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Prototype station dedicated to aircraft engine propeller profiles and advanced materials testing

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This paper presents the ideas and shows an example of a test bench that allows for full testing and verification of new thermal and anti-wear coatings used in piston engines of small aircraft. The authors present the design idea, technical answers and methods for monitoring key parameters such as temperature, load, rotational speed and friction forces. The test bench allows to open the operating state typical for aircraft engines, facilitating the verification of friction and thermal properties of selected coatings and their performance under specific conditions. Example test results are presented, as well as the possibility of reading specific engine parameters using appropriate devices mounted on the engine stand. The novelty of this work was the development of a unique measurement and control system for real-time monitoring of all critical engine parameters and adaptation of appropriate conditions to different test scenarios. The test bench allows not only to accurately repeat the loads typical for small aircraft engines, but also to prepare and test multilayer anti-friction and thermal coatings with increased durability. The aim of the article was to present the design of a research stand enabling the performance of various tests of two-stroke aircraft engines intended for small aircraft, in particular thrust measurements for various propeller variants and tests of protective coatings.

Key words: *test stand, anti-wear coatings, thermal coatings, piston internal combustion engine, aircraft engine*

1. Introduction

Modern aviation, especially aircraft equipped with small piston internal combustion engines, requires the use of increasingly advanced technological solutions in terms of both materials and design. Intensive operation, as well as high thermal and mechanical loads, pose a serious challenge for designers striving to enhance the durability of the engine's main mechanism. Current development trends and new coating application technologies make it possible to create any combination of coatings that serve as a thermal barrier or reduce friction and wear on the engine's primary components. This is mainly for the piston, piston rings, and cylinder liner.

Studies on airplane engines done using test stands create a real chance to check and compare the parameters of engine operation for different options of materials under various loads, and the way the machine works depending on the choice of propeller selection.

This then improves the safety of the engine operation as soon as it is fitted in the airplane.

Some studies conducted indicate that indeed the most common cause of accidents in general aviation is piston-engine malfunction, as is evidenced by the clear increasing trend in failure rates of these power units in the ECCAIRS database [11]. Available statistics confirm that a key factor affecting safety is inadequate engine operation, particularly the lack of ongoing technical condition monitoring. The authors emphasize that the implementation of modern diagnostic methods, including condition-based operation, would significantly reduce the number of emergency situations related to piston propulsion systems. In [1], it was noted that there is currently intensive research and ongoing improvement in manufacturing processes, as well as the adaptation of aircraft engines to new types of fuels, which may bring significant ecological and economic benefits in the future [19]. This is of crucial importance for the development of new test stands for small aircraft engines.

In [1], it was observed that the development of piston internal combustion aircraft engines, in contrast to the intensively improved automotive engines, nearly came to a standstill after World War II, limiting their application mostly to tourist, sport, and agricultural aviation. The authors note, however, that there are significant possibilities for improving cylinder gas exchange (including optimizing intake and exhaust systems and utilizing supercharging), which can substantially enhance the overall efficiency and performance parameters of aircraft piston engines – particularly within the narrow speed range typical of engines with a variable-pitch propeller [1]. Nonetheless, such tests require the use of appropriate test stands, which are currently scarcely available on a commercial scale. In [20], it was shown that in light of the growing popularity of ultralight aircraft, the introduction of mechanisms to analyze and compare the operating parameters of aircraft engines and their automotive counterparts has become necessary, with real-time monitoring of engine performance parameters being highly desirable. The author [20] points out the different operational characteristics of both types of power units, emphasizing the much higher requirements for technical supervision and safety in the case of aircraft engines, as well as differences in the selection of key performance indicators (including rotational speed and specific mass), which stem from different usage profiles and legal regulations.

Piston engines are the most commonly used power units in tactical unmanned aerial vehicles (weighing over 50 kg) – both specially designed (e.g., by UAV Engines or Zanzottera) and adapted versions of Rotax aircraft engines or Subaru automotive engines in an "aviation" variant.

Approximately 32–38% of all malfunctions in American and Israeli UAVs stem from powertrain failures, partly due to challenging operating conditions (high temperatures, dust, icing risk) and the requirement to reduce acoustic and thermal detectability [5]. In Poland, producing engines for UAVs may be unprofitable, but a viable option is to integrate purchased engines with domestic airframe designs [5].

The accumulated experience gained from the use of piston internal combustion engines in both tourist applications and combat unmanned aerial vehicles demonstrates that the reliability of their powertrains remains a critical challenge [5]. From the standpoint of increasing the efficiency of the propulsion system, it is essential to develop propellers with profiles specifically adapted to operate at low Reynolds numbers. Selecting an aerodynamic profile under these conditions allows for better utilization of airflow properties, which directly affects the performance of the combustion engine. As a result, it becomes possible to balance higher production costs against a significant boost in reliability and overall system efficiency [13].

It should be noted that icing in the intake systems of a piston engine can occur under conditions in which the sensors installed on the airframe are unable to detect it [12], [21]. Meanwhile, the intake systems of aircraft piston engines can experience icing at ambient temperatures exceeding +30°C, whereas, at lower temperatures, engine fuel system components may freeze [4]. In-flight tests conducted on a Rotax 582 engine revealed that the induction system can be susceptible to icing even at temperatures above 20°C and relative humidity below 30%. An analysis of 13 flights carried out in the fall of 2011 confirmed that modern induction systems in ultralight aircraft, such as the UL-JIH Sedláček "Kolibřík," require a thorough assessment of icing risk [18]. Engine inlet icing can occur at positive temperatures, which crews often fail to consider. Typically, anti-icing system sensors detect icing on airframe components but do not register the early stages of engine icing, necessitating manual activation of anti-icing systems under specific conditions [7].

Analysis [6] showed that icing in the intake systems of piston engines results from water ingestion, condensation of water vapor, and fuel evaporation, leading to ice deposits in the fuel supply systems. The article presents effective solutions to prevent icing, such as heating carburetor walls, preheating intake air, and using inertial methods to remove water droplets from intake air. It also offers guidelines for pilots to facilitate early detection of icing symptoms, which is crucial for flight safety [6]. In this case, the need to consider air turbulence and dust entering the combustion chamber is also emphasized. Research on air filtration and cyclones has been conducted in [8, 9].

A key factor in this context is evaluating changes in cylinder head temperature resulting from airflow generated by the propeller while taking the actual ambient temperature into account – something that is challenging for ground-based test stands. Nevertheless, such stands can significantly improve the assessment of this parameter. The necessity of incorporating research on combustion chamber temperature and its impact on oil film distribution in piston internal combustion engines was noted in [22]. Similarly, attention must be paid to the appropriate geometry of piston rings and coatings used in piston internal combustion engines [23]. This is particularly crucial for small aircraft engines, which are subject to extreme thermal loads and high stresses in the powertrain and drive transmission systems.

In [3], the need to create test stands for small aircraft engines was highlighted. The designed stand enabled precise monitoring of key operating parameters of miniature turbine jet engines, as confirmed in both laboratory and field conditions. The system is characterized by high mobility, user safety, and flexibility, which helps reduce diagnostic costs compared to foreign solutions. The research results confirm that implementing proprietary design and measurement solutions significantly increases the efficiency and reliability of unmanned aerial vehicle operations [3].

The research also underlines the need to update piston engine designs with ideas from flow aerodynamics, which can ensure more efficient use for general aviation [2]. It gives ways in which cylinder filling may be optimized, improving efficiency and overall performance of engines, particularly in powering light and ultralight aircraft [2].

Structural and strength analyses of the materials used to build key engine components, such as turbine blades, are essential both during the design phase and in emergency testing [14]. Similar material tests and structural analyses are equally important for aircraft piston engines, as they facilitate optimal material selection, thereby enhancing the safety and longevity of aircraft propulsion systems. Aerodynamic calculations concerning the aircraft in relation to power unit selection are also crucial.

In [10], static aerodynamic characteristics of an unmanned aerial vehicle (UAV) were presented, obtained through both experimental research and numerical calculations. Moreover, effective calibration of the numerical model – based on mass correction, stiffness adjustments, and vibration testing – is essential to minimize uncertainties in the results stemming from inaccurate geometry or structural defects in the actual aircraft [15].

The need to consider technical parameters, particularly for military aircraft, is discussed in [25, 26]. Unfortunately, most technical, technological, and operational data for military vehicles is classified, and access requires appropriate clearances [17]. In particular, the station equipment should include many sets of indicators and control devices necessary to control the UAV [16].

In [24], a concept for building test stands for aviation piston engines intended for ultralight aircraft was also presented, taking on the challenge of creating a stand to test a small hybrid aircraft engine designed to power drones and small aircraft.

This article presents the assumptions and implementation of a prototype test stand dedicated to testing coatings on the main components of small, two-stroke, two-cylinder piston aircraft engines. The described design enables precise real-time measurements of the most important parameters of a piston combustion engine, while allowing for full control of testing conditions. As a result, it is possible not only to reproduce the engine's operation under aircraft flight conditions but also to assess wear patterns, anti-friction properties, and the thermal insulation parameters of selected coating combinations applied to the engine's main components. This approach provides valuable support in the process of designing and optimizing these solutions.

2. Design and construction of a test stand for a small piston internal combustion engine

2.1. Preliminary design and component selection

Designing a test stand for an aircraft piston internal combustion engine requires consideration of a range of technical factors, such as an appropriate support frame structure, corrosion protection, measurement systems, and the engine's operating conditions. This type of research makes it possible to evaluate operating parameters and test new solutions in the fields of anti-wear and thermal coatings, as well as external forcing parameters – namely, propeller profiles. Two-stroke internal combustion engines are particularly prone to intensive wear and overheating; therefore, selecting proper components and ensuring precise measurements under controlled conditions is crucial. Since two-stroke engines are more susceptible to wear, heating, and vibrations, it is essential to provide stable conditions that closely replicate real-world operation. Such realistic conditions are indispensable for accurately testing anti-wear coatings under various operating and lubrication scenarios. Precise measurement of thrust, temperature, and other parameters not only allows for analyzing standard aspects of engine performance but also enables testing prototype anti-wear and thermal barrier coatings.

The stand stands out from others in that it can measure thrust for various engine operating parameters. There are a large number of different test stands for testing combustion engines. These are mainly four-stroke engines designed to power cars. In the case of small two-stroke aircraft engines, such stands are rarely constructed. Most test stands include jet engines. Recently, there has been a growing interest in small two-stroke combustion engines. Testing their parameters under the load of various propeller variants and their operation in various conditions provides an opportunity to improve their design.

The test stand has been designed to allow, in addition to standard analyses of the operational parameters of the DLE170 piston engine and the 3W 275 XI B2 TS/CS model, the testing of anti-wear and thermal barrier coatings. The stand can also be used to measure engine thrust depending on shaft speed, air humidity, and the installed propeller profile and number of leading blades. It additionally permits assessment of cylinder head temperature based on the intensity and direction of the airflow toward the engine. Furthermore, it will be equipped with additional strain gauges to measure stress values in various working areas of the powertrain system, enabling the evaluation of load on individual components depending on the engine's operating parameters and other factors, such as propeller load. The technical data of both assembly engines in the position is presented in Table 1.

The choice of the DLE170 engine and the 3W 275 XI B2 CS engine as the power units for the test stand was driven by their technical parameters, wide availability, and appropriate dimensions, which translate into a relatively high torque and power across a broad range of rotational speeds (Fig. 1). This choice facilitates obtaining reliable data and allows for comprehensive testing. The stand itself was designed not only to measure the standard operating parameters of a piston engine but also to test new material solutions and assess the external thermal parameters of the engine's operation.

Table 1. Parameters of aircraft engines that can be mounted on the test stand

Parameter	DLE170 Engine	3W 275 XI B2 CS Engine
Type	Two-stroke, two-cylinder piston	Two-stroke, two-cylinder piston
Total displacement	170 cm³	273 cm³
Compression ratio	9.5:1	No data
Cylinder diameter	52 mm	59 mm
Piston stroke	40 mm	50 mm
Torque characteristic	~12 Nm at 3250 rpm	No data
Maximum output power	17.5 HP (13 kW) at 7500 rpm	27.5 HP (20.22 kW) at 7500 rpm
Cooling	Air-cooled, no additional circuit	Air-cooled, no additional circuit
Rotational speed range	1100–9000 rpm	1000–7500 rpm
Weight	Approx. 3.5 kg	Approx. 7.0 kg
Crankshaft	3 ball bearings	3 ball bearings
Connecting rod	Needle bearings on both ends	Needle bearings on both ends
Fuel	1:50–1:80 mixture, synthetic oil, 98 octane	1:50–1:80 mixture, synthetic oil, 98 octane
Ignition system – power supply	Electronic module powered by IIS, 6.0 V (NiCd) or 7.4 V (LiPo)	Electronic module powered by IIS, 6.0 V (NiCd) or 7.4 V (LiPo)
Propeller	2-blade: 36×12, 36×14; 3-blade: 32×12, 34×12	2-blade: 36×12, 36×14; 3-blade: 32×12, 34×12

The construction of the stand enables the measurement of thrust generated by the propeller under various engine operating conditions – primarily different crankshaft rotational speeds and cylinder temperatures – by controlling the ignition system (Fig. 2). To achieve this, the engine was mounted on a special frame that can be tilted relative to the propeller's rotation, thereby applying force to a load cell installed at the rear of the stand.

The stand's design is based on a corrosion-protected steel mounting base equipped with a vibration absorption system, which reduces vibrations transmitted to the measuring components and the external environment (Fig. 3). The innovation of this concept lies in combining typical testing procedures with advanced research on the strength and surface durability of engine components, thus providing a comprehensive view of the tribological and thermal processes occurring in a two-stroke engine during operation.

The test stand is attached to the ground with special transport belts to eliminate measurement errors. The supporting frame itself, in order to limit the impact of vibrations and oscillations, has been designed to minimize the clearance during engine tilting during thrust measurement. Additionally, special rubber sleeves and appropriate nuts have been used. In the future, the stand will be additionally damped with special engine cushions. Similarly, the impact of oscillations on the measurement result will be minimized. Special vibration tests will be carried out for this purpose.

2.2. Fuel supply, cooling, and lubrication systems

Properly designed fuel supply, cooling, and lubrication systems are critical factors determining the efficiency and durability of an aircraft engine. In the case of a two-stroke piston engine, precise control of the fuel-air mixture composition, effective heat dissipation, and appropriate lubrication form the foundation for achieving stable operating conditions and conducting reliable research. Integrating the complex components of the measurement path into a single, cohesive test stand makes it possible to replicate engine operating conditions over various load ranges. In particular, the propeller – mounted directly to the engine's crankshaft – plays a decisive role in defining the load range that modifies both the operating characteristics and the resulting thrust parameters.

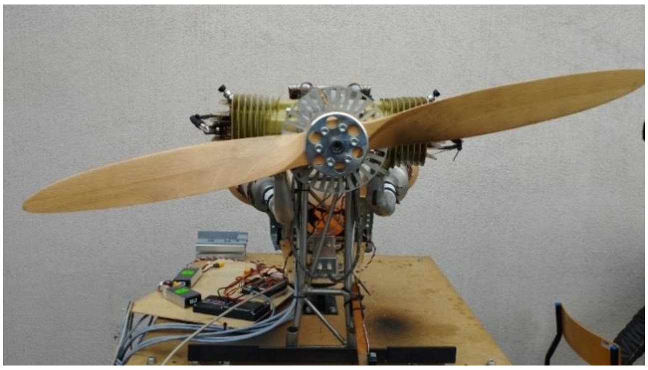

Fig. 1. Construction of the test stand with the 3W 275 XI B2 CS engine installed after the propeller has been mounted

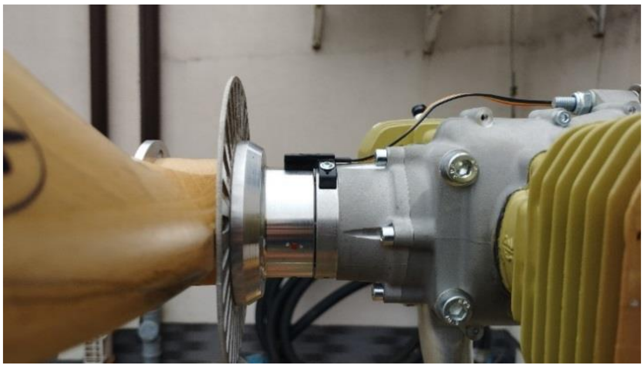

Fig. 2. Connection of the propeller with the 3W 275 XI B2 CS engine shaft and a view of the speed sensor necessary for controlling the engine's ignition system

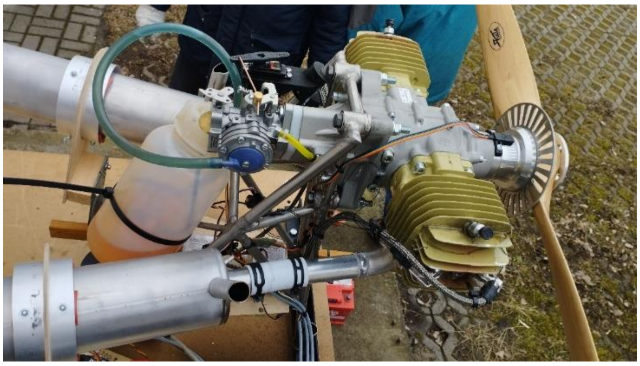

Fig. 3. Arrangement of the measurement assemblies on the test stand and integration of the exhaust system

The fuel supply system of the DLE170 and 3W 275 XI B2 CS piston engines features a mechanically adjustable diaphragm carburetor (Fig. 4). To alter the fuel-air mixture composition, the airflow and fuel supply can be adjusted accordingly, and the idle speed can also be regulated. This approach enables achieving different engine operating conditions for different fuel-air mixtures outside the stoichiometric range. In laboratory testing, the optimal stoichiometric mixture was set at 14.7:1. For richer mixtures, the amount of lubricating oil added to the 98-octane fuel was increased by about 5% to ensure adequate lubrication under higher combustion temperatures.

Fig. 4. Fuel system of the installed 3W 275 XI B2 C engine

The measurement apparatus includes a set of K-type thermocouples located on both cylinders, a load cell measuring the power unit's thrust, a throttle position sensor, an engine speed sensor (read from the DLE engine ignition module), and an optical sensor recording propeller speed (Fig. 5). The measurement system also incorporates SBS-01T telemetry temperature sensors, which are designed to work with Futaba FASSTest, T-FHSS Air (for aircraft), and T-FHSS Surface (for model cars) transmission systems (Fig. 6). These sensors can measure temperatures ranging from –20°C to +200°C, making them particularly useful for monitoring the cylinder head temperatures of two-stroke piston engines intended for aviation or other components exposed to elevated temperatures.

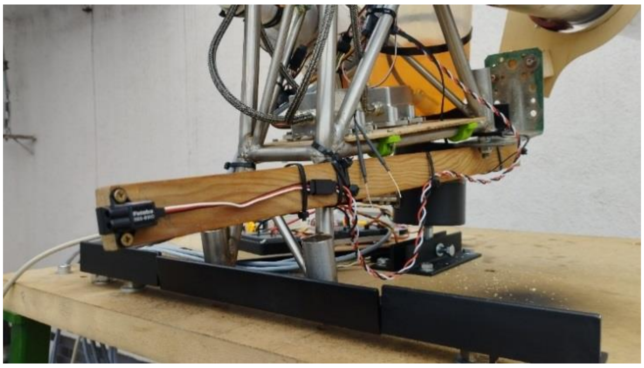

Fig. 5. View of the optical sensor used for recording the propeller's rotational speed

The sensor is compatible with Futaba receivers equipped with an S.BUS2 port, connecting via an S.BUS2 connector and requiring only one address ("slot") on the serial bus for proper operation. By default, it is set to 1, but if needed, the address settings can be changed directly in the receiver or in the transmitter menu that supports telemetry. The measurement is carried out by an integrated sensor, weighing just 4.7 g, with a cable length of 535 mm, allowing for precise placement on the engine heads in the test stand.

Its power source can range from 3.5 to 8.4 V, corresponding to the standard operating range of battery packs (e.g., LiPo 1–2S). During operation, the sensor indicates its status with an LED, making it easier to verify connection integrity and functionality for the entire telemetry system. Thanks to direct integration with Futaba's telemetry system, the current temperature is transmitted in real time to the RC transmitter, from which it can be displayed on a receiver screen equipped with a telemetry function or on other compatible devices (Fig. 7).

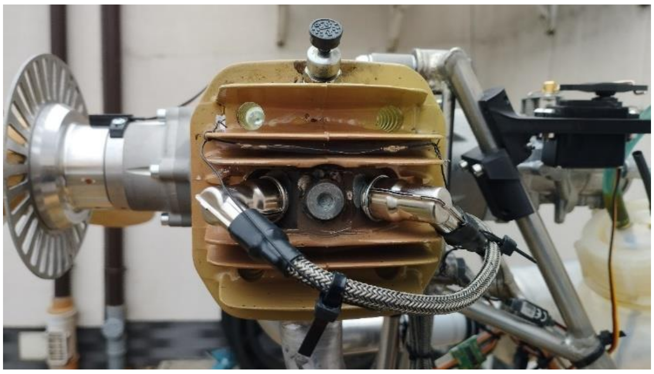

Fig. 6. View of the method for mounting air temperature sensors on the engine head

Fig. 7. Remote control set with radio communication

The measurement system also includes a regulated voltage source of 4.8–14 V, used to power the electronic ignition module. Fuel is supplied in the form of 95-octane gasoline mixed with synthetic oil for two-stroke engines. The oil-to-gasoline ratio is 30:1 during the break-in period for newly installed components of the engine's main assembly (pistons, piston rings, cylinder surfaces) and 40:1 under measurement conditions at various crankshaft speeds. Castrol Power1 A747 Racing 2T high-performance oil is used to lubricate the main engine mechanism. Additional fans are employed to force airflow over the cylinder cooling fins for effective cooling of the power unit.

The stand also supports various types of propellers – 2-blade (36×12, 36×14) and 3-blade (32×12, 34×12) – to generate different dynamic loads and measure engine operating parameters under conditions close to real-world scenarios.

The ignition system is based on an electronic module that generates sparks in conjunction with NGK CM6 spark plugs. The manufacturer recommends a supply voltage in the range of 4.8–14 V, enabling the use of different power sources for testing and allowing comparisons of how supply voltage affects combustion stability. An essential feature protecting the engine from overheating is adaptive ignition timing, which automatically adjusts the spark's thermal characteristics as temperature increases (Fig. 8).

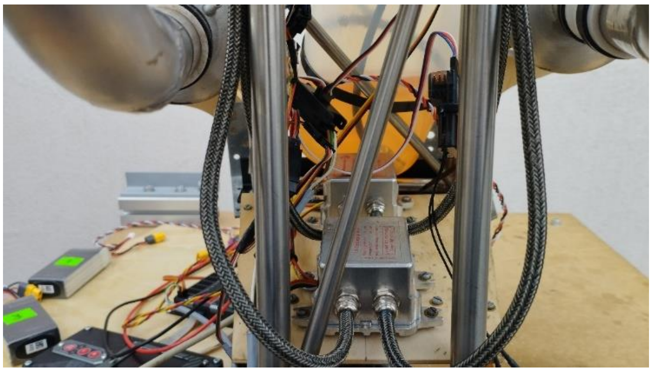

Fig. 8. Ignition system assembly of the test stand for the 3W 275 XI B2 C engine

Both the ignition module (weighing approximately 190 g) and the muffler (approximately 470 g) are integral components of a piston internal combustion engine. Because the engine employs air cooling, it is necessary to maintain the recommended ratio of intake to exhaust port cross-sections (1:3) to ensure effective heat dissipation. If the operating altitude exceeds 1800 m above sea level, adjustments to the fuel-air mixture composition become necessary. The cooling airflow is simulated by varying the propeller's rotational speed.

The test stand enables safe engine mounting, recording a full spectrum of diagnostic data (such as cylinder temperatures at various points, thrust of the power unit, and crankshaft speed), and the safe execution of tests. This setup allows for detailed analysis of the combustion process, as well as the torque and power characteristics, and facilitates the verification of different carburetor adjustments or ignition timing settings under varied load and environmental conditions. Thus, the entire system constitutes a complete laboratory for measuring engine parameters under controlled conditions. It allows for the application of various anti-wear and thermal coatings and for conducting tests under conditions that closely replicate the operating parameters and ambient conditions of the power unit. The test stand also permits evaluating engine performance based on the installed propeller, providing the opportunity to assess the maximum achievable thrust, engine rotational speed, the temperature of the airflow around the cylinder heads, and many other parameters.

The fuel supply, cooling, and lubrication system of the engines has been designed to adjust operating parameters to meet both testing and operational requirements. The use of a diaphragm carburetor with adjustable mixture composition, along with additional forced-cooling fans and telemetry temperature sensors, allows for real-time monitoring of combustion processes and engine thermal control. This solution has been preferred because of its reliability and flexibility; it allows the full regulation of the engine operation with automated real-time parameter logging. The novelty of the concept lies in the bridging of traditional components – diaphragm carburetors and simple air-cooling systems – with modern telemetry measurement modules. This approach will continuously give accurate diagnostic data about the performance and reliability of the engine.

This readiness to vary the oil content in the fuel and to change the ignition timing on the move enables the engine to be tried out in different setups, and leads towards more experiments, including those with fresh anti-wear and thermal coatings. The constructed test stand constitutes a comprehensive tool for adapting engines to the requirements of modern aircraft designs and emerging material technologies.

2.3. Measurement and control system

To record accurately the thrust made by the aircraft engine and to control fully how the measurement is made, it is necessary to use special sensors and data acquisition systems.

The test stand comes with a CL14 strain gauge force sensor meant for measuring both pull and push forces over an operating frequency range of 0 to 5 kHz. This sensor mounts into the engine support frame and is used to measure the force of thrust of the power unit, depending on the parameters of engine operation, the outside load, such as the type of propeller, and the outside conditions. The measuring system is made up of a spring element, steel/aluminum alloy, on which foil strain gauges are mounted.

This design ensures high accuracy and long-term measurement stability. The force sensor has a default measurement range from 0.05 kN to 200 kN. Adapters are appropriately designed on the stand to accommodate the measurement of forces of varying types (tension and compression). An output signal of 1 or 2 mV/V and a nominal supply voltage of 10 V make the CL14 sensor suitable for use with measurement devices such as the CL10D or CL100P amplifier and microprocessor meters from the CL300 or CL450 series. The measurement range of the CL14 sensor used on the test stand is 5 kN with a sensitivity of 1 mV/V.

The design employs a strain gauge bridge with an input resistance of 410 ±10 Ω (for ranges up to 10 kN) or 380 ±10 Ω (for ranges above 20 kN up to 100 kN) and an output resistance of 350 ±5 Ω. The bridge's unbalance signal is at most ±0.2% (calculated relative to the nominal signal), and the error at nominal load does not exceed 0.03% over 30 minutes. The sensor's sensitivity is characterized by temperature stability of ≤ 0.05%/10 K, with a recommended operating range of –20°C to +100°C and temperature compensation provided in the range from 20°C to 90°C. The apparatus shows a top flex in the thrust of up to 0.5 mm, which is key when planning systems that need accuracy and repeatability. High mechanical strength (with an allowed overload of up to 50% of the named value) ensures safe operation under demanding test conditions.

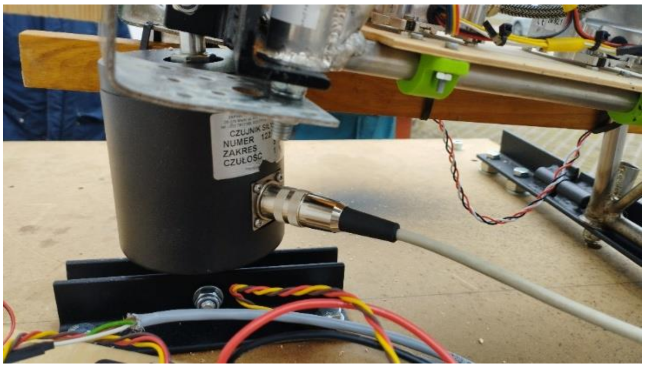

Fig. 9. View of the CL14 force sensor mounted on the test stand

The test stand has a CL 450 data recorder, which is a single-channel measuring and recording tool intended to cooperate with a strain gauge sensor. This combination makes accurate measurements and recordings of those physical quantities converted into electrical signals in a system with a bridge of strain gauges. Owing to a built-in 24-bit analog-to-digital converter, the data recorder possesses high resolution, at the lowest acquisition speeds, up to 200,000 divisions that can be obtained with a sensitivity of 2 mV/V for a sensor. The recorder also has high measurement accuracy (total error below 0.0025% at 300 K), suitable for laboratory applications and for research requiring high precision, specifically in tests for aircraft power unit parameters. Also, the CL 450 recorder can take in up to 14 correction points for sensor non-linearity, which allows more precise results even when using strain gauges with unusual characteristics.

The recorder features one strain gauge channel (with an input supporting a wide range of sensor resistances from 220 Ω to 4000 Ω) and is powered by a nominal voltage of 5.0 VDC (±0.1 V). The tool gives fifteen sensor parameter banks, letting users change from one to another without having to set up all over again each time. The speed of getting is changeable from 1.25 to 2400 samples per second, and more averaging (from 2 to 64 samples in a moving time window) helps to make noise and oscillations settle down. Also, the tool lets you make up any shown units (up to five letters) right in the real units used for the test.

Recorded waveforms are saved in memory, allowing for the archiving of any amount of data according to the capacity of the removable memory. The data recorder features a built-in OLED display. Thanks to the integrated real-time clock (RTC), samples are time-stamped, facilitating later analysis. A lithium-ion battery powers the CL 450 recorder. An important feature of the recorder is the ability to start recording measurements immediately or to initiate recording once a predefined start threshold is exceeded automatically. The CL 450 recorder offers extensive options for signaling the exceedance of defined thresholds through acoustic signals (Fig. 10).

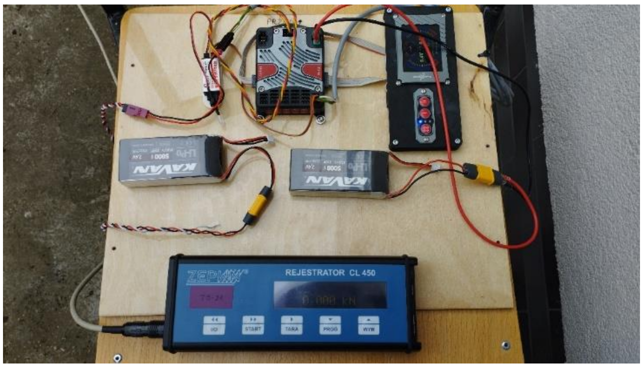

Fig. 10. View of the CL450 recording set, power batteries, and control systems

A dedicated program, CL450_WYSW_PARAM, has been provided for configuration and data retrieval, which communicates with the device via a USB 2.0 port. This software allows, in particular, monitoring of the current status of the data recorder, reading of recorded measurements (at a speed of approximately 29,000 samples/s), exporting them to text files, setting the real-time clock, and programming all operational parameters of the data recorder, including sensor configuration, non-linearity corrections, and averaging mode. The device can work well within a temperature range of –20°C to +50°C and a relative humidity range of 20% to 80%. This, in turn, promises to form the very base on which the thrust force of the power unit and other dynamic parameters for the aircraft engine will be evaluated. Very high mechanical toughness, a wide range of operating temperatures, and the ability to compensate for external influences (e.g., non-linearity of the sensor) provide stable and accurate measurements, which are very important for the operation of the power unit. This solution's novelty consists first in the capability to perform data acquisition simultaneously with an accuracy to the order of thousandths of a percent and second in a high degree of configuration flexibility, which permits a multi-faceted test under the closest conditions to real-life operation.

This makes the test stand fully suitable for research needs in diagnostics, analysis of engine dynamic performance, and evaluation of the impact of various external parameters on the durability of the power unit of a piston internal combustion engine designed for aircraft propulsion.

2.4. Assembly and preliminary tests

The assembly of the prototype test stand began with the preparation of a support structure made of corrosion-protected steel and equipped with vibration-damping elements. The frame was leveled using adjusting screws and a laser level, which eliminated any tilting and ensured repeatable results. Anti-vibration pads minimized the transmission of vibrations to the surroundings, thereby improving the stability of readings from the strain gauge sensors. First, the DLE170 engine is mounted on the test stand frame. Then, the 3W 275 XI B2 CS engine is mounted on a special bracket with an adjustable angle. This gives proper alignment of the shaft axis of the engine and allows the desired pressure on the CL14 force sensor to be achieved. The engine is bolted down with high-strength bolts, together with spring washers. Care was taken to keep proper distances between the cylinder heads, exhaust systems, and other components. The entire construction was complemented by a vibration-damping system employing rubber and elastomer elements that allow for the adjustment of mounting stiffness, thus preventing the adverse effects of engine-generated vibrations.

Next, the measurement sensors were installed and configured. The most important of these is the CL14 strain gauge force sensor, built into the rear bracket of the test stand frame. Its role is to measure the thrust force generated by the propeller along the engine's longitudinal axis. The sensor, based on foil strain gauges mounted on a spring element, was connected to the amplifier system and the CL 450 data recorder via shielded signal cables, which minimized the impact of electromagnetic interference. The sensor's sensitivity (1 mV/V) and its nominal range of 5 kN were defined in the measurement device, and any non-linearity was corrected using calibration points entered into the recorder's memory.

Additionally, SBS-01T temperature sensors and K-type thermocouples were installed in the cylinder heads, enabling real-time temperature monitoring via the Futaba telemetry system. The wiring was routed along the engine's body, ensuring that it did not come into contact with the hot components of the exhaust system. The monitoring system is further complemented by a rotational speed sensor and a throttle position sensor, which allow for the correlation of engine revolutions, load, and thrust with the actual thermal load on the engine.

At the same time, the CL 450 data recorder was being installed and adjusted. The strain gauge bridge got its power at 5 VDC (±0.1 V), and details of all the sensors were set using the CL450_WYSW_PARAM program.

Once the mechanical and measurement components were assembled, the fuel supply, lubrication, and cooling systems were set up. Set the diaphragm carburetor for the first instance to get a fuel-air mixture near the stoichiometric ratio of 14.7:1. At the same time, the site was also made ready to add petrol in different proportions with the oil if required. Fuel and ignition systems were tested using adaptive ignition timing. Fans provide effective engine cooling and at the same time support in further increasing the airflow over the cooling fins of the cylinder blocks. Tests were done to confirm the flow through the intake and exhaust channels.

After this, a set of prior tests was done which included static adjustment of the force sensor and brief engine starts to check some parameters like temperature, speed, composition of the mixture, and thrust force. The static setup of the CL14 sensor, using weights that were known, proved that the difference between the guide point values and the saved values was inside 0.3% of the promised span, following what the maker said. The first idle engine starts indicated constant readings from the SBS-01T sensors, which proved that the ignition system was working well. A gradual increase in speed between 2000 and 7500 turns per minute gave a chance to confirm that the force, temperature, and speed were taking steady measurements, all logged by the CL 450 data recorder with no kind of upsets. Controlled increases in load further checked the right operation of the sensor underweight.

The results of the preliminary tests demonstrate that the designed test stand provides high measurement quality and enables stable operation of both the DLE170 and the 3W 275 XI B2 CS engines while maintaining full control over their parameters. Careful preparation of the structure, elimination of vibrations, proper calibration of the force sensor, and the matching of the cooling and lubrication systems to the testing requirements were of key importance. The engine maintained safe temperature limits when the appropriate fan speed was applied. The initial data analysis indicates a negligible influence of ignition system disturbances on the measurement signal received. The results that were obtained have confirmed that our test stand is prepared to start doing proper research on advanced thermal and anti-wear coatings. This can be researched under different operating ranges with types of propellers and fuel-air and oil mixture configurations. This data is to be used in the long term to verify the durability and efficiency of diverse coatings under the most appropriate conditions that come closest to the real operation of an aircraft engine. The test results would thus support the developmental process of such solutions for two-stroke piston aircraft engines meant for use in light aircraft.

3. Research methodology and sample results

3.1. Test scenarios and measurement procedures for coating tests

Begin tests by starting the DLE170 engine and holding it at a rotational speed of about 2000 rpm. It is assumed that the minimum duration of the initial test should not be less than 10 hours, with the aim of breaking in the main engine components. During this period, an enriched fuel-air mixture with an increased amount of synthetic oil is used. Next, the major engine check is done at various turn speed adjustments (from slow, through part load, up to levels near the most), while watching main operating measures like the push force of the power unit, head temperature, shaft speed, and position of the throttle.

The time courses of these parameters are then recorded at strictly defined measurement points – at fixed crankshaft speeds from 1000 to 7000 rpm, in increments of 500 rpm, with the throttle fully open. The obtained data serve as a reference for further tests using various combinations of anti-wear and thermal coatings. It should be noted that the maximum engine speed mainly depends on the engine type and the characteristics of the mounted propeller.

In the subsequent stages, on selected engine elements – mainly the piston and piston rings – any layers of coatings can be applied, which can be grouped into two main categories: thermal coatings and anti-wear coatings. To maintain uniform testing conditions, before restarting the engine, the same protocol for adjusting the fuel-air mixture composition and monitoring the ambient temperature and humidity in the test facility or surrounding area should always be followed. After completing the startup procedures, which include several minutes to stabilize the crankshaft's rotational speed, data logging begins on the recorders: first under partial load conditions (e.g., 30–50% throttle opening), and then at higher power ranges until the nominal rotational speed is reached. In every range, measurements have to be repeated five times – this is to find out the percentage deviation of measurement errors. In the end, the final value for a particular trial is taken as the arithmetic mean of five measurements, with the proviso of measurement error deviation.

After each set of checks, the motor is turned off and looked at for a quick view of the covering condition. More care is given to any rubbing, cuts, or color that may show local high temperatures have been surpassed or improper lubrication has taken place.

Recorded continuously or saved directly at the time of measurement, using recording devices, include all data on thrust force, temperature, rotational speed, sensor signals, and exhaust gas analysis. At the end of each session, there is a control calibration of the force sensor and a check on the stability of the thermocouple and SBS-01T readings. In case any abnormalities are detected, for example, the readings (temperature or thrust force) go beyond the specified range for an extended period, the test session shall be re-conducted after setting the engine to the initial conditions. This developed procedure – from the start-up cycle, through a series of load measurements, to the final assessment of the surface condition – should be carried out to ensure reliable results, which form the basis for evaluating both the tribological properties and the thermal insulation parameters, as well as the resistance to thermal overload of the analyzed coating combinations. This will make it possible to compare various material solutions from different suppliers credibly and draw light, easy-to-follow, and ready-to-use recommendations for the application of coatings to the main components of small aircraft piston engines.

3.2. Measurement scenarios for various propeller characteristics

To widen the scope of the research and obtain more precise information on the influence of various parameters, a series of test scenarios were drawn up that take into consideration different propeller configurations, specifically two-blade (36×12, 36×14) and three-blade (32×12, 34×12) designs. Each configuration offers different dynamic loading, and hence distinct thrust characteristics with changes in rpm, and therefore affects the airflow cooling the cylinder area. The tests planned also varied the crankshaft speeds from idling to maximum values, the angle at which the engine is mounted to the ground, the composition of the fuel-air mixture (i.e., the proportion of oil in the fuel), as well as the intensity of the cooling airflow. Long-term tests under a constant load with cyclic speed changes were also considered to emulate the full array of conditions in practice.

In all cases, key engine parameters (cylinder head temperature, thrust force, rotational speed, fuel consumption, etc.) and signals from the strain gauge sensors (load and stress) plus telemetry (S.BUS2) are recorded. Sample photos from the measuring device are shown in Fig. 11 and 12. The thrust force graph obtained during the preliminary test is shown in Fig. 13. Use of the CL 450 data recorder with force sensor CL14 allows accurate real-time recording of changes in thrust force. In contrast, thermocouples and SBS-01T sensors give detailed data on temperature distribution within the engine. This information forms the basis for comparing the efficiency of the different propeller configurations available and verifying the effective application of the anti-wear and thermal coatings and their impact on friction, as well as wear of the piston and piston rings, and changes in the thermal characteristics under prolonged loading. This broad research area allows for a precise copy of different engine operating conditions. It helps form detailed conclusions about the choice of propellers, ways of cooling, and coating types which can be practically applied in light piston-powered aircraft.

Fig. 11. Preliminary measurements on the test stand – sample measurement 1 (cylinder head 1 – 36°C, cylinder head 2 – 37°C, crankshaft speed 2358 rpm, measurement displayed on the recorder 122 N; after scaling, the thrust force value is 95.68 N)

Fig. 12. Preliminary measurements on the test stand – sample measurement 2 (cylinder head 1 – 35°C, cylinder head 2 – 42°C, crankshaft speed 4952 rpm, measurement displayed on the recorder 481 N; after scaling, the thrust force value is 377.25 N)

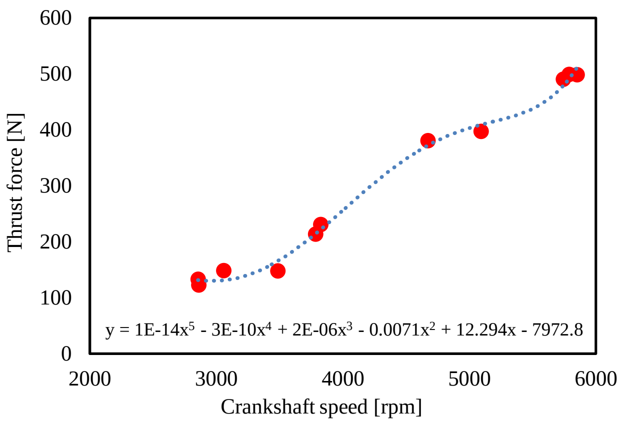

Fig. 13. Example of thrust results for a Fiala 32/16 propeller as a function of crankshaft speed

3.3. Sample results and analysis

Preliminary stand tests demonstrated the measurement capabilities of the test setup. An initial calibration of the force sensor was performed, with its reading representing the thrust force value. Radio integration of the remote control systems for adjusting the engine's rotational speed, controlling the throttle, reading temperatures from both cylinder heads, and recording the engine's rotational speed was completed. The initial measurements were done using a two-blade propeller. All results of the measurements were recorded and discussed to define the thrust of the propeller as a function of future tests and tests in this paper, as well as to define external factors and parameters of the propeller. It has been determined that the test stand does, in fact, offer wide-ranging capabilities for measurements involving thrust as a function of propeller parameters as well as external factors. The CL 450 recorder shows the force value taken by the sensor, which is calibrated at the factory to the recorder. But the value shown does not show the absolute final value. The engine's thrust must account for the difference between the distance from the propeller axis (the thrust force vector) and the rotation axis of the test stand, in relation to the distance from the rotation axis to the force sensor's mounting point. A two-point calibration of the thrust measurement system was carried out, which empirically determined a correction parameter by which the displayed result should be scaled to obtain the actual thrust value of the power unit. The correction factor is 1:1.275.

4. Perspectives for application in the aviation industry

The developed prototype test bench for the two-stroke piston engine DLE170 offers possibilities for a detailed analysis of the power unit's performance. It has been indicated from initial tests that it is feasible to simulate both partial and full load conditions, thus drawing adequate conclusions with regard to the durability and efficiency of new solutions. In turn, the test bench will be used for tests on the propeller choice for an engine as well as its forced parameters. This gives the opportunity to assess hot parameters, such as thrust that can be achieved maximally, maximal rpm of the engine, and rpm flexibility of the engine performance.

The ongoing development of small piston aircraft engines – particularly those used in ultralight aircraft, helicopters, or unmanned aerial vehicles (UAVs) – significantly intensifies the search for modern material and design solutions aimed at reducing friction and wear, as well as improving thermal characteristics. The increasing demands for efficiency, low weight, and reliability in these power units are reflected in the pursuit of advanced tribological coatings and barrier coatings that can effectively protect components exposed to elevated combustion temperatures and high mechanical loads. It is also crucial to understand the changes in the engine's cylinder head temperature depending on the propeller profile and the achieved thrust at given crankshaft speeds.

In the light of growing ecological demands and more stringent emission legislation, the use of thermal barrier coatings becomes more attractive. They increase the potential working temperatures (and hence improve the efficiency of the engine) while preserving the walls and the piston of the cylinder from overheating. However, a main drawback of the applied TBCs is their potential to increase NO_x emissions, which is a major point in environmental investigations. In this respect, the newly developed test stand can come to be a major advancement since it enables comprehensive experiments under nearly real operating conditions, and among many other parameters, the effect of various coating designs on the emissions of single exhaust gas components.

Equally important is the development of innovative anti-wear coatings that not only reduce friction but also prevent microcracks and wear in the areas of piston rings, the piston itself, and the cylinder liner. The use of the test stand allows for the evaluation of their effectiveness over a wide range of rotational speeds and loads under various lubrication conditions. Promising approaches include, for example, hybrid coatings that combine anticorrosion, tribological properties, and high-temperature resistance. The dynamic development in the field of surface engineering and PVD/CVD techniques may contribute to the creation of multilayer structures tailored to the specific requirements of aircraft engines.

Potential modifications aimed at engines intended for the UAV and light sport aircraft segments also deserve particular attention, as high reliability and extended faultless operation are crucial for performing tasks under challenging conditions. Coatings with reduced friction and enhanced thermal resistance enable longer maintenance intervals, which is especially important for unmanned aerial vehicles operating in hard-to-reach areas or areas requiring continuous monitoring. The ability to quickly verify the effectiveness of coatings on the test stand – before they are implemented in production or put into service – is a significant asset in terms of cost and the safety of aviation operations.

The same applies to the selection of parameters and propeller profiles for a given engine. Evaluating these parameters during the simulation stage is subject to considerable error regardless of the sophistication of the mathematical model. Factors such as progressive wear during each engine cycle and changes in environmental conditions mean that simulating the parameters of the oil film or fuel-oil mixture is only a starting point for designing the geometry of these components for a given engine. A similar situation is observed in the design of the propeller system – the shaft and the air cooling system. Only test stand experiments can provide high reliability for the conclusions drawn.

It is worth emphasizing that the developed test stand not only facilitates the selection and evaluation of new coating variants but also accelerates their commercialization process. On one hand, it allows for demonstrating the effectiveness of solutions under conditions close to actual flight, and on the other, it fosters close cooperation among coating manufacturers, engine producers, and end users (including aviation companies, rescue services, and UAV operators) who strive to improve operational efficiency and reduce fleet maintenance costs. Moreover, the possibility of diversifying tests (e.g., changing propellers, adjusting the fuel mixture composition, simulating cooling) contributes to a more accurate adaptation of coatings to the actual operating environment of a specific aircraft.

Summary

The designed test stand, based on the two-stroke piston aircraft engines DLE170 and 3W 275 XI B2 CS, constitutes a comprehensive test facility for evaluating advanced materials and engine characteristics as a function of propeller selection under conditions closely resembling actual aviation operation. Tests carried out have proved that the two-stroke engines available in the stand, together with the adjustment of the rotational speed and fuel mixture composition plus the intensity of air-cooling, largely simulate real thermal and mechanical loads characteristic of small power units. The use of CL14 thrust sensor, CL 450 recorder, and SBS-01T temperature sensors (together with thermocouples) provides means for accurate, real-time registration of a wide set of key parameters for the materials introduced to enable adequate wear protection as well as prevention against overheating.

The test stand proves useful not only for the ultralight aircraft and UAV sectors but also for engine manufacturers, who can shorten the process of introducing new material solutions based on the obtained results. It is also worth emphasizing the potential for modifications of the entire system, including further reduction of vibrations, the introduction of automatic test parameter control, and the expansion of the measurement apparatus to include exhaust emission analysis or visual systems for assessing wear and thermal changes in the engine. This implies that the simultaneous consideration of tribological and thermal characteristics acquires new materials with propeller profiles to be accurately selected and applicative ultralight aviation and other such industries with highly reliable two-stroke piston aircraft engines.

In the time of quick growth in automation and green changes in air travel, devices like this are meant to become an important part of the study and planning process, adding to the increased competition in the field and improving the safety of aviation work.

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Bibliography

[1] Balicki W, Chachurski R, Głowacki P, Godzimirski J, Kawalec K, Kozakiewicz A et al. Lotnicze silniki turbinowe. Konstrukcja, eksploatacja, diagnostyka (in Polish). Wydawnictwa Naukowe Instytutu Lotnictwa. Warszawa 2010.

[2] Balicki W, Korczewski Z, Szczeciński S. Possibilities of the performance improvement of the aero- and marine propulsion units equipped with combustion piston engines. Journal of Polish CIMEEAC. 2010;5(1):7-22.

[3] Chachurski R, Omen Ł, Panas AJ, Zalewski P. Mobilne stanowisko przygotowania i obsługi miniaturowych turbinowych silników odrzutowych – Zestaw odrzutowych celów powietrznych ZOCP-JET2. Biuletyn WAT. 2020;LXIX(4). https://doi.org/10.5604/01.3001.0015.3819

[4] Chachurski R, Szcześciak J, Zduńczyk M. Lodowate zaskoczenie. Przegląd Lotniczy Aviation Revue. 2006;5.

[5] Chachurski R. Powerplants of tactical unmanned aerial vehicles. Journal of KONES Powertrain and Transport. 2007;14(2):91-98.

[6] Chachurski R. Zagrożenia oblodzeniem lotniczych silników tłokowych (in Polish). Prace Instytutu Lotnictwa. 2009;4:141-150.

[7] Chachurski R. Zdarzenia lotnicze związane z oblodzeniem silników turbinowych (in Polish). XIII Ogólnopolska Konferencja Mechanika w Lotnictwie; Kazimierz Dolny2008.

[8] Dziubak S, Dziubak T. Experimental study of an axial flow cyclone with ongoing dust removal from a settling tank. Chem Eng Process–Process Intensif. 2025;209:110167. https://doi.org/10.1016/j.cep.2025.110167

[9] Dziubak T, Dziubak S, Tomaszewski M. Numerical study of the effect of axial cyclone inlet velocity and geometrical parameters on separation efficiency and pressure drop. Powder Technol. 2023;427:118692. https://doi.org/10.1016/j.powtec.2023.118692

[10] Frant M, Kachel S, Maślanka W. Gust modeling with state-of-the-art computational fluid dynamics (CFD) software and its influence on the aerodynamic characteristics of an unmanned aerial vehicle. Energies. 2023;16:6847. https://doi.org/10.3390/en16196847

[11] Głowacki P, Loroch L. Zagrożenia w lotnictwie cywilnym wynikające z niesprawności silników lotniczych. Przegląd Komunikacyjny. 2017;12:24-29.

[12] Haulman DL. U.S. Unmanned aerial vehicles in combat, 1991–2003. Air Force Historical Research Agency. 2003.

[13] Johnson RO, O'Neil M. Unmanned aerial vehicles in perspective: effects, capabilities, and technologies. United States Air Forces Scientific Advisory Board. 2003.

[14] Kozakiewicz A, Jóźwiak S, Jóźwiak P, Kachel S. Material origins of the accelerated operational wear of RD-33 engine blades. Materials. 2021;14:336. https://doi.org/10.3390/ma14020336

[15] Olejnik A, Kachel S, Rogólski R. Techniques for adjusting qualities of aircraft structural models for more effective aeroelastic flutter analyses. J Phys Conf Ser. 2023;2526: 012040. https://doi.org/10.1088/1742-6596/2526/1/012040

[16] Olejnik A, Kiszkowiak Ł, Rogólski R, Chmaj G, Radomski M, Majcher M et al. The use of unmanned aerial vehicles in remote sensing systems. Sensors. 2020;20:2003. https://doi.org/10.3390/s20072003

[17] Oszczypała M, Ziółkowski J, Małachowski J. Reliability analysis of military vehicles based on censored failures data. Appl Sci. 2022;12:2622. https://doi.org/10.3390/app12052622

[18] Panas AJ, Chachurski RZ, Jakielaszek Z. In-flight testing of the susceptibility to icing of the induction system of the Rotax 582 engine. Journal of KONES. 2016;23(4).

[19] Pągowski Z. Lotnicze paliwa i oleje (in Polish). Prace Instytutu Lotnictwa. 2009;4(199):117-128.

[20] Świątek P. Porównanie parametrów eksploatacyjnych samochodowych silników spalinowych i do samolotów ultralekkich. TTS Technika Transportu Szynowego. 2015;22(12): 2159-2162.

[21] Unmanned Aerial Vehicles Reliability Study. Office of Secretary of Defense, Department of Defense. 2003.

[22] Wróblewski P, Iskra A. Problems of reducing friction losses of a piston-ring-cylinder configuration in a combustion piston engine with an increased isochoric pressure gain. SAE Technical Paper 2020-01-2227. 2020. https://doi.org/10.4271/2020-01-2227

[23] Wróblewski P, Koszalka G. An experimental study on frictional losses of coated piston rings with symmetric and asymmetric geometry. SAE Int J Engines. 2021;14(6):853-866. https://doi.org/10.4271/03-14-06-0051

[24] Wróblewski P, Świątek P, Kachel S, Zyska T. Development and research of a hybrid power unit for ultralight aircraft: an innovative approach to energy efficiency and operational flexibility. Combustion Engines. 2024;197(2):83-96. https://doi.org/10.19206/CE-174721

[25] Ziółkowski J, Małachowski J, Oszczypała M, Szkutnik-Rogoż J, Lęgas A. Modelling of the military helicopter operation process in terms of readiness. Defence Sci J. 2021; 71(5):602-611.

[26] Żurek J, Małachowski J, Ziółkowski J, Szkutnik-Rogoż J. Reliability analysis of technical means of transport. Appl Sci. 2020;10:3016. https://doi.org/10.3390/app10093016

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