered better altitude characteristics and the ability to easily obtain higher flight speeds than the piston engines produced at that time. There are many indications that a change in their design would, however, allow for their parallel coexistence. The proposed two-stroke engines, usually with spark ignition, could in theory, provide comparable or better operating indicators than turboprop drives.

Undertaking work on the design of a two-stroke engine for record-racing aircraft allows for the verification of these assumptions on the basis of the developed comparative characteristics. As an example of a typical turboprop engine, the currently produced and used in modern aircraft Pratt & Whitney PW 150A engine were chosen.

As part of the work, two versions of the engine are designed: the proper, record racing and designed for passenger or transport aircraft. Whereas their design will be similar, they will differ primarily in the charging system. Long-engine operation is not required during air races or when breaking a record. For this reason, the supercharger can be powered by an electric engine, and all exhaust energy can generate thrust for the turbo compound. The engine in a transport or passenger aircraft must ensure the highest possible altitude characteristics and constant boost pressure during many hours of operation. For this reason, it is necessary to use a turbocharger with regulation by means of exhaust gas extraction.

The article will present the general concept of the engine, the results of calculations, and the comparative characteristics of turboprop engines. During the design works, many solutions have been developed that can lead to an increase in the thrust force of the drive system and a reduction in the weight of the engine or its dimensions. Basic calculations and a description of the construction will also be presented.

2. Development of two-stroke engines in aviation

Two-stroke engines were first used in aviation in 1908. In fact, these were designs applied to drive motor boats produced by the American Elbridge [27]. However, aircraft constructors paid attention to their low weight compared to four-stroke engines [34]. These were primarily Type A with 10 hp (7 kW) and Type C with 30 hp (22 kW) [35]. For this reason, a series of in-line engines with the common name Featherweight [34] with a bore of 117 mm and a stroke of 114 mm was developed on their basis. The first of them in a three-cylinder system with a displacement of 3.72 dm^3 reached a maximum power of 45 hp (33 kW) and a nominal power of 30 hp (22 kW). Its weight was 69 kg. Another four-cylinder with a displacement of 4.96 dm^3 reached a power of 60 hp (44 kW) and a nominal 40 hp (29 kW) at a weight of 89 kg. The last one had six cylinders with a total displacement of 7.43 dm^3. Its maximum power was 90 hp (66 kW), and the nominal power was 60 hp (44 kW). The weight was 118 kg. These three engines reached their maximum power at 1400 rpm [1]. Encouraged by their success, Elbridge developed a new, typically aircraft engine called the Aero Special [34]. It was a modification of the four-cylinder Featherweight. The weight was reduced to 68 kg, and the rotational speed was increased to 2000 rpm. This allowed to obtain a maximum power of 60 hp (44 kW) and a nominal power of 50 hp (37 kW) [1]. Despite this, the engine turned out to be a failure for the company because at that time, there were no propellers adapted to such a rotational speed [29].

In 1910, in Japan, Captain Kumazo Hino developed his own 8 hp (6 kW) two-stroke aircraft engine. The designer was inspired by a trip to Germany, which he made in order to get acquainted with the local aviation industry. The following year, he built an in-line, two-cylinder engine with 18 hp (13 kW), which, according to the project, was to reach 30 hp (22 kW). It uses two reciprocating compressors. This made it one of the first supercharged aircraft engines. In 1915, its improved version, with a power of 25 hp (18 kW) was used in a prototype aircraft [11].

In the following years of aviation development, two-stroke engines were used to propel small, light aeroplanes. Several well-known constructions, such as the American Roberts from 1919 or the Meteor produced since the 1920s, can be mentioned. They were also used in unmanned aircrafts. An example is the experimental flying bomb from 1917 Sperry Aerial Torpedo [34]. Since 1945, McCulloch in the USA has been producing four-cylinder engines with an opposite-cylinder system for flying unmanned aerial vehicles. The first one, the Model 4300, with a displacement of 1.45 dm^3 , achieved 65 hp (48 kW) at 4100 rpm. It was produced until 1952. From 1950 to 1988, a 4318 model with an increased cylinder diameter was produced. The displacement volume was thus increased to 1.63 dm^3. Depending on the model, the maximum power ranged from 72 hp (53 kW) to 84 hp (62 kW) at 4100 rpm. It also powered several types of gyroplanes. A 110 hp (81 kW) version equipped with a turbocharger was also created [24].

Two-stroke engines in aviation are currently small power units designed primarily for drones and ultralight aircraft [16], motor gliders or ultralight trikes. Rotax or Hirth can be mentioned here. These are engines with a simplified design, without supercharging, with spark ignition. They are often adapted to automotive gasoline, which is cheaper than avgas. In addition, the basic type of drives used in flying aircraft models are two-stroke engines. They are produced as so-called glow-ignition engines, i.e., simple compression-ignition engines with a carburetor and a glow plug. Larger model engines are equipped with spark ignition [28]. Larger ones can also drive smaller drones.

Most of the compression-ignition engines used in aviation were also built as two-stroke engines. Only a few types were created due to the difficulty of obtaining a favorable power-to-weight ratio. One of the few examples can be Junkers Jumo diesel engines. The first of them, the six-cylinder, in-line Jumo 204, was created in 1929 [14]. Thanks to the use of light alloys and an unconventional arrangement of cylinders, a fairly favorable rate of 1.03 hp/kg was achieved. In most spark ignition engines created this year, this indicator was about 0.9–1.5 [29]. It was a six-cylinder engine with twelve opposed pistons. This allowed its dimensions to be reduced. At the same time, this arrangement forced the resignation of the warhead. This led to a significant reduction in weight. Its displacement was 28.5 dm^3, the bore was 120 mm, and the stroke of the pistons was 210 mm. The compression ratio was 17:1. It reached 770 hp (566 kW) at 1800 rpm.

His successor from 1932 was Junkers Jumo 205. The diameter of the cylinders was reduced to 105 mm and the stroke to 160 mm. Thus, the displacement volume was 16.6 dm^3. At the same time, it was possible to increase the rotational speed to 2200 rpm. It reached a maximum power of 600 hp (441 kW) [42]. The hp/kg ratio was 1.15. For most in-line engines of this period, this value fluctuated around 0.9–1.9 [29]. The D version already achieved 700 hp (515 kW) at 1600 rpm. Its development, created in 1940, was Junkers Jumo 207. It was equipped with a better supercharger, adapted for high-altitude flights. The rotational speed was increased to 3000 rpm. This allowed to obtain a maximum power of 950 hp (699 kW) in version A and 1000 hp (735 kW) in version B. The B-3 variant was equipped with a G-1 system injecting nitrous oxide into the intake system. This increased engine power at high altitudes [3, 42].

In the 1930s, research on the sleeve valves was carried out in the USA and Great Britain. It was thought to be more advantageous in aircraft engines than popped valves systems. This arrangement aroused particular interest in the United Kingdom, where several companies undertook the production of such structures [26]. Napier Sabre was a twenty-four-cylinder engine in the H system. It powered fighter planes such as the Hawker Typhoon and the Hawker Tempest. Bristol has produced a series of radial engines equipped with sleeve valves: Perseus, Aquila, Taurus, Hercules and Centaurus [22].

Due to its construction, however, the sleeve valves is easiest to use in a two-stroke engine. The British engineer Sir Harry Ricardo conducted research on such engines. For this reason, in 1937, the British Ministry of Aviation commissioned him and Rolls-Royce to design a two-stroke aircraft engine. Ultimately, they decided on a spark-ignition engine with direct injection. The first prototype was built in 1941. It was named the Rolls-Royce Crecy I. It was a V system, twelve-cylinder, liquid-cooled engine. The bore was 129.5 mm and the stroke of the pistons was 165.1 mm. The displacement volume was thus 26.11 dm^3. In the Crecy II version (Fig. 1), the shape of the combustion chamber and the ignition system were modified. The main source of boost was a single-stage, centrifugal mechanical supercharger. Three of the eight Crecy engines used a turbo compound. Thus, it was the first engine equipped with it. It was connected to the supercharger with a gearbox. In this way, it was both the drive of the supercharger and gave additional power to the crankshaft. The engine rotational speed was 2750 rpm, and when the turbo compound system was installed, it was 3000 rpm. This resulted in an increase in the maximum power from 1768 hp (1300 kW) to 2729 hp (2007 kW) [25]. The hp/kg ratio was over 3, and the power to displacement ratio was 105 hp/dm^3 [29].

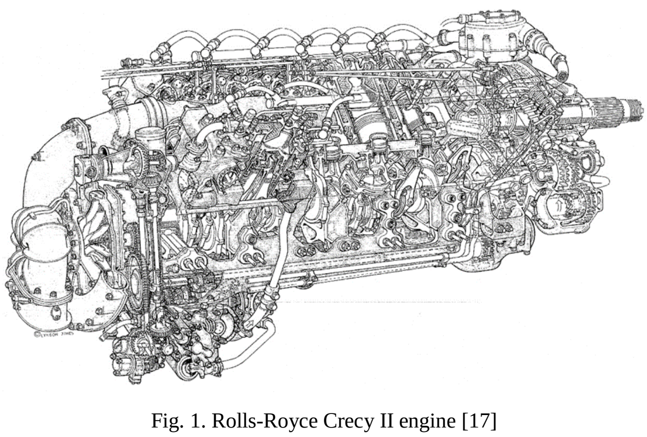

Fig. 1. Rolls-Royce Crecy II engine [17]

In addition, a properly shaped exhaust system in the Crecy engine allowed for a thrust power of 1.44 kN without a turbo compound and 1.28 kN with a turbo compound. At an altitude of 3000 m, this value would already be 1.43 kN. Using a two-stroke cycle allowed for the obtainment of much higher exhaust energy, which can be used to drive a turbocharger, a turbo compound, or to obtain additional thrust. This can be likened to a four-stroke Rolls-Royce Merlin engine with a similar displacement and a similar maximum rotational speed. It generated only 0.67 kN of thrust, although it was equipped with a mechanical supercharger and did not have a turbo compound.

The use of the Rolls-Royce Crecy engine in several aircraft, such as the Supermarine Spitfire or de Havilland Mosquito, was considered. The former could reach a top speed of 792 km/h. However, due to the strength of the structure, it would be impossible to use the engine capabilities in these aircraft fully. Finally, the North American P-51 Mustang was chosen. According to calculations, it would be able to reach a maximum speed of 965 km/h. Ultimately, the engine was not used in practice [25].

Another British, two-stroke, high-power engine was the Napier Nomad. Unlike Crecy, it was equipped with a compression ignition. Its original concept was created on the basis of the 1945 specification for a 6000 hp (4412 kW) drive, a design of a compression ignition, twenty-four-cylinder H-engine with a displacement of 75 dm^3 was created. Ultimately, it was considered that there would be no demand for an engine of this size and the design was halved, creating a system with twelve opposite cylinders (the so-called boxer). Its displacement volume was 41.1 dm^3. The diameter of the cylinders was 152.4 mm, and the stroke of the pistons was 162 mm [17].

The first version, the Nomad I, was equipped with a charging system with a connected turbocharger with a turbo compound. It was developed on the basis of the Napier Naiad turbojet engine. The supercharger had an axial arrangement; its last stage was centrifugal. Its drive was a two-stage turbine, which at the same time, it was connected directly to the crankshaft and to the propeller shaft through the supercharger shaft to transfer part of the power to the crankshaft and directly drive the first stage of the propeller. The second stage of the propeller was driven only from the crankshaft. In addition, an additional combustion chamber was used in front of the turbine, into which fuel could be injected. The engine reached a maximum power of 3000 hp (2006 kW) and 1.4 kN of thrust. The prototype was created in 1949. It was tested on an Avro Lincoln aircraft.

In the Nomad II version (Fig. 2) the charging system has been significantly simplified. The turbine was changed to axial, and the supercharger's last centrifugal stage and combustion chamber were removed. The shaft between the turbine and the supercharger was directly connected with a hydraulic clutch to the crankshaft. It allowed the power to be increased to 3250 hp (2390 kW) at 2050 rpm [29]. The Napier Nomad II was proposed to power the Avro Shackleton bomber. Two engines were installed in the prototype version of the Shackleton MK IV, which was never tested with them in flight [22].

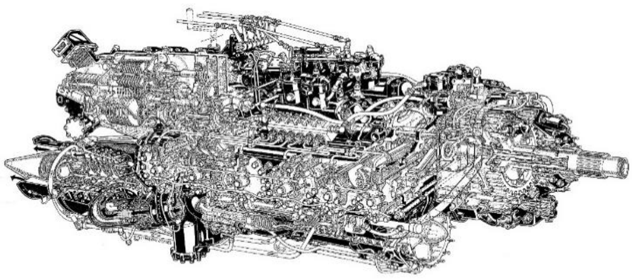

Fig. 2. Napier Nomad II engine [17]

The development of piston aircraft engines in the period after World War II was expected for two-stroke engines. Especially those that would be equipped with a sleeve valves. In 1946, the British Aeronautical Research Committee predicted that new, two-stroke engines would soon be created, which would reach about 200 hp (147 kW) from 1 dm^3 of displacement. This would probably be the next phase of the development of piston aircraft drives, if it were not for the development of turbine engines that exceeded them in terms of operational indicators or altitude characteristics [25].

After the end of World War II [40], research on the development of aircraft engines was carried out by engineer Steward Tresilian working for Rolls-Royce. He was significantly inspired by the design of the Crecy engine. However, he considered that the engine dimensions should be reduced as much as possible. As a comparative drive, he chose the well-known and mass-produced twelve-cylinder Rolls-Royce Griffon V engine with a power of 2500 hp (1838 kW). Starting from the simple assumption that reducing the displacement of the cylinders would allow to increase the speed of the piston movement and thus the rotational speed of the entire engine, he came to the following conclusions: by reducing the engine by half, the power would decrease by only 37%, and the power to displacement ratio would increase by 25%. The griffon had a displacement volume of 36.7 dm^3. Assuming the use of a better fuel, it would be possible to reduce its displacement to 23.4 dm^3, while maintaining the same power. Changing the number of cylinders (while reducing the stroke of the pistons) to 16 in the X system would allow the engine to be further reduced. Its displacement would then be only 20.3 dm^3. The main limitation in further reducing the engine was the size of the valves. According to Tresilian, the maximum reduction in displacement could occur in a nine-cylinder radial engine. The piston speed would increase by 33% while reducing the displacement volume to 13.2 dm^3 [25].

However, increasing the boost pressure would reduce the size of the valves. As a result, the bore of the cylinders in the X system could be reduced to 99 mm. The stroke would be 84 mm. The displacement volume would then be equal to 10.3 dm^3. The engine, despite such a significant reduction in displacement, would still be able to reach 2500 hp (1838 kW). However, the rotational speed would be increased to as much as 7250 rpm [25].

The next step in the analysis was to change the work cycle to a two-stroke one. Sleeve valves would be used instead of a poppet valve. With the proper layout of the inlet and outlet system, the engine displacement could be further reduced to 9 dm^3. Its power would be the same as in the Griffon with a displacement of 36.7 dm^3. The rotational speed in this version would be 6800 rpm. The engine with a compression ratio of 8:1 would be equipped with a mechanical supercharger from the Griffon engine and a turbo compound. The exhaust system would be arranged in such a way so as to be able to obtain additional thrust [25].

The designed engine was compared to the Rolls-Royce Tweed turbojet engine being developed at that time (which was eventually not completed). The Tresilian engine would have a slightly smaller frontal area. However, the main determinant of suitability was the fuel consumption, which would be 26% lower than in a four-stroke engine of a similar size and 36% lower than in the Tweed. This would allow for a significant increase in the range of the aircraft flight [25].

Tresilian showed that it would theoretically be possible to reduce the displacement volume to 7.8 dm^3 while maintaining the same power all the time. He also proposed a twenty-four-cylinder X engine with a 152 mm cylinder diameter (the same as in the Griffon engine) and 91 mm of stroke. The displacement volume would be 39 dm^3. It could achieve 8100 hp (5956 kW) at a rotational speed of 4600 rpm [25].

3. The problem of using the propeller in high-speed flights

Piston aeroplane engines have been replaced with turbine drives in most applications. They are used in light aircraft, usually not exceeding a maximum speed of 300–400 km/h. The direct source of thrust is the propeller, which is driven by the engine, similar to turboprop engines. For this reason, the maximum speeds for both piston and turboprop aeroplane are theoretically the same.

The official speed record for a propeller-driven aeroplane belongs to the Tupolev Tu-114 turboprop, which was 877 km/h [38]. However, the unofficial record belongs to the experimental Republic XF-84H aeroplane, which was supposed to be 1080 km/h [31]. It was equipped with special propellers designed to rotate at supersonic speeds. They were highly impractical to use due to the noise they generated. In theory, they could allow supersonic speeds to be achieved.

The speed record for a piston-engine aircraft for a very long time belonged to the Rare Bear racing aircraft, which is a converted Grumman F8F Bearcat fighter. It is 850 km/h [10]. The appropriately modified North American P-51 Mustang, known as the Voodoo, reached a speed of 893 km/h in 2017 [30].

The main problem in the development of high speeds by aircraft in which the main source of thrust is the propeller is the decrease in its efficiency with the speed of flight [21]. Most common propellers lose their efficiency significantly at the Mach number of the aircraft exceeding the value of 0.7–0.8. As, in fact, the speed of the propeller blades is a component of two speeds: the propeller blades' linear speed and the aeroplane's forward speed. Thus, the speed of the propeller blade is greatest at its end, so the efficiency of the propeller may vary with the radius. The Republic XF-84H propeller was designed to operate only at supersonic speeds. This allowed to maintain efficiency at transonic and potentially supersonic speeds. However, it was not practical due to the noise they generated, which prevented normal operation.

The solution would be to reduce the rotational speed of the subsonic propeller so that the tips of its blades do not exceed Mach = 1. For obvious reasons, this excludes flights with supersonic speeds. Assuming that the speed of sound is approximately 1200 km/h, the following can be considered:

$$\sqrt{v_p^2 + v_a^2} < 1200\ \text{km/h} \tag{1}$$

where: v_p – linear speed of propeller blade tip, v_a – aircraft speed.

Thus, it is necessary to use a sufficiently large rotational speed reduction in the engine. Based on the formula, it can be concluded that the maximum speeds for an aircraft powered by a classic propeller cannot exceed 900–950 km/h. Assuming the use of a propeller with a diameter of about 4 m, its rotational speed should be reduced to no more than 1000 rpm. Further increasing the reduction in rotational speed leads to excessive enlargement and complication of the gear in the piston engine, and thus also to an increase in its weight while reducing efficiency.

4. General engine concept

The general concept of the engine assumes a propulsion design that would allow to break the speed record for aeroplane powered by a piston engine and for aeroplane in which the main source of thrust is a common subsonic propeller. At the same time, the design should be a hypothetical alternative to turboprop engines in passenger or transport aircraft.

In order for the engine to meet the above requirements, several assumptions were made. It should achieve as much power (and thrust) as possible with as little weight as possible. In addition, its construction should be as simple as possible. These are particularly important features compared to turboprop drives, which are characterized by a high power-to-weight ratio and simplicity of construction. For these reasons, it is necessary to use a two-stroke cycle. It allows for the achievement of more power than a four-stroke engine with a similar displacement. In contrast to the concept of eng. Tresilian and the Rolls-Royce Crecy engine [25], a complicated valves system should also be removed from the engine since it increases weight. Air cooling will be used to further reduce weight and simplify construction [9]. Light alloys will be used. Whenever possible, the use of aluminium alloys should be limited in favor of titanium and magnesium alloys (Fig. 3).

For the purposes of the project, it was assumed that the engine would have a displacement of 32 dm^3. The rotational speed needed to obtain the appropriate power has been tentatively estimated at 7000 rpm. Based on the different designs of aircraft engines, it can be seen that air cooling can be effective if there are no more than four cylinders in one row [29]. For this reason, several possible layouts can be adopted:

- fifteen-cylinder three-row radial
- fourteen-cylinder two-row radial

– eighteen-cylinder two-row radial
– sixteen-cylinder x-system
– sixteen-cylinder h-system.

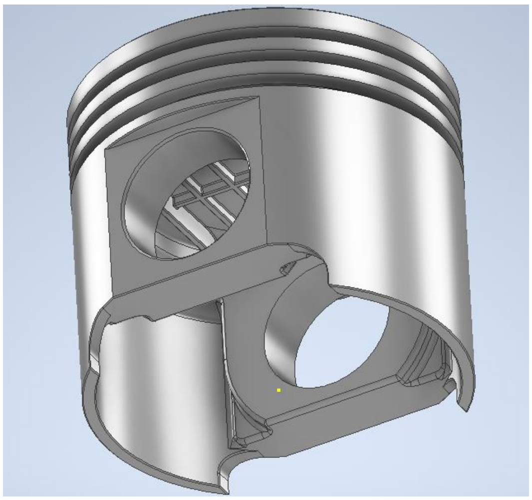

Fig. 3. Engine piston, which can be made of magnesium alloy WE43A or silumin AK12

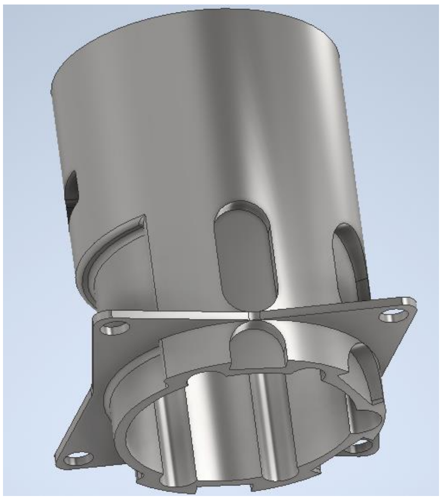

Fig. 4. The cylinder of the designed engine made of 36NiCrMo16 steel. Intake ducts are visible on the inner surface

A radial engine would be very beneficial because of the cooling. However, it is difficult to achieve significant rotational speeds in this system, which usually do not exceed 3000 rpm [29]. This is due to the small number of ignitions occurring simultaneously and the large mass focused on one crankshaft crank. For this reason, it would be preferable to have an X system, which, unlike the H system, has only one and not two crankshafts. For this reason, H is characterized by a greater mass. However, the H system allows the use of scavenging from the crankcase (the Schnürle system was selected (Fig. 4), five-channel [33]). Thanks to this, using a mechanical supercharger is unnecessary, and the engine can be naturally aspirated and charged with a turbocharger. Treating the H system as two combined systems with opposite cylinders (the so-called boxer) allows for better balancing and reduction of balancing masses.

Both crankshafts must be connected by a gearbox, which can also act as a rotational speed reduction. The project envisages the use of a single-stage cylindrical gear with helical teeth with a gear ratio of 1:7 (small gears at the ends of the shafts connected to one large wheel located on the propeller shaft). Due to the diameter of the large wheel, it is impossible to place it between the crankshafts [27]. This forces the engine to rotate 90°, with two rows of standing cylinders and two rows of hanging cylinders. The propeller axis, together with the gear, will be moved up in this solution. This will also provide an additional air inlet to the intercooler below the engine.

In order to simplify the crankshaft, reduce weight and improve balance, the connecting rod system that has been tested in aero engines in the boxer system by Anzani and Argus companies will be used. For this reason, it is reasonable to refer to it as Anzani-Argus [34]. Gas forces acting in opposite piston-connector systems (Fig. 5, Fig. 6) completely balance each other, which can be proved by the bending moment equation [39, 44].

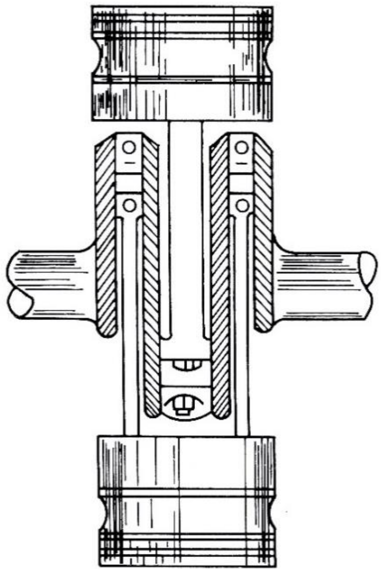

Fig. 5. Anzani-Argus connecting rod system [35]

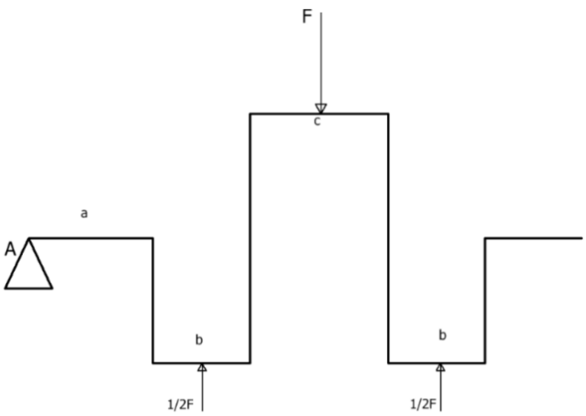

Fig. 5. Distribution of forces in the Anzani-Argus system

$$\sum_{M_{gA}} = 0 \tag{2}$$

$$0 = \frac{1}{2}F\left(a + \frac{b}{2}\right) - F\left(a + b + \frac{c}{2}\right) + \frac{1}{2}F\left(a + \frac{3}{2}b + c\right) \tag{3}$$

$$0 = F\left(\frac{a}{2} + \frac{b}{4} - a - b - \frac{c}{2} + \frac{a}{2} + \frac{3b}{4} + \frac{c}{2}\right) \tag{4}$$

$$0 = F(0a + 0b + 0c) \quad (5)$$

$$0 = 0F \quad (6)$$

At the same time, the balance of inertia forces must be ensured. This was probably the main problem during the research of this system by Anzani and Argus. They were unable to complete this research. Anzani soon went bankrupt, and Argus began producing engines for the Luftwaffe. However, currently using CAD programs, it is not a problem to accurately determine the masses located on both sides of the crankshaft axis.

Another advantage of the Anzani-Argus system is the shortening of the crankshaft and thus the entire engine, because the opposite connecting rods are not offset from each other along the crankshaft. As the calculations have shown, the bending moments of the forces in the piston-crank system that act on the crankshaft are balanced within the piston pair. This means that no bending moments are transferred to the rest of the crankshaft, which remains only loaded with torque and bending moments coming from the gearbox, in the case of using a rotational speed reduction. The shaft journals and the crank arms must transfer the significant forces within the pair. This requires their large dimensions and the use of steel with sufficiently high bending strength. In order to make it more endurable, 65S2WA steel with Re = 1665 MPa was selected [47].

The supercharging with an electrically powered flow mechanical supercharger was selected for the engine intended for a racing aircraft. The record speed should be reached at an altitude of 3000 m. This maximum height allows for trouble-free breathing without an oxygen system for the pilot. At the same time, the air density is lower at higher altitudes, so are the resistance forces during flight. At the presumed height, the engine should be charged with a supercharger with a compression equals to $\pi = 4.2$. In addition, the engine will be charged by turbo compound. Based on the references [5, 25, 41], its impact on engine power was determined at 25.4%. A crankshaft gearbox would permanently connect the turbo compound. The supercharger would only operate during record-breaking or racing flights. The aircraft would take off without a working supercharger.

The engine intended for passenger or transport aircraft would have to be equipped with a supercharger that could operate much longer than a battery-powered electric supercharger. The smaller turbo compound turbine will also drive the turbocharger. Its impact on engine power will be 18%. It would be the second stage of charge. The first stage would be carried out by a turbocharger, the turbine of which would not be connected to crankshafts. Their total compression should be variable and adjusted to the flight altitude. At the level of 0 m above sea level it should be, the compression should be $\pi = 2.77$, at a height of 3000 m it should equal $\pi = 4$ and at 7500 m, it should be $\pi = 7.34$. The most optimal compression in terms of charge air cooling at an altitude of 7500 m would be $\pi = 2.71$ for each stage. Compression adjustment would be carried out by means of exhaust gas extraction. This would maintain a constant boost pressure and, thus a constant engine power over a wide range of heights. Throughout its operation, it would be supercharged at the same time with a turbo compound and turbochargers.

In order to obtain additional thrust from the drive unit, the following system will be used. The air-cooled engine will be located inside an appropriately shaped duct, at the inlet of which there would be a fan with a compression of $\pi = 1.05$. The flowing air would absorb some of the thermal energy of the motor while cooling it. Downstream of the engine, exhaust gases would be added to the air stream, at the same time increasing the flow energy. The outlet of the duct would be directed towards the rear of the aeroplane, and the gases escaping from it would create additional thrust.

5. Basic operational indicators

The basic operational indicator of the piston engine is the power obtained by it. On its basis, the power-to-weight ratio or the ratio to the displacement volume can also be determined. Based on "Obliczenia tłokowego silnika spalinowego" ("Calculations of a reciprocating internal combustion engine") by J. Jędrzejowski [16], a simple optimization of engine power was created depending on the compression ratio taking into account the temperature in the cylinder during compression, and thus taking into account the risk of knocking. The use of gasoline 115/145 with a high self-ignition temperature of 744 K [37] in the engine for a record aeroplane would allow the use of a compression ratio $\varepsilon = 10$. The assumption introduces some difficulty in designing passenger or transport aircraft versions. The use of gasoline 115/145 would not be a good solution due to the price. In this version, it would be necessary to use basic 100LL gasoline with a self-ignition temperature lower by about 30 K compared to 115/145 or cheaper, unleaded UL91 [18] with a self-ignition temperature lower by about 100 K. In order to avoid major changes between engine versions, it was decided to maintain the compression ratio. At the same time, adding an additional intercooler and extending the intake system is necessary [13].

The calculations take into account the efficiency of gears and piston-cylinder assemblies. To calculate the friction power of forty plain bearings and twelve rolling bearings, friction coefficients were adopted based on literature [19, 45]. This allowed for a more accurate determination of the engine's effective power than in the case of adopting a specific mechanical efficiency value based on the literature [16]. The overall engine efficiency was determined at $\eta_o = 29.94\%$ for the racing engine and $\eta_o = 29.66\%$ for the passenger or transport aircraft engine. It was calculated according to the formula [16]:

$$\eta_o = \frac{P_e \times V_s}{W_u} \quad (7)$$

where: P_e – effective pressure (741750.2 Pa for racing engine and 73489.3 Pa for passenger or transport aircraft engine), V_s – displacement volume needed to burn 1 kg of fuel (17.758 m^3/kg), W_u – gasoline calorific value (44 MJ/kg).

To determine the power-to-weight ratio, it is necessary to know the weight of the engine. Unfortunately, its exact value would only be known after the entire engine has been designed. For the purposes of the initial comparison, a value of 550 kg was assumed based on literature data from several hundred engines [29].

Based on the calculations [16], the basic operational indicators were determined. For simplicity, one table contains data for both the basic version of the engine designed as a drive for the record aircraft and the version of the engine that could be hypothetical propulsion of passenger or transport aircraft (Table 1). For the racing version, the cruising values were not taken into account because when breaking the record, it significantly has only the maximum power. The throughput power of the communication engine was determined for a rotational speed of 90% of the maximum rotational speed, i.e., 6300 rpm.

Table 1. Operational indicators of the designed engine

Motor	Racing	Passenger/transport
Maximum rotation speed:	7000 rpm	7000 rpm
Max. power	5014.68 hp (3687.27 kW)	4,652.04 hp (3420.61 kW)
Cruising power	–	4186.83 hp (3078.55 kW)
Power-to-weight ratio (estimate)	9.12 hp/kg	8.46 hp/kg
Power to Stroke Volume Ratio	156.71 hp/dm^3	145.38 hp/dm^3
Fuel consumption when operating at maximum power	1007.62 dm^3/h	943.58 dm^3/h
Fuel consumption when operating at cruising power	–	849.22 dm^3/h

Calculating the thrust power obtained thanks to A properly shaped channel requires certain calculations and assumptions to be made. If the aircraft moved at a speed of about 950 km/h at an altitude of 3000 m, and the engine gave off ambient heat through direct cooling, based on the energy balance, its impact on the temperature of the air flowing around it would be approximately ΔT = 11 K [15].

The next step is to determine the exhaust gas mass stream. Taking into account the rotational speed, power, excess air coefficient, and the supercharger value, it can be determined as follows: $\dot{m}_s$ = 5.959 kg/s [15, 32]. Further thrust calculations require the use of a flow machine model.

Assuming the air density at an altitude of 3000 m, the aircraft speed at v_1 = 950 km/h = 264 m/s and the surface area of the inlet to the channel, the mass stream of air entering the channel would be $\dot{m}_p$ = 91.7 kg/s. Heating the air by 11 K would increase the motor speed to v_p = 303 m/s, according to the principle of energy conservation. Assuming that the exhaust gas has a higher energy and velocity of about m_s = 450 m/s (it is an underestimated value, since the exhaust gas of the Rolls-Royce Merlin engine reached A speed of about 580 m/s), the velocity of the stream at the outlet from the channel, based on the weighted average referred to the mass stream, would be equal to 312 m/s. The thrust of the exhaust gas alone would be:

$$F_s = \dot{m}_s \times v_2 = 3.162 \times 312 = 1859.21\ \text{N} \qquad (8)$$

The total air and exhaust draught can be calculated from the momentum change formula, which in this case will take the form of [15, 23, 43]:

$$F = (\dot{m}_p \times v_2) - (\dot{m}_p \times v_1) + F_s \approx 6.27\ \text{kN} \qquad (9)$$

6. Comparative characteristics

Based on the calculated results, some comparative characteristics can be determined. This is particularly important for the engine for propulsion of passenger or transport aeroplanes. It will be compared to a turboprop engine of similar power, Pratt & Whitney PW 150A (Fig. 7) [6]. It can be considered a typical example of a turboprop engine used in aviation. In order to more accurately illustrate the advantages of a two-stroke engine, the approximate value of the propeller thrust will be calculated. For the purposes of calculations, the propeller efficiency of 80% can be assumed [36]:

– for a two-stroke engine, the propeller thrust is 19.7 kN
– for the PW 150A engine, the propeller thrust is 21.8 kN.

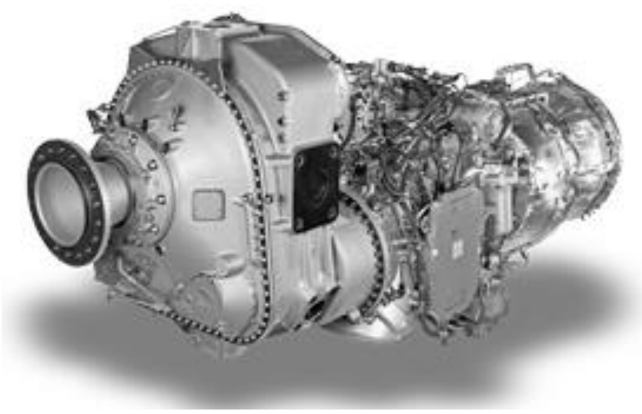

Fig. 7. Pratt & Whitney PW 150A engine [2]

The thrust obtained from the exhaust gas is more difficult to calculate than in the case of a racing engine. However, it should be considered to be the same or greater. There, heated air from the intercooler will be added to the flow in the duct. For comparison, a string of 6.27 kN was adopted (Table 2).

Table 2. Operational indicators of the designed engine

Motor	Two-stroke	PW 150A
Power	4652.04 hp (3420.61 kW)	5142.16 hp (3781 kW)
Weight	Approx. 550 kg	717 kg
The fuel consumption	943.58 dm^3/h or 669.94 kg/h	740 dm^3/h or 592 kg/h
Thrust obtained from exhaust gas	6.27 kN	3.75 kN
Thrust power of drive unit	25.97 kN	25.55 kN

Two completely different engines are compared. Although the PW 150A achieves more power by about 11%, the thrust force, which is obtained, is lower by 1.5%. It can be noted that a two-stroke engine can obtain greater thrust from the exhaust gas thanks to a properly shaped duct. The fuel consumption about the volume unit is lower for PW

150A. However, a jet has a higher density than gasoline, thanks to which the difference in fuel consumption in the kg/h unit is smaller.

In order to more reliably compare both drives, specific indicators will be compared, which will allow for a more effective determination of the hypothetical suitability of two-stroke engines, according to the presented concept as an alternative to turboprop drives (Table 3).

Table 3. Operational indicators of the designed engine

Motor	Two-stroke	PW 150A
Power-to-weight ratio	8.46 hp/kg	7.17 hp/kg
Specific fuel consumption	0.389 dm^3/kWh or 0.276 kg/kWh	0.196 dm^3/kWh or 0.157 kg/kWh
Propulsion unit thrust to engine weight ratio	47.22 N/kg	35.63 N/kg
Propulsion unit thrust to engine power ratio	7.59 N/kW	6.76 N/kW
Motor	Two-stroke	PW 150A

The presented comparative characteristics prove that two-stroke piston engines can be an alternative to turboprop drives. This is shown by operational indicators that are similar to or better than in the case of the PW 150A which was used for comparison. The proposed engine probably has a more favorable power-to-weight ratio, which is one of the most important features of an aircraft propulsion system. More important than the power issue, however, is the thrust power of the entire propulsion unit, which translates into the aircraft's actual performance. The proposed engine is able to reach 47.22 N from each kg of its weight, which is 11.59 N/kg more than the PW 150A. The difference is as much as 25%. In addition, it can be seen that in the presented concept, a greater thrust force can be obtained from a specific power unit than in the case of a turboprop engine.

In addition to operational indicators, it is important to compare economic factors. For comparison, the prices of fuels without excise duty were adopted, which airlines are exempt from (Table 4).

Table 4. Operational indicators of the designed engine

Motor	Two-stroke engine (UL91 gasoline)	Two-stroke engine (100 LL gasoline)	PW 150A (JET A-1 kerosene)	PW 150A*
Fuel consumption per hour	849.22 dm^3/h	849.22 dm^3/h	740 dm^3/h	752.16 dm^3/h
Flight price hourly	PLN 5944.54	PLN 6793.76	PLN 3478	PLN 3535.17
*thrust reduced to an equal value with a two-stroke engine, JET A-1 kerosene				

The conditions for the throughput power of 4186.83 hp (3078.55 kW) at 6300 rpm were adopted for comparison. Prices of aviation fuels are approximate, according to the price list of November 2024 [46]:

- gasoline UL91 PRICE PLN 7 PLN/dm^3
- gasoline 100LL PRICE PLN 8 PLN/dm^3
- aviation kerosene PRICE PLN 4.7 PLN/dm^3.

The presented analysis shows that the cost of one hour of operation of a two-stroke engine would be higher than for a turboprop engine. This is due to the slightly higher hourly fuel consumption in dm^3/h and the higher price of aviation gasoline than aviation kerosene. It is possible that increasing the popularity of piston engines in aviation would lead to a reduction in its price. It should be noted, however, that according to calculations, the two-stroke engine achieves greater thrust, which may positively affect the economic issues of its operation. Further optimization of the two-stroke engine could lead to greater thrust from the exhaust gases or greater thrust power from the propeller thanks to a turbo compound.

An important aspect is the lower emission of harmful substances from the engine powered by UL91 gasoline. While CO_2 emissions can be comparable, UL91 will generate less particulate matter and nitrogen oxides during combustion [8, 20]. Therefore, using piston drives powered by UL91 gasoline instead of turboprop engines may be a simple and eco-friendly solution, leading to better environmental conservation and the fulfilment of increasingly stringent regulations regarding emission standards.

As already mentioned, the design of a two-stroke engine assumes its simple construction, unlike other high-power aircraft piston engines (e.g., Pratt & Whitney R-4360, Rolls-Royce Merlin or Daimler-Benz DB605). This would reduce its price and make it easier to use. Taking into account the calculated operational indicators, it could be a hypothetical alternative to turboprop engines, especially in transport aeroplanes, military transport aeroplanes, sports aeroplanes or business aeroplanes.

It would be possible to improve the operational indicators further. However, this would entail ignoring the economic aspect. Filling efficiency can be improved by replacing simple carburetors with direct fuel injection. This would also allow to increase the compression ratio to $\varepsilon = 13$ and increase the boost pressure. The approximate value of mechanical efficiency was adopted in the calculations [16]. The direct injection version would achieve a maximum power of 5476.35 hp (4026.73 kW) at 7000 rpm. Unfortunately, this would increase fuel consumption. Higher compression temperatures in the cylinder would not necessarily allow unleaded UL91 gasoline. Instead, the engine would likely have to be powered by the more expensive 100LL or 115/145 leaded gasolines.

7. Alternative avionics development paths in the past and future

In the history of the development of piston aircraft engines, the following stages can be distinguished:

1. The period from the beginning of the 20^{th} century to the end of World War I. This was the time when basic aircraft engine systems were developed. The basic components were specified. Research has also been initiated into the influence of fuel composition on the combustion process and the problem of high-altitude flights.
2. Inter-war period. During this time, supercharging systems were developed. In addition, the combustion process in the cylinder was studied and effective fuel additives protecting against premature ignition based on tetraethyl lead were introduced.
3. World War II period. Solutions from the interwar period were developed, including supercharging systems and

turbochargers. There were also the first systems of using exhaust gas energy to create thrust power and turbo compounds transferring the energy contained in the exhaust gas to the crankshaft.

4. The next period is the time when, in parallel with the first turbine engines, more and more perfect piston aircraft engines began to be designed. This is the period from the mid-1940s to the early 1950s.
5. The period when turbine drives replaced aircraft piston engines in most of their applications. This is the time from the 1950s to today [29].

The further development of piston engines would have been expected had the turbine drives not been developed. Research on piston engines focused on the use of sleeve valves instead of the classic poppet valve. Especially in two-stroke engines, they could be successfully applied.

Using turbochargers regulated with exhaust gas extraction would allow maintaining a constant altitude characteristic over a wide range of altitudes, even up to 8000–10,000 m. To the extent that they provide a constant boost pressure, their efficiency increases with flight altitude. Exhaust gases expanding into a less dense atmosphere have more energy, even after passing through the turbine. As they can be used to drive the turbo compound and to generate thrust force, the engine power and thrust of the entire drive unit could be increased to the height to which a constant boost pressure could be provided. In this respect, piston engines have the potential to outperform modern turbine drives. In this case, two-stroke engines have special advantages, which generate more exhaust gases than four-stroke engines. Thus, one could certainly expect an increase in the maximum flight ceilings of aircraft.

Theoretically, subsonic propellers allow for flights up to a speed of about 950 km/h. The use of supersonic propellers could lead to an increase in this speed, perhaps even to supersonic values. However, due to the noise they generated, they would not go beyond the experiment phase. Their use in military aviation is doubtful, while it is totally impossible in civil aviation. Nevertheless, increasing the speed of combat aircraft to about 950 km/h would still occur in the 1950s, and, in the longer term, perhaps also in civilian aircraft.

As shown in the article, two-stroke engines may also now be an alternative to turboprop aeroplanes. They could be particularly useful in transporting aeroplanes performing non-commercial flights in the army. Short-range commercial aeroplanes would require a more accurate analysis of costs fuel consumption compared to higher thrust power and turboprop engines of similar power. The weight, simplicity of construction, and price of two-stroke engines are also very important.

It can be expected that theoretically, it would be possible to build a piston-powered passenger aircraft reaching a speed similar to turboprop aircraft (about 850 km/h). This would require optimizing the system for generating thrust. This would probably be a beneficial solution in terms of the weight of the drive unit and its unit price, but the operating costs, including fuel and oil consumption, would be very high.

The current speed record for a piston-engine powered aeroplane is 890 km/h. It was achieved by a modified World War II fighter that originally had a speed of around 700 km/h (430 mph) powered by an improved Rolls-Royce Merlin engine with 3100 hp (2279 kW) whose design dates back to the 1930s. Faced with these facts, an aircraft designed according to the principles of high-speed aerodynamics, taking into account the compressibility of the fluid, could more easily achieve higher flight speeds. It would be necessary to use swept wings and empennage. The designed drive would allow for the obtaining of much more power, more thrust, and, at the same time, less weight. For these reasons, it can be concluded that it is possible to achieve a speed of about 950 km/h. The designed two-stroke engine would be a very good solution for driving racing and record-breaking aeroplanes. For this purpose, appropriate aerodynamic calculations will be made for a specific aeroplane body.

In aviation, the use of two-stroke engines would be much simpler than in the automotive industry in the face of existing standards and regulations. There are no emission standards for harmful compounds similar to those used, for example, when a car is allowed in traffic. The certification of an aircraft does not consider its emissions, which are only accounted for by the airlines, in relation to the entire fleet. This does not apply to aircraft with a maximum take-off weight not exceeding 5700 kg and aircraft performing non-commercial flights, such as experimental or racing [7].

8. Summary

The designed engine is to be used primarily to propel a record-racing aircraft. Its goal is to exceed the current speed record of 890 km/h for a piston-powered aeroplane. It is planned to reach a speed of about 950 km/h, which is also the maximum speed that can be achieved by using a subsonic propeller.

The engine's operating indicators have been accurately calculated. Currently, individual parts are being designed and their graphic documentation is being prepared. The work currently carried out focuses on propulsion for a record-racing aeroplane. However, most parts will be able to be used in the version for propulsion of passenger or transport aeroplanes. Both variants differ primarily in the charge system.

At the same time, the presented comparative analysis shows that a two-stroke engine can achieve more favorable operating indicators than a turboprop engine. A racing aircraft capable of reaching record speeds could be a good demonstrator of the possibilities of such propulsion. However, this would require building its prototype and testing it in a specially designed aeroplane.

Theoretically, a two-stroke engine could be an alternative to a turboprop engine. However, turbine drives are now predominant in most applications. However, replacing them with another type of drive would require large financial outlays. It would be necessary to train mechanics to adapt the infrastructure for servicing piston engines. In addition, increasing the production and distribution of aviation gasoline would be necessary instead of aviation kerosene. Aero-engine manufacturers specializing in the construction of turbine engines would have to adapt their assembly lines, which would also generate costs.

A two-stroke engine offering favorable operating indicators would probably not displace widespread turbine drives. However, as part of the following project, several solutions are developed that can be used in smaller aeroplane engines. Attention can be drawn to the methods of generating additional thrust by cooling the engine with exhaust gases. In the presented concept, the propeller does not generate as much as 24% of the thrust. This would allow better use of engine power and thus more economical operation. An engine with less power could thus generate as much thrust as an engine with more power. The smaller drive unit has a lower weight, which would benefit the weight of the load or fuel carried by the aircraft. The two-stroke system has many advantages over the four-stroke system, such as simple construction, lower price, easy operation. In the face of numerous methods of using exhaust gas energy, their higher emission than four-stroke engines can be considered an advantage. Even the oil that is often found in them can have a beneficial effect on the mass flow and, consequently, the thrust power generated by the exhaust gas.

Another solution that could be widely introduced in aeroplane engines is the Anzani-Argus system. Its numerous advantages are described in the article. Reducing the weight and dimensions of the engine is very beneficial, not only in aviation. Designing a system requires a very precise determination of inertia masses. However, it should not be difficult with modern CAD programs. The use of the Anzani-Argus system is possible in boxer engines (which are also found in the automotive industry) and in the H system, which is treated as a combination of two such engines. However, it might be possible to adapt it to the radial system. In this case, using an even number of cylinders (six or eight) would be necessary. Opposite each other would be the master connecting rods: double and single between them. Link connecting rods would protrude from the master connecting rod. In this way, two "sets" of piston crank systems would be obtained, which would be, in a sense, their mirror image ("set" with single connecting rods in relation to "set" with double connecting rods). This could be described as a radial engine with opposing cylinders. A smaller number of pistons connected to one master connecting rod and, consequently, a smaller number of piston-connector assemblies on a single crank of the crankshaft could allow an increase in the rotational speed of the radial engine [29].

The presented concept of a two-stroke engine can not only drive racing and sports aircraft. According to the presented comparative analysis, it shows many advantages over the currently used turboprop drives. Therefore, it can be concluded that two-stroke engines could replace them, at least in some applications. Moreover, during the design work, many solutions were developed and investigated that could be used in general aviation aircraft and in the automotive industry.

Bibliography

[1] Angle GD. Airplane engine encyclopedia. Dayton: The Otterbein Press 1921.

[2] Bombardier Q400 Engine – PW150A. https://www.flyradius.com/bombardier-q400/engine-pw150a (accessed on 2024 Nov 25).

[3] Bridgman L. Jane's all the world's aircraft 1945/6. Newton Abbot: Sampson Low Marston & Company Limited 1946 (reprint 1970).

[4] Chmielniak TJ. Maszyny przepływowe (in Polish). Wydawnictwo Politechniki Śląskiej; Gliwice 1997.

[5] Connors J. The engines of Pratt & Whitney: a technical history. American Institute of Aeronautic and Astronomics, Inc. Reston 2010.

[6] EASA Type-Certificate Data Sheet, Pratt & Whitney Canada PW150 series 2014.

[7] Emisja spalin i hałas statków powietrznych. Certyfikacja w zakresie hałasu i emisji spalin (in Polish). https://www.ulc.gov.pl/pl/prawo/projekty/krajowe/136-departamenty/technika-lotnicza/80-emisja-spalin-i-halas-statkow-powietrznych (accessed on 2024 Nov 25).

[8] Environmental Report 2022: Aviation and the Environment. International Civil Aviation Organization (ICAO). Montreal 2022.

[9] Fayette TC. Aircraft propulsion, a review of the evolution of aircraft piston engines. Smithsonian Institution Press. Washington 1971.

[10] F8F-2 Bearcat "Rare Bear". lewisairlegends.com/f8f2-bearcat-rare-bear (accessed on 2024 Nov 10).

[11] Goodwin M, Starkings P. Japanese aero-engines 1910-1945. Stratus sp.j. Sandomierz 2017.

[12] Grabowski Ł, Karpiński P, Barański G. Experimental research of two stroke aircraft diesel engine. Combustion Engines. 2019;179(4):75-79. https://doi.org/10.19206/CE-2019-412

[13] Gunston B. The development of piston aero engines, from the Wrights brothers to microlights: a century of evolution and still a power to be reckoned with. Patric Stephens Ltd. Sparkford 1993.

[14] Gunston B. World encyclopedia of aero engines, all major aircraft power plants, from the Wright brothers to the present day. Patric Stephens Ltd. Sparkford 1998.

[15] Heywood JB. Internal combustion engine fundamentals. McGraw-Hill. New York 1988.

[16] Jędrzejowski J. Obliczanie tłokowego silnika spalinowego (in Polish). Wydawnictwa Naukowo-Techniczne. Warszawa 1988.

[17] Jones L. Sectioned drawings of piston aero engines. Rolls-Royce Heritage Trust. Derby 1995.

[18] Karta charakterystyki. Benzyna lotnicza WA UL 91 (in Polish). Warter Fuels 2019.

[19] Kusznierewicz Z. Metoda obliczania momentu tarcia w łożyskach tocznych kulkowych zwykłych niedociążonych. Pomiary Automatyka Kontrola. 2011;57(9):1063-1066.

[20] Lee DS, Fahey DW, Skowron A, Allen MR, Burkhardt U, Chen Q et al. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. Atmospheric Environment. 2018;244:117834. https://doi.org/10.1016/j.atmosenv.2020.117834

[21] Leonard J. A White Paper on XF-84H Propulsion. https://www.enginehistory.org/GasTurbines/Allison/XF-84/XF-84.shtml (accessed on 2024 Oct 13).

[22] Lumsden A. British piston aero-engines and their aircraft. Airlife Publishing Ltd. Shrewsbury1994.
[23] Łapiński M. Maszyny i urządzenia energetyczne (in Polish). Państwowe Wydawnictwa Szkolnictwa Zawodowego. Warszawa 1972.
[24] Mc Cutcheon KD. McCulloch Aircraft Engines. https://www.enginehistory.org/members/McCulloch.php (accessed on 2024 Nov 10).
[25] Nahum A, Foster-Pegg RW, Birch D. The Rolls-Royce Crecy. The Rolls-Royce Heritage Trust. Derby 2013.
[26] Opara R, Historia i tendencje rozwojowe napędów lotniczych. Combustion Engines. 2006;127(4):3-18. https://doi.org/10.19206/CE-117335
[27] Ochęduszko K. Koła zębate (in Polish). Wydawnictwa Naukowo-Techniczne. Warszawa 1985.
[28] Pełczyński J. Outline of history and comparative analysis of internal combustion engines for flying models. Combustion Engines. 2023;193(2):36-44. https://doi.org/10.19206/CE-155865
[29] Pełczyński J. Etapy historycznego rozwoju tłokowych silników lotniczych (in Polish). Master Thesis. Faculty of Civil and Transport Engineering. Poznan University of Technology. Poznan 2023.
[30] P-51 Voodoo najszybszy na świecie (in Polish). https://dlapilota.pl/wiadomosci/avweb/p-51-voodoo-najszybszy-na-swiecie (accessed on 2024 Nov 23).
[31] Republic XF-84H Thunderscreech. https://en.wikipedia.org/wiki/Republic_XF-84H_Thunderscreech (accessed on 2024 Nov 22).
[32] Rogers G, Mayhew Y. Engineering Thermodynamics: Work and Heat Transfer. Longman Scientific & Technical. New York 1992.
[33] Rychter T. Silniki dwusuwowe pojazdów (in Polish). Wydawnictwo Komunikacji i Łączności. Warszawa 1988.
[34] Smith H. Aircraft piston engines, from Manly Balzer to the Continental Tiara. McGraw-Hill Book Company 1981.
[35] Smith H. A history of aircraft piston engines. Sunflower University Press. Manhattan 1986.
[36] Strzelczyk P. Wybrane zagadnienia aerodynamiki śmigieł (in Polish). Oficyna Wydawnicza Politechniki Rzeszowskiej. Rzeszów 2011.
[37] Summary of ignition properties of jet fuels and other aircraft combustible fluids. Pittsburg 1975.
[38] Swopes BR. Tupolev Tu-114 Rossiya. https://www.thisdayinaviation.com/tag/tupolev-tu-114-rossiya (accessed on 2024 Nov 23).
[39] Szczeciński S. Lotnicze silniki tłokowe (in Polish). Wydawnictwo Ministerstwa Obrony Narodowej. Warszawa 1969.
[40] Walentynowicz J. The aircraft engines in the land vehicles, Combustion Engines. 2021;187(4):52-59.
[41] Wisłocki K. Systemy doładowania szybkoobrotowych silników spalinowych (in Polish). Wydawnictwo Komunikacji i Łączności. Warszawa 1991.
[42] Wisniewski J. Powering the Luftwaffe, German aero engines of World War II. Friesen Press. Victoria 2013.
[43] Wiśniewski S. Termodynamika Techniczna (in Polish). Wydawnictwa Naukowo-Techniczne. Warszawa 2023.
[44] Worobiow P. Teoria silników lotniczych (in Polish). Wydawnictwo Ministerstwa Obrony Narodowej. Warszawa 1951.
[45] Zariczny P. Modelowanie zasilania łożyska ślizgowego olejem z wykorzystaniem prowadnicy hydrodynamicznej (in Polish). Doctoral Thesis. Gdansk Univeristy of Technology. Gdańsk 2007.
[46] Zestawienie aktualnych cen paliw lotniczych na polskich lotniskach (in Polish). https://dlapilota.pl/aktualizacja-ceny-paliw-lotniczych-na-polskich-lotniskach (accessed on 2024 Nov 23).
[47] 65S2WA – stal sprężynowa (in Polish). https://virgamet.pl/oferta/65s2wa-65s2va-65s2gwa-65s2gva-652sw-stal-sprezynowa (accessed on 2024 Oct 15).

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