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Systems for generating thrust force outside the propeller

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This article presents conclusions on the potential to improve the operational indicators of piston aircraft engines by using thrust-generation systems outside the propeller. In this case, energy normally lost as emitted heat and exhaust kinetic energy is utilized through a proprietary flow channel design, which is significantly more efficient than previously used confusor-based solutions. The analysis is based on ongoing design work. To further illustrate the issue, calculations for an existing aircraft engine and its impact on operational indicators are also presented. The article provides a computational procedure as a basis for further research and reports favorable results.

Key words: *aircraft piston engines, thrust force, thrust force generation systems, operational indicators*

1. Introduction

Piston aircraft engines have not been significantly developed since the 1950s. The use of modern structural analysis tools and new design solutions enables better development of the propulsion system than in the 1950s [25]. Based on the engine design, two versions were developed: a record-breaking racing engine that would allow for breaking the speed record for piston-powered aeroplane and for aeroplane in which the main source of thrust is a classic, subsonic propeller [27, 48], and a version that could be an alternative to turboprop engines [27].

Based on the designs, solutions are developed to significantly improve the operational indicators of piston aircraft engines, including the power-to-weight and thrust-to-weight ratios. These solutions can be used for various applications, but simply adapting them to currently produced piston aircraft engines can significantly improve the propulsion's operational parameters, and therefore aeroplane's performance. At the same time, while maintaining the same engine power, significantly greater thrust can be achieved with less mass [27].

The article will discuss the concept of a thrust-generating system outside the propeller, along with the calculation procedure. Based on the calculated system parameters, the thrust force will be determined, which, in turn, will enable a comparative analysis.

2. Using propeller propulsion in high-speed flights

Currently, piston engines have given way to turbine propulsion in most aviation applications. They are still used in light aircraft, which usually do not exceed 300–400 km/h [43]. Similar to turboprop engines, the propeller is powered by the engine, which results in similar theoretical speed limitations for both types [22, 27].

The highest officially recognized speed of a propeller-driven aeroplane is held by the Tu-114, at 877 km/h [39]. Unofficially, this record was broken by the experimental Republic XF-84H, which reached 1080 km/h [18, 30] thanks to special propellers designed to work in supersonic conditions. However, their considerable noise made them impractical for use. Theoretically, they were supposed to allow a plane to break the sound barrier.

Among piston-engine aeroplane, the speed record for a very long time was held by the Rare Bear, a modified Grumman F8F Bearcat, which reached 850 km/h [7]. In 2017, the record was broken by a specially prepared P-51 Mustang "Voodoo", reaching 893 km/h [26].

The main obstacle to increasing the speed of propeller-driven aeroplane remains the decrease in propeller efficiency as it approaches the speed of sound [37] – most classic designs lose significant efficiency at M > 0.7–0.8. The propeller blade speed is a component of two velocities: the linear velocity of the propeller blades and the forward velocity of the aeroplane, so in reality it is greater than the speed perpendicular to its radius [37].

One way to limit the problem is to reduce the propeller's rotational speed so that the tips of the blades do not exceed Mach 1. Assuming the speed of sound is 1200 km/h, it can be estimated that classic propellers do not allow for flights faster than 900–950 km/h. For a 4 m propeller, the rotational speed would have to decrease to about 1000 rpm. Further reductions would require more complex gears, increasing the weight and reducing the mechanical efficiency of the entire system [27]:

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

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

3. General concept

To develop methods for improving operational indicators, it is necessary to rely on data derived from calculations of the designed engine. Developing its concept, along with determining masses and operational indicators, allows for developing appropriate improvement methods and comparing the advantages of solutions that generate thrust outside the propeller. At the same time, theoretical development of the propulsion system can confirm the thesis that a properly designed two-stroke engine with thrust-generating systems outside the propeller can provide operational indicators comparable to or better than those of turboprop engines [27].

Additionally, a second version of the engine is presented, which may enable setting a speed record for aircraft with a piston engine and a classic propeller. The planned speed is 950 km/h at an altitude of 3000 m. Due to the key requirements, the most important features are the highest possible power and thrust with the lowest possible weight and a simplified design. These are important features compared to turboprop engines. Therefore, a two-stroke cycle [9] is planned, which allows a higher power density than in a four-stroke engine. Unlike the complex Rolls-Royce Crecy or Napier Nomad [23] engine, the planned design will not have a complex valve train to reduce weight [41]. Instead of liquid cooling, air cooling will be used, and lightweight materials will be used in the construction, with limited use of aluminum in favor of titanium and magnesium alloys (Fig. 1 and Fig. 2) [27].

The article will present the advantages of the proposed system for generating thrust outside the propeller, based on the engine design and on sample calculations for the existing propulsion system.

The adopted engine displacement is 32 dm^3, and the estimated rotational speed is 7000 rpm. For efficient air cooling, there should be no more than four cylinders in a row [28], allowing several systems to be considered: double- and triple-row radial, H and X systems. Despite the air-cooling system being favorable, radial engines do not reach high rotational speeds [28]. This is due to the large mass concentrated on a single crankpin of the crankshaft and the small number of simultaneous ignitions. The X system with a single shaft is more suitable, but the H system allows for crankcase scavenging (the Schnürle system was chosen) (Fig. 3) [33], which allows the mechanical compressor to be dispensed with and only the turbocharger to be used for supercharging [27]. The H system, in this case two connected engines with an opposed-cylinder arrangement, also allows for better balancing and reduced balancing masses [27].

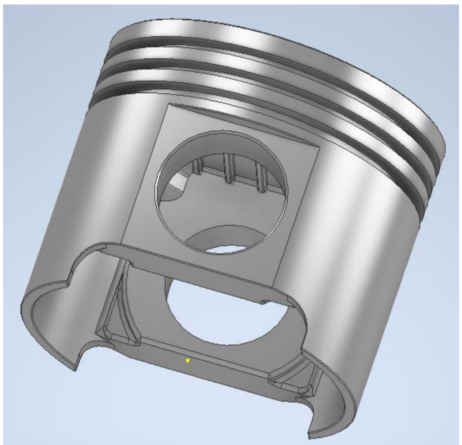

Fig. 1. Engine piston, which can be made of magnesium alloy WE43A or Al-Si casting alloy AK12 AK12

Both crankshafts will be connected by a helical gear (ratio 1:7), which will also serve as an rpm reducer. Due to the dimensions of the large gear, it will be moved above the shaft line [24], forcing the entire engine to be rotated by 90°, with two rows of vertical cylinders and two rows of overhead cylinders [27].

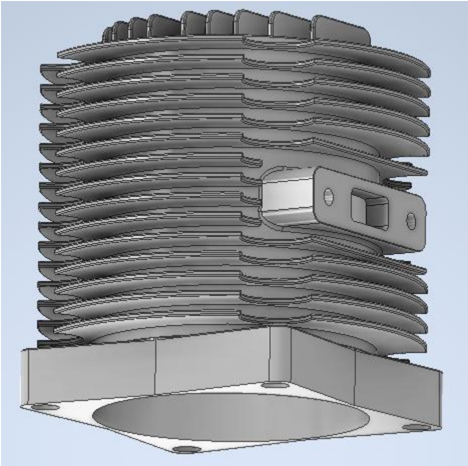

Fig. 2. One of the engine heads made of WE43A magnesium alloy

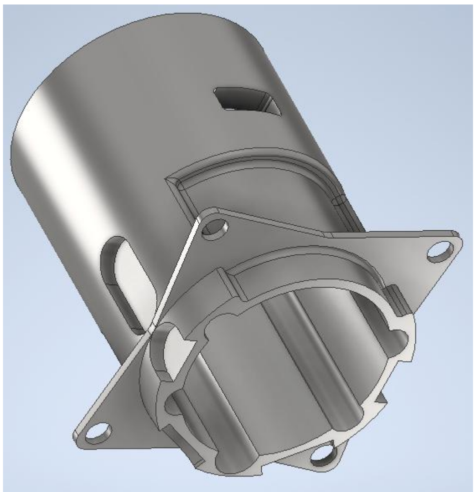

Fig. 3. Cylinder of the designed engine made of 36NiCrMo16 steel; the intake ducts are visible on the inner surface

For the racing version of the engine, a mechanical supercharger with an electric drive is planned, which is activated only when breaking a record. The aircraft's maximum speed would be achieved at an altitude of 3000 m, where the pilot does not need an oxygen system and air resistance is lower than at sea level. The compression ratio of the supercharger should be $\pi = 4.2$. Additionally, the engine will be supported by a turbocompound system, providing 25.4% additional power through a gear connected to the crankshafts [3, 23, 27, 44].

The transport version would require a supercharging system capable of operating throughout the flight. The turbocompound turbine would be smaller, contributing 18% to engine power. It would also drive the second-stage turbocharger. The first stage would be a conventional turbocharger, not connected to the crankshafts. The total pressure ratio would depend on altitude: $\pi = 2.77$ at sea level, $\pi = 4$ at 3000 m, and $\pi = 7.34$ at 7500 m. Compressor pressure would be varied by exhaust gas bleed. This would maintain constant power over a wide altitude range. During operation, the engine would be continuously boosted by both the power turbine and the turbochargers [27].

To increase thrust, the entire propulsion system will be placed in a special channel. The air cooling the engine would take up some of the heat, increasing its flow velocity, and then it would combine with the exhaust gases, which would increase the kinetic energy in the channel. The outlet directed toward the rear of the aircraft would generate additional thrust force [27].

4. Anzani-Argus connecting rod system

To simplify the crankshaft design, reduce its mass, and improve dynamic balance, a connecting-rod system was used, based on solutions tested in aircraft engines with a set of opposite cylinders developed by Anzani and Argus in the 1930s [36]. Therefore, it is justified to call it the Anzani-Argus system. Thanks to its design, the gas forces in the opposing piston-connecting rod systems (Fig. 4 and Fig. 5) completely balance each other, as demonstrated by the analysis of bending moment distribution in the crank-piston system [40, 47].

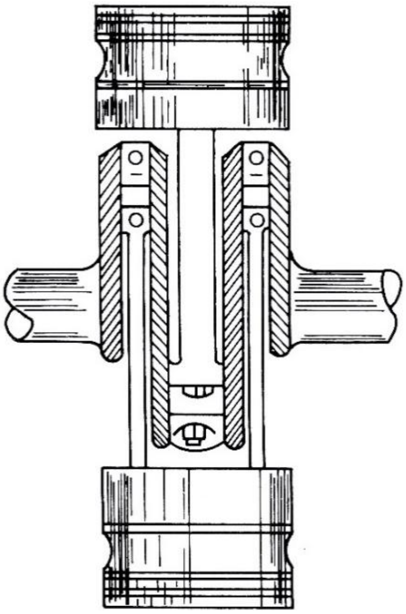

Fig. 4. Anzani-Argus connecting rod system [35]

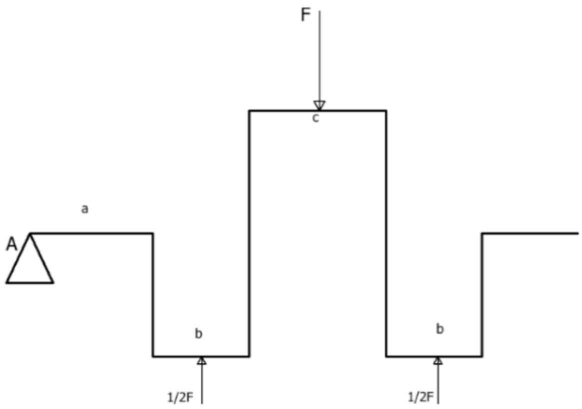

Fig. 5. Distribution of forces in the Anzani-Argus system

$$\sum_{M_{gA}} = 0 \quad (2)$$

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

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

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

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

It is important to balance the forces resulting from the inertia of moving elements, which was probably the main design challenge during the 1930s experiments conducted by the mentioned companies. For various reasons, the tests were not completed at that time – the Anzani company went bankrupt, while Argus focused on producing power units for Luftwaffe aeroplanes [36, 45]. However, with CAD programs, it is possible to accurately determine the masses on both sides of the crankshaft axis, which greatly facilitates balancing the entire system [27].

The discussed system also has the advantage of allowing the crankshaft to be shortened, and consequently the total length of the engine. This is possible because the opposing connecting rods are not offset relative to each other along the crankshaft. The presented calculations showed that the bending moments of the forces in the piston-crank system acting on the crankshaft are balanced within the piston pair, so the rest of the shaft is not loaded with additional bending moments, but only with the torsional moment and any torques from the speed reducer [27].

Significant forces within the pair must be transferred to the shaft journals and crank arms. This requires their larger dimensions and the use of materials with high bending strength. In this case, 65S2WA alloy steel was selected, with a yield strength of R_e = 1665 MPa [51], which ensures adequate bending resistance under demanding operating conditions.

5. Basic operational indicators of a piston engine

The basic operational indicator characterizing a piston engine is its power. This allows for estimating values such as the power-to-weight ratio and the power-to-displacement ratio. Based on Jędrzejowski's publication *Calculations of a Piston Combustion Engine* [13], a simple comparison of engine power as a function of compression ratio was developed, accounting for the cylinder temperature during compression and thus the risk of advanced ignition. Aviation gasoline 115/145, with a self-ignition temperature of 744 K [38], allows for the use of a compression ratio of ε = 10 in a record-breaking aircraft engine. However, when designing an engine version intended for passenger aircraft, this fuel proves impractical due to its high cost. For this reason, it is justified to use 100LL gasoline, with an auto-ignition temperature about 30 K lower than 115/145 or cheaper [50], or unleaded UL91 [15], with an auto-ignition temperature about 100 K lower. To avoid major differences between the two engine versions, it was decided to keep the same compression ratio. At the same time, this necessitates the addition of an additional charge air cooler and the extension of the intake system pipes [10].

During the calculations, the efficiencies of the gears and piston-cylinder assemblies were accounted for. When determining power losses due to friction in forty plain bearings and twelve rolling bearings, the friction coefficients given in the literature [16, 49] were used, which allowed for a more precise estimation of the engine's effective power than in the case of assuming a constant value of mechanical efficiency based on the literature [13]. Based on the calculations, the overall efficiency was determined to be η_o = 29.94% for the racing engine and η_o = 29.66% for the transport aeroplanes engine. It was calculated according to the formula [13]:

$$\eta_o = \frac{P_e \cdot V_s}{W_u} \tag{7}$$

where: P_e – effective pressure (741 750.2 Pa for racing engine and 734893.3 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 accurately determine the power-to-weight ratio, the actual mass of the entire engine must be known, which is only possible after the design phase is completed. For the comparative analysis, an approximate mass of 550 kg was assumed, based on previous design work and literature data covering many existing designs [1, 8, 11, 14, 19, 21, 27, 28, 42]. Based on the calculations [13], the most important operational indicators were identified. The table presents both the engine version for powering a high-performance aircraft and the engine version intended as a hypothetical power source for commercial aircraft (Table 1). Cruise values are not provided for the racing version, as only maximum power is important for breaking records. The cruise power of the commercial aircraft engine was determined at 90% of the maximum speed, i.e., 6300 rpm [27].

Table 1. Operational indicators of the designed engine

Engine	Racing	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 m^3/h

6. Thrust force generated outside the propeller

To determine the thrust generated outside the propeller, it is important to take into account that calculations and considerations must be conducted separately for both versions of the engine, however, some characteristic features will be common to both versions. The thrust will be generated by a flow channel, inside which the engine will be located, giving off its heat to the air flowing around it, and an exhaust outlet in the shape of a convergent pipe that increases the speed of the exhaust gases. The exhaust gases mix with the air in the flow channel, which would further increase the flow rate by giving up some of their kinetic and thermal energy. An accelerated stream of air mixed with exhaust gases would generate additional thrust, in addition to the propeller [27].

The method of generating thrust using the kinetic energy of exhaust gases was widely used during World War II. An example is the Rolls-Royce Merlin engine, with a displacement of 26 dm^3 [1, 19], in which the exhaust gases were accelerated at the outlet to 580 m/s. This allowed approximately 0.67 kN of thrust to be generated [23]. This is approximately equivalent to 188 hp, assuming that, due to propeller efficiency, 80% of the engine power is converted to thrust. A similarly sized experimental two-stroke Rolls-Royce Crecy engine generated 1.4 kN of thrust in the same way [23]. This also demonstrates the advantage of two-stroke engines in aviation, which not only can achieve higher power but also emit more exhaust gases, the kinetic energy of which can be used to increase the thrust of the powerplant. At the same time, the higher exhaust energy allows for more efficient use of the turbocharger and power turbine. Another example is the Rolls-Royce Crecy, in which the power turbine increased maximum power by 54% [23].

First, the thrust of the racing engine will be determined. To do this, several assumptions must be made (Table 2).

Table 2. Parameters assumed to calculate the mass flow rate in the flow channel for the racing engine version

Fuel consumption	G_e = 1007.62 l/h = 0.2805 l/s
Theoretical amount of air required to burn 1 kg of fuel	M_t = 15
Air-fuel ratio	λ = 0.9
Gasoline density	ρ = 0.72 kg/dm^3

Based on the data in the table, the exhaust gas mass flow can be determined, taking into account the approximately 3% oil content in the fuel mixture [12, 31].

$$\dot{m}_{pa} = G_e \cdot \rho = 0.2805 \cdot 0.72 = 0.202\ \mathrm{kg/s} \tag{8}$$

$$\dot{m}_p = \dot{m}_{pa} \cdot M_t \cdot \lambda = 0.202 \cdot 15 \cdot 0.9 = 2.727\ \mathrm{kg/s} \tag{9}$$

$$\dot{m}_{sp} = 1.03 \cdot (\dot{m}_{pa} + \dot{m}_p) = 1.03 \cdot (0.202 + 2.727) = 3.017\ \mathrm{kg/s} \tag{10}$$

where: $\dot{m}_{pa}$ – fuel mass flow, ρ – aviation gasoline density, $\dot{m}_p$ – air mass flow rate through the engine, $\dot{m}_{sp}$ – air mass flow.

Assuming that the aircraft is traveling at a speed of 950 km/h and that air enters the flow channel at this speed and the engine releases heat to the environment through direct cooling, then based on the energy balance, its effect on the temperature of the air flowing around it would be approximately ΔT = 21 K [12]. Assuming the air temperature at an altitude of 3000 m is T_p = 268 K, after heating, T_1 = 289 K, allowing the flow velocity to increase to v_p = 285 m/s. Using the data from the table (Table 3), further calculations can be performed. The exhaust gas velocity at the outlet was assumed to be v_s = 450 m/s. The weighted-average velocity of the mixing exhaust gas and air, based on their mass flow rates, is v_2 = 293 m/s (Fig. 6) [2].

Table 3. Assumptions needed to calculate the thrust for the racing version of the engine

Flight speed (at 3000 m altitude)	v_1 = 950 km/h = 264 m/s
Channel inlet area	A = 0.4 m^2
Air mass flow rate	$\dot{m}_p$ = 96 kg/s
Air heating by the engine	ΔT = 21 K
Air temperature after heating	T_1 = 289 K
Air velocity after heating	v_p = 285 m/s
Exhaust mass flow rate	$\dot{m}_s$ = 3.017 kg/s
Exhaust velocity at the convergent pipe outlet (minimum design value)	v_s = 450 m/s
Weighted average of air and exhaust velocity	v_2 = 293 m/s
Exhaust temperature based on calculations	T_s ≈ 1050 K
Air density at 3000 m altitude	ρ_1 = 0.909 kg/m^3

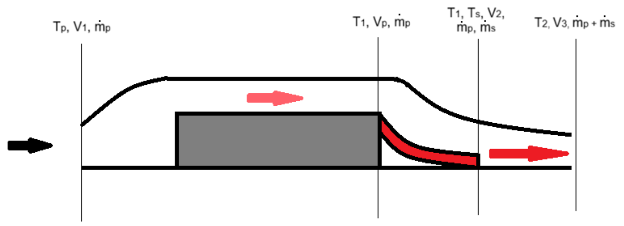

Fig. 6. System generating thrust operation diagram; the first section from the left shows inlet parameters; the second shows parameters directly after the engine (gray); the third shows the moment when exhaust fumes leave the exhaust system (red); and the fourth section shows outlet parameters when the air and exhaust streams have mixed

Based on additional data, the effect of exhaust temperature at the outlet of the piston engine's exhaust system can be determined. Based on the further energy balance, the average air and flue gas temperature in the duct can be determined as T_2 = 313 K. Based on the continuity of the flow, the continuity equation:

$$\frac{\rho_1}{\rho_2} = \frac{T_2}{T_1} = \frac{313}{289} = 1.083 \quad (11)$$

$$\rho_2 = \frac{\rho_1}{1{,}083} = 0.839\ \text{kg/m}^3 \quad (12)$$

$$\frac{v_3}{v_2} = \frac{(\dot{m}_p + \dot{m}_s) * \rho_1}{\dot{m}_p * \rho_2} = 1.117 \quad (13)$$

$$v_3 = v_2 \cdot 1.117 = 323\ \text{m/s} \quad (14)$$

where: ρ_2 – density of mixed air and exhaust gases, v_3 – the velocity of the mixed air and exhaust gases at the end of the flow channel.

Based on the determined velocities and mass flow rates, the thrust generated in the flow channel can then be calculated. First, for the exhaust gas mass flow rate itself:

$$F_s = \dot{m}_{sp} \cdot v_3 = 3.017 \cdot 323 = 975.4\ \text{N} \quad (15)$$

The total air and exhaust thrust can be calculated using the momentum change formula, which in this case will have the form [12, 20, 46]:

$$F = (\dot{m}_p \cdot v_3) - (\dot{m}_p \cdot v_1) + F_s = 6667.74\ \text{N} \approx 6.67\ \text{kN} \quad (16)$$

The exhaust gas velocity at the convergent pipe outlet of 450 m/s is not high compared to other engines [23]. When it is increased to 550 m/s, the weighted average of the air velocity after heating behind the engine and the exhaust gases is v_2 = 293 m/s. Using the same calculation procedure, the velocity will be v_3 = 327 m/s. Naturally, the thrust will be higher and equal to:

$$F_s = \dot{m}_{sp} \cdot v_3 = 3.017 \cdot 327 = 985.66\ \text{N} \quad (17)$$

$$F = (\dot{m}_p \cdot v_3) - (\dot{m}_p \cdot v_1) + F_s = 7004.38\ \text{N} \approx 7\ \text{kN} \quad (18)$$

A transport or passenger aeroplane typically achieves lower flight speeds than those assumed for a racing aeroplane. For the purposes of this calculation, a maximum speed for such an aircraft was assumed at 750 km/h. The flight altitude was assumed to be 7500 m. Some assumptions must be established first (Table 4):

Table 4. The adopted parameters necessary to calculate the mass flow in the flow channel for an engine of a transport aeroplane

Fuel consumption	G_e = 943.58 l/h = 0.2621 l/s
Theoretical amount of air required to burn 1 kg of fuel	M_t = 15
Air-fuel ratio	λ = 0.9
Gasoline density	ρ = 0.72 kg/dm^3

The exhaust gas mass flow calculated according to the same calculation procedure will be:

$$\dot{m}_{pa} = G_e \cdot \rho = 0.2621 \cdot 0.72 = 0.202\ \text{kg/s} \quad (19)$$

$$\dot{m}_p = \dot{m}_{pa} \cdot M_t \cdot \lambda = 0.189 \cdot 15 \cdot 0.9 = 2.552\ \text{kg/s} \quad (20)$$

$$\dot{m}_{sp} = 1.03 \cdot (\dot{m}_{pa} + \dot{m}_p) = 1.03 \cdot (0.189 + 2.552) = 2.823\ \text{kg/s} \quad (21)$$

Based on the energy balance, the effect of the engine on the air temperature around it is approximately ΔT = 38 K [12]. Assuming the air temperature at an altitude of 7500 m is T_p = 245 K, after heating it will be T_1 = 283 K. This will allow the flow velocity to increase to v_p = 240 m/s. The exhaust velocity of the piston engine was set to v_s = 450 m/s. The weighted-average speed of the mixing exhaust and air, based on their mass flows, is v_2 = 252 m/s. Here, the necessary parameters for further thrust force calculations will also be presented in Table 5 [2].

The additional thrust generated by heated air flowing through the charge air coolers should also be considered. Due to the inferior properties of UL91 and 100LL gasolines compared to 115/145 gasoline, two intercoolers are required. The engine design does not currently include a detailed supercharger system. However, it is possible to rely on some approximations. The cross-section of both intercoolers can be defined as A_c = 0.1 m^2. According to the design, after the first stage of the compressor, the air temperature will be 358 K. Assuming that the first intercooler must absorb a temperature of 60 K, the air flowing through it as a cooling agent will increase its temperature by approximately ΔT_{c1} = 27 K. Its density after passing through the intercooler can then be determined using the ideal gas equation and the proportion of the velocity behind the cooler. This can be determined as v_{c1} = 230.5 m/s. The thrust generated by the air flowing through the radiator will be:

$$\dot{m}_c = A_c \cdot v_1 \cdot \rho_1 = 12.27 \frac{kg}{s} \quad (22)$$

$$F_{c1} = (\dot{m}_{c1} \cdot v_{c1}) - (\dot{m}_{c1} \cdot v_1) = 276.08\ N \quad (23)$$

where: $\dot{m}_c$ – air mass flow through the intercooler.

Table 5. Assumptions needed to calculate the thrust for the engine version of the transport aeroplane

Flight speed (at 7500 m altitude)	v_1 = 750 km/h = 208 m/s
Channel inlet area	A = 0.4 m2
Air mass flow rate	ṁp = 49.1 kg/s
Air heating by the engine	ΔT = 38 K
Air temperature after heating	T_1 = 283 K
Air velocity after heating	v_p = 240 m/s
Exhaust mass flow rate	$\dot{m}_s$ = 2.823 kg/s
Exhaust velocity at the convergent pipe outlet (minimum design value)	v_s = 450 m/s
Weighted average of air and exhaust velocity	v_2 = 252 m/s
Exhaust temperature based on calculations	T_s ≈ 950 K
Air density at 7500 m altitude	ρ_1 = 0.59 kg/m^3

The second intercooler cools the air after the second compressor stage from 377 K to 337 K. The temperature change of the air flowing through the condenser will change by ΔT_{c2} = 18 K. Based on the same calculation procedure as before, the air velocity after the condenser will be v_{c2} = 223.3 m/s. The obtained thrust force can thus be calculated:

$$\dot{m}_c = A_c \cdot v_1 \cdot \rho_1 = 12.27 \frac{kg}{s} \quad (24)$$

$$F_{c1} = (\dot{m}_{c2} \cdot v_{c2}) - (\dot{m}_{c2} \cdot v_{c2}) = 187.73\ N \quad (25)$$

In the same way as for the racing version of the engine, the effect of the exhaust gas temperature at the outlet of the exhaust system of a piston engine can be determined. It can be assumed that the exhaust gas temperature at the exhaust system outlet will be approximately 200 K lower. The temperature of the air in the flow channel mixed with the exhaust gas will therefore be approximately T_2 = 310 K. Based on the flow continuity equation:

$$\frac{\rho_1}{\rho_2} = \frac{T_2}{T_1} = \frac{310}{283} = 1.095 \quad (26)$$

$$\rho_2 = \frac{\rho_1}{1{,}095} = 0.539\ kg/m^3 \quad (27)$$

$$\frac{v_3}{v_2} = \frac{(\dot{m}_p + \dot{m}_s) \cdot \rho_1}{\dot{m}_p \cdot \rho_2} = 1.156 \quad (28)$$

$$v_3 = v_2 \cdot 1.156 = 292\ m/s \quad (29)$$

Based on the determined speeds and mass flows, the thrust generated in the flow channel is calculated. First, for the exhaust mass flow itself:

$$F_s = \dot{m}_{sp} \cdot v_3 = 2.823 \cdot 292 = 825.03\ N \quad (30)$$

The total air and exhaust gas thrust can be calculated using the momentum change formula, which in this case will have the form [13, 41]:

$$F = (\dot{m}_p \cdot v_3) - (\dot{m}_p\ x\ v_1) + F_s + F_{c1} + F_{c2} = \\ = 5424.67\ N \approx 5.42\ kN \quad (31)$$

By increasing the exhaust gas outlet velocity from the convergent pipe to 550 m/s, the flow velocity in the duct will increase. The weighted average of the air and exhaust gas velocities will be v_2 = 257 m/s. Using the same calculation procedure, the velocity will be v_3 = 299 m/s. The thrust force will change as calculated:

$$F_s = \dot{m}_{sp} \cdot v_3 = 2.823 \cdot 299 = 842.85\ N \quad (32)$$

$$F = (\dot{m}_p \cdot v_3) - (\dot{m}_p \cdot v_1) + F_s + F_{c1} + F_{c2} = \\ = 5752.36\ N \approx 5.75\ kN \quad (33)$$

7. Comparative analysis with turboprop engines

Assuming an efficiency of 80% for the propeller, the thrust it generates can be determined. For a racing engine, this would be 11.17 kN at a flight speed of 950 km/h, and for the passenger and transport version, 13.16 kN at a flight speed of 750 km/h. The passenger and transport versions will be further compared. The comparative object will be the Pratt & Whitney PW 150A turboprop engine (Fig. 7) [4]. According to the manufacturer, it delivers 5142.16 hp (3781 kW) [4]. Assuming it would move at the same speed as the two-stroke engine of 750 km/h, its propeller would generate a thrust of 14.55 kN. At the same time, thanks to the exhaust energy, it gains an additional 3.75 kN of thrust. A detailed comparison is shown in Table 6.

Fig. 7. Pratt & Whitney PW 150A engine [29]

Table 6. Comparison of the designed two-stroke engine with the PW 150A engine

Engine	Designed a two-stroke engine	PW 150A
Power	4652.04 hp (3420.61 kW)	5142.16 hp (3781 kW)
Mass	Approximately 550 kg	717 kg
Fuel consumption	943.58 dm^3/h or 669.94 kg/h	740 dm^3/h or 592 kg/h
Propeller thrust at 750 km/h	13.16 kN	14.55 kN
Thrust obtained from exhaust gases	5.75 kN	3.75 kN
Thrust of the entire power unit	18.91 kN	18.3 kN

Two completely different engines are being compared. Although the PW 150A delivers approximately 11% more power, its thrust is reduced by more than 3%. This is due to the use of a properly shaped channel that captures almost all the energy lost in piston engines, i.e., the energy of exhaust gases and the thermal energy given off to the environment, excluding friction losses. The fuel volume consumption is lower for the PW 150A. However, aviation kerosene has a higher density than gasoline, which results in a smaller difference in fuel consumption [27].

To provide a more meaningful comparison of both propulsion systems, specific indicators will be compared, allowing a more effective determination of the hypothetical suitability of two-stroke engines as an alternative to turboprop propulsion, as presented in Table 7. To better illustrate fuel consumption, not only the specific fuel consumption will be compared, but also the specific fuel consumption in relation to thrust, calculated using the following formula:

$$g_c = \frac{G_e}{F} \tag{34}$$

where: g_c – specific fuel consumption in relation to thrust, G_e – hourly fuel consumption, F – thrust of the entire power unit.

Table 7. Comparative characteristics of the specific indicators of the two-stroke engine concept with the PW 150A turboprop engine

Engine	Designed a two-stroke engine	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
Specific fuel consumption in relation to thrust	0.0499 dm^3/Nh or 0.0354 kg/Nh	0.0404 dm^3/Nh or 0.323 kg/Nh
The ratio of the power unit's thrust to the engine's weight	34.38 N/kg	25.52 N/kg
Ratio of power unit thrust to engine power	5.53 N/kW	4.84 N/kW

The specific indicators presented in the table demonstrate the advantage of the two-stroke engine over the turboprop. It is characterized by greater maximum power per unit of mass. The thrust-to-weight ratio is even more favorable. The engine under development also demonstrates improved power utilization in generating thrust, the most important indicator of aircraft propulsion. The main disadvantage is high fuel consumption. This would require in-depth economic analyses, taking into account the specific engine application and the type of operations performed.

If the racing version of the engine were used for comparison, the comparative performance would be even more favorable. For example, the 9.12 hp/kg figure is over 30% higher than the 7.17 hp/kg of the PW 150A engine.

Environmental factors are also important. While CO_2 emissions may be comparable to those of a turbine engine, unleaded UL91 gasoline will generate fewer particulates and nitrogen oxides during combustion [5, 17]. Therefore, using appropriately designed piston engines using UL91 gasoline instead of turboprop engines may be a simple and ecological solution leading to better environmental protection and compliance with increasingly stringent emission regulations.

8. Application of a thrust generation system outside the propeller in a four-stroke engine adapted for this purpose

The developed solution can potentially be easily adapted to existing engines. Most general aviation aircraft are powered by four-stroke engines [43], which is why this will be the model chosen for comparison in this article. It will be the latest product from Rotax – the 916 iS [52] (Table 8).

Table 8. Rotax 916 iS engine basic operating indicators [32, 52]

Maximum rpm	5800 rpm
Maximum power	160 hp (117 kW)
Maximum cruising power	137 hp (101 kW)
Weight	86 kg
Displacement volume	1.35 dm^3
Power to weight ratio	1.86 hp/kg
Power to displacement ratio	118.52 hp/dm^3
Fuel consumption when operating at maximum power	49 dm^3/h = 0.0136 dm^3/s
Specific fuel consumption when operating at maximum power	0.29 kg/kWh

For the Rotax 916 iS, a similar calculation procedure will be performed as for the designed two-stroke engine. It was assumed that the method of generating additional thrust would be the same as in the racing version of the previously analyzed propulsion unit. λ=1 was assumed. Based on the data from the table, the exhaust mass flow rate can be determined [12, 31].

$$\dot{m}_{pa} = G_e \cdot \rho = 0.0136 \cdot 0.72 = 0.0098\ \text{kg/s} \tag{35}$$

$$\dot{m}_p = \dot{m}_{pa} \cdot M_t \cdot \lambda = 0.0098 \cdot 15 \cdot 1 = 0.147\ \text{kg/s} \tag{36}$$

$$\dot{m}_{sp} = \dot{m}_{pa} + \dot{m}_p = 0.0098 + 0.147 = 0.157\ \text{kg/s} \tag{37}$$

where: $\dot{m}_{pa}$ – fuel mass flow, ρ – density of aviation gasoline, $\dot{m}_p$ – air mass flow through the engine, $\dot{m}_{sp}$ – exhaust mass flow.

Assuming that the aircraft is traveling at a speed of 300 km/h and that air enters the flow channel at this speed and the engine releases heat to the environment through direct cooling, then based on the energy balance, its effect on the temperature of the air flowing around it would be approximately ΔT = 3.21 K [12]. Assuming the air temperature at an altitude of 3000 m is T_p = 268 K, after heating it will be T_1 = 272 K, allowing the flow velocity to be increased to v_p = 84.3 m/s. Further assumptions, as in the case of calculations for a two-stroke engine, are given in Table 9. The exhaust gas velocity at the outlet was assumed to be v_s = 500 m/s. The weighted-average velocity of the mixing exhaust gas and air, based on their mass flow rates, is v_2 = 88.6 m/s [2].

Based on the energy balance, the average air and exhaust gas temperature in the channel is T_2 = 277 K. According to the flow continuity equation:

$$\frac{\rho_1}{\rho_2} = \frac{T_2}{T_1} = \frac{277}{272} = 1.018 \tag{38}$$

$$\rho_2 = \frac{\rho_1}{1{,}018} = 0.89\ \text{kg/m}^3 \tag{39}$$

$$\frac{v_3}{v_2} = \frac{(\dot{m}_p + \dot{m}_s)\cdot\rho_1}{\dot{m}_p\cdot\rho_2} = 1.028 \tag{40}$$

$$v_3 = v_2 \cdot 1.028 = 91.1\ \text{m/s} \tag{41}$$

where: ρ_2 – density of mixed air and exhaust gases, v_3 – the velocity of the mixed air and exhaust gases at the end of the flow channel.

Table 9. Assumptions needed for calculations of the Rotax 916 iS engine

Flight speed (at 3000 m altitude)	v_1 = 300 km/h = 83 m/s
Channel inlet area	A = 0.2 m^2
Air mass flow rate	$\dot{m}_p$ = 0.147 kg/s
Air heating by the engine	ΔT = 3.21 K
Air temperature after heating	T_1 = 272 K
Air velocity after heating	v_p = 84.3 m/s
Exhaust mass flow rate	$\dot{m}_s$ = 0.157 kg/s
Exhaust velocity at the convergent pipe outlet (minimum design value)	v_s = 500 m/s
Weighted average of air and exhaust velocity	v_2 = 88.6 m/s
Exhaust temperature based on calculations	T_s ≈ 700 K
Air density at 3000 m altitude	ρ_1 = 0.909 kg/m^3

Next, the thrust force calculations are performed according to the same procedure:

$$F_s = \dot{m}_{sp} \cdot v_3 = 0.157 \cdot 91.1 = 14.3 \text{ N} \quad (42)$$

The total air and exhaust thrust can be calculated using the momentum change formula, which in this case will have the form [12, 20, 46]:

$$F = (\dot{m}_p \cdot v_3) - (\dot{m}_p \cdot v_1) + F_s = 137 \text{ N} \approx 0.14 \text{ kN} \quad (43)$$

Assuming a propeller efficiency of 80% at a speed of 300 km/h, it would generate 1.13 kN of thrust. With the tested and calculated system, the powerplant thrust would be 1.27 kN, over 12% higher. However, this value is approximate, as it would require a more detailed analysis of the exhaust gas temperature at the end of the exhaust system. The presented example demonstrates the capabilities of the tested system. Although the greatest increase in thrust is achieved in two-stroke engines, it can be applied to four-stroke engines as well. It only requires appropriately shaping the exhaust system and designing a suitable flow channel within the aircraft.

Summary

Thermodynamic calculations of the engine were performed, along with the determination of its operational indicators. Using the obtained data, the thrust generated by the designed flow channel outside the propeller was determined. The solutions being developed allow for a significant increase in the thrust of the propulsion system based on a piston aircraft engine and for improving its operational indicators. At the same time, they show that two-stroke engines using the proposed solutions can achieve, in most cases, operational indicators comparable to or better than those of turboprops. The presented solutions can be successfully adapted to general aviation aircraft propulsion systems, which mostly use piston engines. The construction of a record-breaking racing aircraft engine is potentially possible.

The use of high-power, high-speed two-stroke engines as an alternative to turboprop propulsion systems is theoretically possible. However, given the higher cost of aviation gasoline compared to aviation kerosene, a detailed economic analysis should be conducted, accounting for the possibility of carrying a larger load due to the lower weight of the propulsion system. The extremely favorable thrust-to-weight ratio of the propulsion system is crucial in this case. Furthermore, the engine from the proposed concept could certainly power transport aircraft not used for commercial flights, e.g., in the military. Similar engines could be successfully used in some aircraft operating from aircraft carriers, where the advantage of a piston engine over a turbine engine in terms of rapid increases in speed and power could significantly improve safety [27].

The design assumes a simple piston engine, unlike other high-power piston engines in aircraft (e.g., Pratt & Whitney R-4360, Rolls-Royce Merlin, or Daimler-Benz DB605 [45]). This would reduce not only its weight but also its price and operating costs.

The use of the proposed solutions in general aviation does not require additional analyses of exhaust emissions or harmful compounds, unlike in the automotive industry [34]. Within the European Union, aircraft performing non-commercial flights are exempt from compliance with emission standards. The same applies to aircraft performing commercial flights, but not exceeding a maximum take-off weight of 5700 kg [6].

Excluding commercial aircraft with a maximum takeoff weight exceeding 5700 kg, it is beneficial to strive to increase the exhaust mass flow, which can drive a turbocharger or power a power turbine, or generate thrust outside the propeller. The proposed concepts and designs for both engine versions serve primarily as examples from which specific solutions can be developed.

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