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Michał CZARNECKI

Combustion Engines
Polish Scientific Society of Combustion Engines

Micro gas turbine evolution, a quarter-century review

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The presented article describes the changes over the past quarter-century in the design and performance of micro-class gas turbine engines. The primary goal is to determine the current stage of development in engine construction. To achieve this, a representative group of 83 micro-class engines was selected and categorized based on the date they were introduced into operation. The main performance criterion was the engine's thrust, as these engines are primarily used in short-lifespan unmanned aerial vehicles (UAVs). A rotational performance characteristic was identified for a family of engines grouped into three geometric series. These characteristics are presented in relative parameters, facilitating convenient implementation in UAV design. A new trend in fanjet engine construction was identified, where thrust generation is primarily driven by the mass flow of the working medium passing through the engine duct. This is observed in modern engines with thrust exceeding 20 daN. It was demonstrated that, while maintaining the same external dimensions, a contemporary engine can deliver three times the thrust of a similar engine designed at the beginning of the 21st century.

Key words: *jet engine, micro, evolution, performance, review*

1. Introduction

The design work on early turbine engines, referred to as model engines, was limited by financial resources allocated for research and the construction of prototype designs. Consequently, the teams carrying out the design work were not large and consisted of individuals associated with the modeling community. The first British design team constructed the pioneering "Barjay" flow micro-engine comprised five members (Jackman J., Write C., Stich D., Carter R., Belcher B.). The design work was initiated in 1975 and completed in 1983 [3]. The American team, led by Bryan Seegers, began work on the S-100 micro-engine in 1978. The first successful test runs of the micro-engine were conducted in 1981, and the project was completed in 1988. In 1986, the German engineer Kurt Schreckling independently began working on his design [13]. The FD-2 project was completed in 1989. In recognition of his contributions to the field of flow micro-propulsion, K. Schreckling was awarded the Whittle-Ohain Trophy in 1994, along with a congratulatory letter from Hans von Ohain. Among the pioneering designers of micro-class engines, Bennie van de Goor (AMT), Mike Murphy (Wren, Xicoy) and Gerald Rutten remain active.

The engine design within a small team requires a "hard" compromise between the time dedicated to project development, the time allocated for technology development, prototype construction and the time needed for performance verification [4]. In the late 1970s and 1980s, the production of micro-turbine engines did not extend beyond individual prototype units. This changed by the late 1990s, as the popularization of aeromodeling led to an increased demand for micro-turbine jet engines, and small-scale production was initiated. Research dedicated to the design of model turbine engines has mainly focused on the use of simple computational methods. Experimentation has been distinctly favored, while thermodynamics calculations have been marginalized and conducted only to a limited extent. Reverse engineering was commonly applied. Today, the micro-turbine engine has become a product, enabling significant technological advancements and access to modern tools.

2. Micro gas turbine generations

Turbine flow engines were first classified by scale in the article "Revolutionary Propulsion Systems for 21st Century Aviation" [16]. Six categories were identified, corresponding to thrust scales: micro – up to 4.45 daN, mini – up to 44.5 daN, small – 4,450 daN, medium – 44,500 daN, and large – above 44,500 daN. Determining whether this classification remains relevant and suitable for contemporary designs is important. It should be noted that while the physics of the phenomenon for engines remains similar, the proportions of engines have changed drastically. For example, considering mass airflow through the engine duct as a criterion and comparing engines developed in the early 1950s, such as the RR Nene and the Turbomeca Palas, the ratio is 12:1 in favor of the RR Royce engine. Today, these boundaries have shifted significantly; comparing the RR Trent XWB engine to the Wren WM54, the ratio is now approximately 9000:1 [8]. Therefore, it is important to initially indicate the scale of the solution, as this involves criteria similarity numbers and engine construction technology. That determines certain processes and imposes design constraints. The author must be aware of this so that, when positioning the solutions under study, they can effectively target the intended audience [5, 17].

This article focuses on engines categorized as micro and mini. A literature review reveals that turbine engines assessed from a design perspective often date back 10 years [7, 12–15]. This reflects a natural progression as solutions transition from open-source concepts to commercial products. The purpose of this article is to review existing designs over the past quarter-century and identify the changes that have occurred during this period. Further analysis will focus on engines divided into three subgroups corresponding to successive generations of designs.

The engines are grouped into three generations based on available technology and the date they were introduced into operation:

Generation 0: Represented by three engines designed between 1995 and 2005, these are pioneering constructions that set the trends for similar designs. Documentation for these engines is publicly available. The most popular example of this era is the FD3-64 engine [13].

Generation 1: Represented by 45 engines introduced to the market between 2005 and 2015.

Generation 2: Represented by 35 engines introduced after 2015.

Generation 0 engines are considered trailblazers, shaping the development of subsequent similar designs. The FD3-64 engine is the first notable example in this category (Fig. 1).

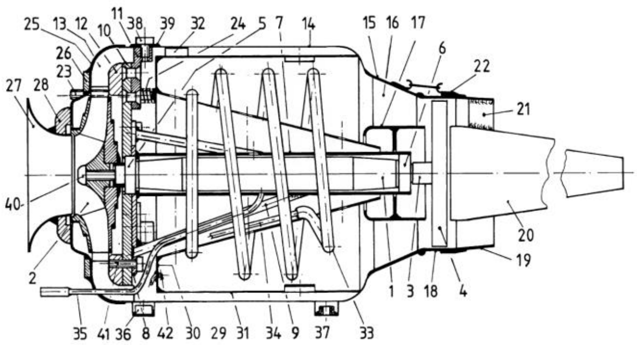

Fig. 1. Kurt Shreckling FD3-64 engine cross-section [13]

The design of this engine was characterized by a maximum allowable rotational speed of 75,000 rpm, directly determined by the strength of the compressor rotor components, which were made from plywood reinforced with carbon composite (Fig. 2). Another limitation arose from turbine components manufactured from sheet metal semi-finished products, chosen to reduce production costs.

Fig. 2. Compressor rotor of the FD3-64 engine [13]

Another engine from the same designer is the KJ66 (Fig. 3), which set trends for the construction of micro-class engines for the following decades [6, 13]. Unlike its predecessor, the KJ66 used a compressor rotor wheel sourced from a turbocharger. Additionally, the combustion chamber and turbine nozzle ring were simplified. These significant modifications resulted in more than doubling the thrust compared to its predecessor.

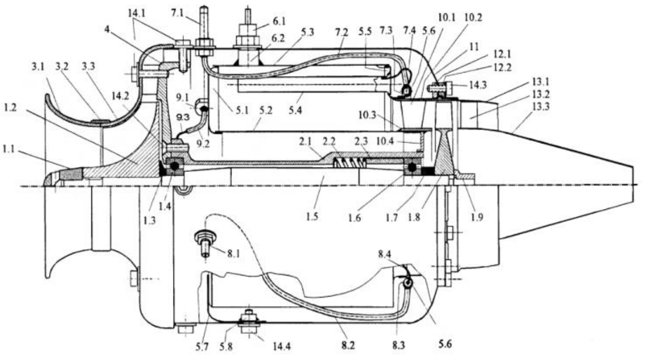

Fig. 3. Shreckling/Artes KJ66 microscale gas turbine cross-section [13]

Following the spectacular success of the KJ66, the MW54 engine was developed in the United Kingdom. This engine featured a 17% reduction in external diameter and a 30% reduction in weight compared to the KJ66. For the first time, the MW54 modified the Garrett GT25 turbocharger compressor wheel by reducing its external diameter (Fig. 4). This adjustment lowered the overall compressor pressure ratio. It reduced the thermal loads on the engine's hot section. This marked the recognition of the commercial potential of such designs. Unlike its predecessors, the MW54 was not the creation of a single individual but rather the result of a design team consisting of four members [12].

A common feature of early versions of Generation 0 engines was the use of six vaporizer tubes in the combustion chamber. These engines were started using an air start method, which involved blowing air toward the compressor rotor.

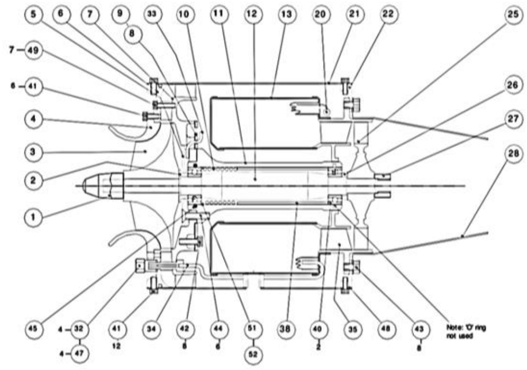

Fig. 4. Wren MW54 mk1 cross-section [12]

These engines required two types of fuel: Jet-A1 kerosene as the primary fuel and LPG. During the start-up phase, LPG was supplied to heat the combustion chamber vaporizers, initiating the kerosene evaporation process. A distinctive characteristic of these engines was the use of a glow plug (Fig. 5).

Fig. 5. Glow plug specific for hybrid ignition – LPG/kerosene

First-generation engines are advancements from their predecessors. The commencement of larger-scale production enabled turbine module components to be manufactured through casting, making the process economically viable. This became possible due to the publication of the design documentation for the early versions of these engines. Turbine modules, which consist of a turbine nozzle ring and a turbine rotor, are sold as kits. Initially, kits compatible with the KJ66 engine (66 mm diameter) were made available, followed by kits with a 54 mm diameter, compatible with the MW54 engine. Over the years, a modified version of the turbine kit with a 70 mm diameter was developed, providing improved engine performance while maintaining the same dimensions [11]. An example cross-section of the first GR180 engine generation was selected (Fig. 6).

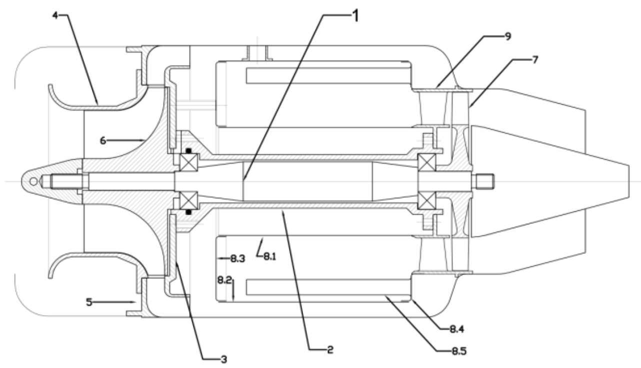

Fig. 6. Gerald Rutten GR180 microscale jet engine cross-section [4]

This engines generation can also be distinguished by its ability to operate on a single type of fuel–kerosene (kerostart). This capability was achieved by using a glow plug with a side fuel inlet (Fig. 7).

Fig. 7. Glow plug with side fuel supply and DC starter

Fuel is injected directly onto the heated glow plug filament in short pulses, generating ignition. This system operates until the combustion chamber is sufficiently heated. These engines were also equipped with an auxiliary starting device, such as a DC electric motor with a clutch mechanism (Fig. 7). Generation 1 engines introduced electronic controllers (Fig. 8), enabling designs with functionality analogous to turbine engines used in the 1980s. This innovation enhanced safety-especially for in-flight start-up procedures and improved user convenience by recording key operating parameters, including RPM, EGT, and others [5, 10].

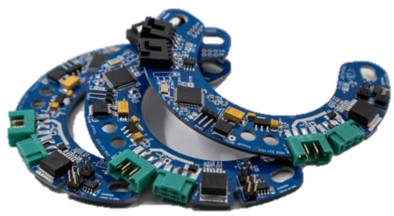

Fig. 8. Sample ECU sensor board manufactured by JetPOL

Second-generation engines represent an evolution of first-generation designs. Compared to the first generation, the starter with a centrifugal clutch has been reduced in size due to the use of a BLDC motor. Similarly, BLDC motors have been implemented in fuel micro-pumps, which has improved the overall reliability of the design. The main drawback of the first generation starting system-overheating and damage to DC motors has been eliminated. Additionally, the spark plug, previously located on the exterior of the engine, is now integrated inside the engine and mounted on the front wall of the combustion chamber. This makes the design more compact, with the engine's outer diameter closely matching the diameter required for installation. Visually, the first-generation Wren MW54 mk2 engine can be compared to the Xicoy X132 engine (Fig. 9), which is its second-generation successor and further refinement of the original design.

Fig. 9. Wren MW54 mk2 vs Xicoy X132 first and second generation external comparison

For second-generation engines, new turbine module sets were introduced, adding a range of diameters: 44, 52, 74, 84, and 99 mm, respectively. This allowed for the development of solutions with more varied thrust capabilities.

3. Micro gas turbine generations comparison

3.1. Rotational speed limitation

Micro gas turbine jet engines of different generations exhibit significant differences in their maximum rotational speed. The baseline design of the FD3-64 engine (Gen 0) was characterized by a maximum allowable rotational speed of 75,000 rpm. This limitation was directly related to the strength of the rotating components, which included a compressor module made from plywood reinforced with composite materials and turbine elements manufactured from sheet metal blanks. In contrast, the compressor in the KJ-66 engine was sourced from the automotive industry and manufactured using casting technology. This advancement allowed the rotational speed to increase to 118,000 rpm.

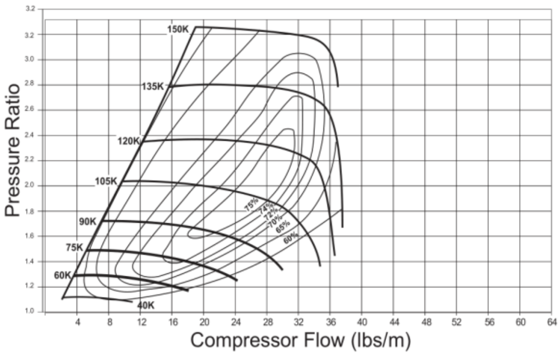

Fig. 10. K26 compressor performance map by BorgWarner [2]

This design has the potential to improve engine performance by increasing the rotational speed to 134,000 rpm, thanks to the capabilities of the K26 compressor rotor (Fig. 10). However, the main limitation of this engine is the durability of the turbine rotor blades (FD3-64 legacy design). A significant advancement came with the MW54 engine, which introduced a new type of bearing, increasing the rotor speed to 154,000 rpm. Unlike the KJ66 engine, the turbine components in the MW54 were specifically designed from the outset for casting technology.

The first-generation engines are mainly derivatives of the KJ66 and MW54 designs. The KJ66 engine was replicated in numerous variants, including the J66, Frank Turbine TJ-67, JetCAT P-80SE, Artes Jet JG100, JetPOL GTM-70, and GR130. Another subgroup consists of modified versions of the JetMax UT160 and GR180 engines. For this group, a new turbine with a 70 mm outer diameter was developed. The rotor design is nearly identical to the KJ66, but the increased mass of the rotor assembly resulted in rotational speeds ranging from 112,000 to 118,000 rpm. The MW44 engine also inspired twin designs, such as the Jet Joe JJ-1400 and PST 600. Additionally, the Lambert Kolibri design emerged, capable of achieving a rotational speed of 240,000 rpm (Fig. 11).

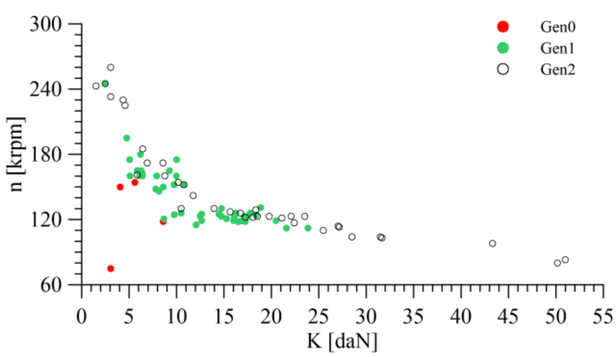

Fig. 11. Rotational speed limitations for selected generations

For second-generation micro gas turbine engines, rotational speeds depend on the diameter of the rotors. A new subgroup of engines has emerged with rotor diameters of 72 mm and 74 mm, operating at speeds ranging from 112,000 to 114,000 rpm. The demand for turbine engines to power UAVs has driven the development of additional designs with turbine components measuring 84 mm and 98 mm in diameter. These engines operate at permissible rotational speeds of 104,000 rpm and 72,000 rpm, respectively.

Table 1. Bearings suitable for micro gas turbine engines

Type	ID	OD	Wd	B	n_{max}
	[mm]				
D6001/604/266C	12	28	8	16	80,000–90,000
D6000/602C	10	28	6	11	75,000–85,000
SV7000C	10	26	8	11	75,000–85,000
D608	8	22	7		140,000–156,000
D688	8	16	6		180,000–200,000

The D688 bearing is used in MW44 and MW54 engines. The D608 bearing is used in FD3-64, KJ66, JetCAT (P80, P120, P160, P200), and GR130 engines. Based on the above considerations, it should be noted that the availability of bearings that meet the design requirements of micro-class engines is the key factor determining the development of this propulsion group. The emergence of new bearing models in the future will enable further expansion of these solutions (Table 1).

3.2. Fuel flow and EGT trend identification

Fuel consumption shows a linear relationship to the thrust generated by the engine (Fig. 12). Estimated fuel consumption is approximately 1/30 of the thrust expressed in daN.

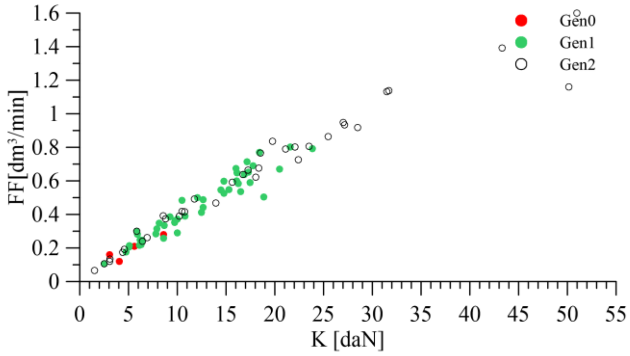

Fig. 12. Fuel consumption trend

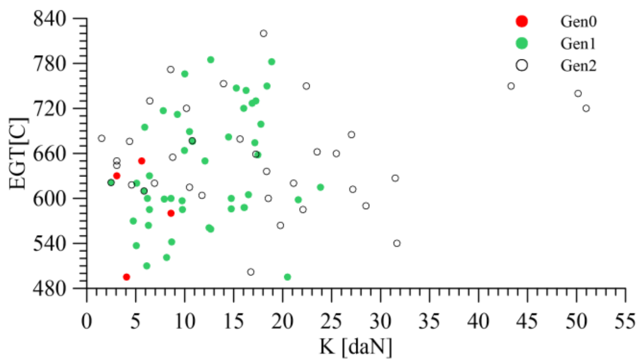

Fig. 13. Exhaust gas temperature distribution

Another key indicator is the exhaust gas temperature, which allows for an approximate assessment of the thermal loads on the engine structure. Exhaust gas temperatures below 650°C characterize Generation 0 engines. Generation 1 brought a significant increase, with 850°C considered the structural limit for micro gas turbine engine systems such as the single spool 1R-1 design (Fig. 13). The rise in temperature can result from increased mass airflow through the engine, higher compressor pressure ratios, or reduced nozzle outlet cross-sections.

For Generation 2 engines, there are two primary trends for achieving thrust:

Conventional approach: Combines working pressure and mass flow, with both primarily responsible for generating thrust.

Fanjet concept: The engine compressor functions more like a fan, generating thrust by increasing mass airflow. This approach allows for reduced exhaust gas temperatures.

3.3. Dimension, weight, thrust-to-weight ratio

The available manufacturing technology primarily determines the external diameters of engines. Housings were produced using welding technology for first-generation engines. Welding posed technological challenges and required stress-relief processes, which complicated construction and increased costs. An alternative solution was the use of gas cartridge housings with diameters of 107 mm (CV470) and 120 mm (CADAC 500). These housings are manufactured using deep-drawing technology from 0.4 mm thick sheet metal, resulting in lightweight and airtight constructions.

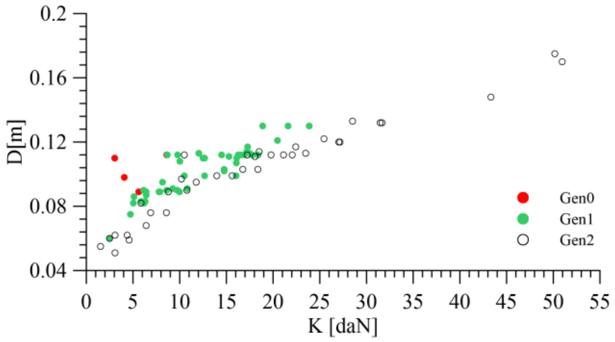

Fig. 14. Engine external diameter trend

Most of the first-generation engines primarily relied on gas cartridge housings. In contrast, the mass production of second-generation engines made the extensive use of gas canisters impractical (Fig. 14). The solution introduced with second-generation engines was the serial spinning of engine housings from aluminium sheet metal.

When the weight of the engine is analyzed as part of the propulsion system, it is observed that the weight is proportional to the thrust at a 1:10 ratio (Fig. 15). It should also be noted that the engine's weight is influenced by the auxiliary equipment included. The first-generation engines are equipped only with the essential components required for operation: a rotational speed sensor, a thermocouple, and occasionally a glow plug. A startup mechanism based on a clutch and a DC motor is used, along with a set of solenoid valves. In the second-generation engines, the DC motor is replaced with a BLDC (Brushless DC) motor. With an estimated mass calculated to have a tolerance of ±10%, an engine that meets the specified requirements can be identified on the market.

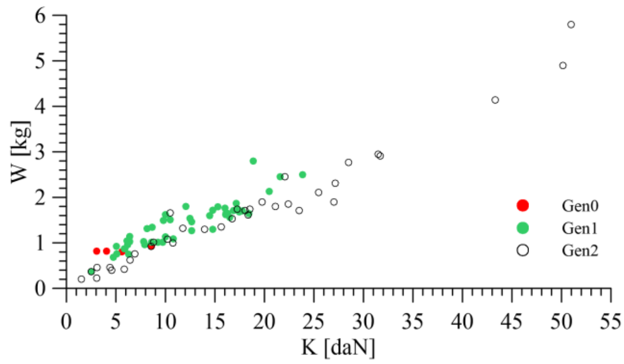

Fig. 15. Engine weight trend

Another important parameter is the thrust-to-weight (T/W) ratio, which indicates how much thrust is generated per kilogram of engine weight. In the graph below, Generation 2 engines are shown, as Generation 1 engines are no longer manufactured, and Generation 0 engines are constructed as hobby projects. Initially, the T/W ratio is estimated to be approximately 10:1 (Fig. 16).

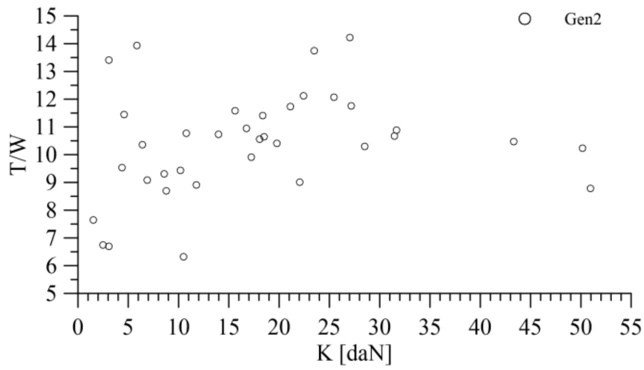

Fig. 16. Thrust-to-weight ratio distribution for modern solutions

It should be emphasized that the engine configuration and the equipment installed determine the T/W ratio. The highest T/W ratios are achieved by engines that utilize air-start mechanisms, as the inclusion of a starter module is not required.

3.4. The fan jet concept

Another important limitation is the engine pressure ratio (PR). The adopted 1R-1 single spool design scheme, due to the technical constraints of a single-stage axial turbine, allows for a compressor pressure ratio of less than 4 (Fig. 17). To maximize engine performance, designers faced the choice between achieving the highest possible pressure ratio or maximizing airflow. With limited space for rotor installation and restrictions on the rotor's allowable outer diameter due to strength constraints, the compressor rotor is selected using a parameter known as rotor trim. A common trim range is 45–55%. There are also designs where airflow is the most critical parameter, and in these cases, trim exceeds 55%; custom-built rotors can even reach a trim of 64.

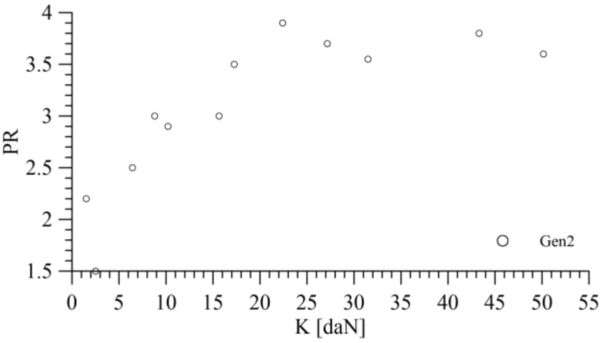

Fig. 17. Engine pressure ratio trend for modern designs

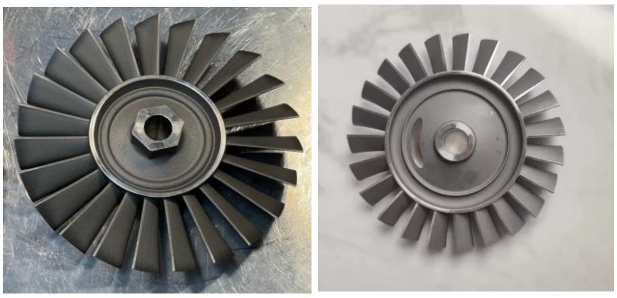

Fig. 18. Fanjet vs. conventional turbine design – 66 vs. 97 mm turbine wheel

The fanjet designs have emerged in engine construction and can be identified by turbines that resemble the final stages of multi-rotor engine turbines. It is important to note that the blades of such rotors, due to their elongated profiles, are extremely sensitive to high temperatures. The design of this turbine is evidently makeshift, with little focus on calculations for the working blade ring during the development phase (Fig. 18).

3.5. Unit price relation

The engine cost is considered a critical factor by UAV designers. When the price lists for Generation 2 engines are analyzed, the price-to-thrust ratio can be used as a criterion to determine the cost per unit of thrust (1 daN). For microclass engines, the cost must not be exceeded beyond $300 USD/daN. A local minimum is observed in the thrust range of 12–35 daN, which is attributed to the mass production of components for this engine subgroup (Fig. 19). The turbine nozzle ring and rotor are included among the critical components, with rotor sizes of 66, 70, and 74 mm being commonly used in this range.

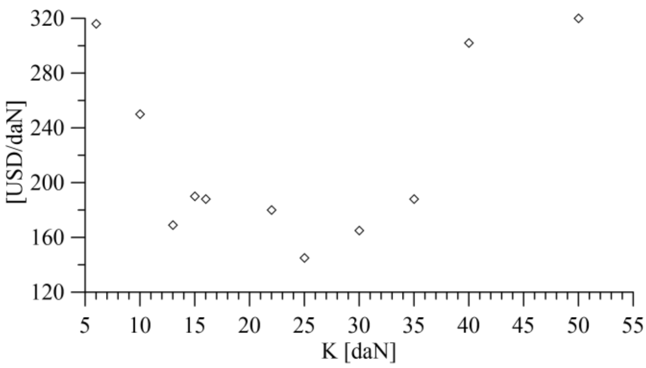

Fig. 19. Modern micro gas turbines price / thrust trend

4. Micro gas turbine engines performance

Key parameters were chosen based on relative engine performance metrics: relative thrust and relative fuel consumption to represent engine performance. The approximation of engine characteristic curves is simplified using this approach.

The relative dependencies describe relationships such as the following:

– Relative rotational speed
– Relative engine thrust
– Relative fuel consumption.

During performance analysis, engines are divided into subgroups. The first subgroup is defined by engines constructed with turbine sets of 44 mm and 54 mm in diameter. An outer diameter of less than 90 mm is characteristic of these engines (Fig. 20).

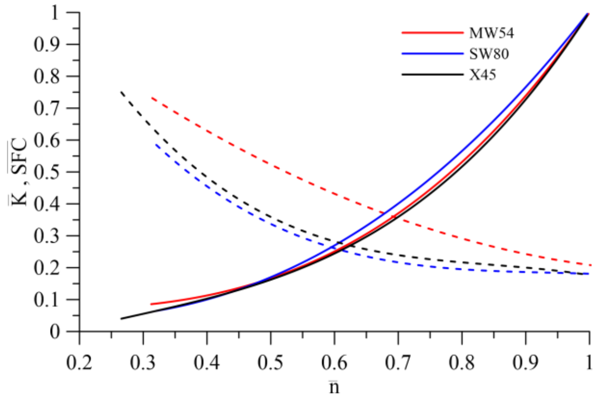

Fig. 20. Performance chart for micro gas turbine engines under 90 mm of external diameter

The engine marked in red, MW54, is classified as a Generation 0 engine. The engine marked in blue, SW80, is identified as a modern version based on the MW54 design. The engine marked in black, X45, is derived from the MW44, which is geometrically reduced by 15% compared to the MW54. Both the X45 and SW80 are categorized as Generation 2 engines. The thrust curves for these engines are observed to be almost identical, indicating that geometric similarity is maintained in the compressor rotors. However, the specific fuel consumption curves are found to be more favorable for the X45 and SW80 engines. This improvement is attributed to advancements in combustion chamber design, as a two-decade development gap exists between these engines and the MW54.

The second group of engines is composed of those constructed using sets with diameters of 66 mm and 70 mm. The first engine in this group, the KJ66/J66, is classified as a Generation 0 engine and is based on a 66 mm set. The SW120 and SW190 are identified as Generation 2 engines constructed using a 70 mm set (Fig. 21). The key difference between these engines is observed in the use of different compressor wheels. The relative thrust curves are noted to be similar and characteristic of radial rotors. Specific fuel consumption is reduced as thrust is increased, which is explained by the higher airflow, taller flow channels, and reduced friction losses of the working fluid against engine components.

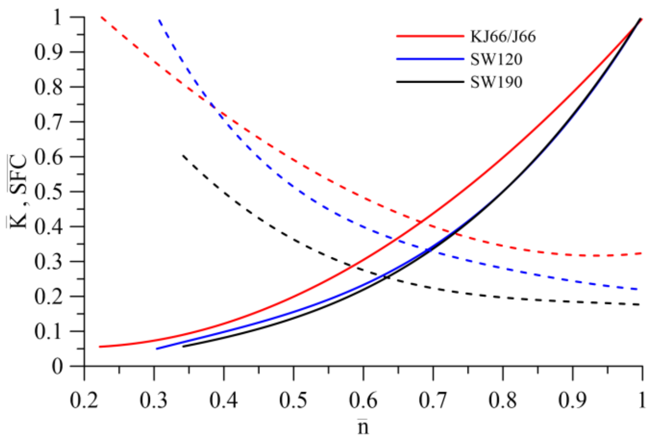

Fig. 21. Micro gas turbine performance comparison by generation

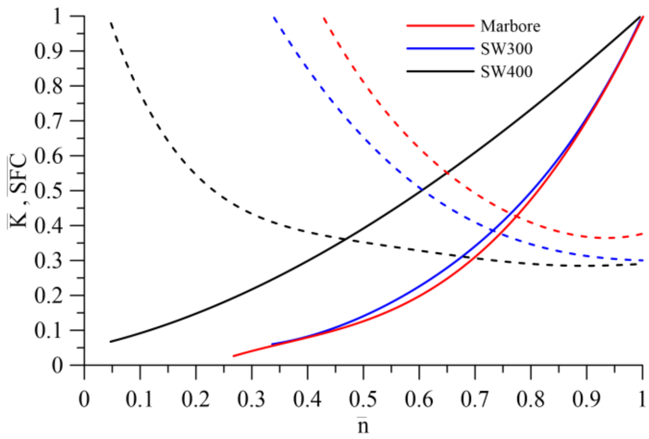

Fig. 22. Performance comparison by a full-scale gas turbine engine (red), micro gas turbine conventional design approach(blue), fanjet design(black)

The last group consists of second-generation engines introduced after 2015, making them modern solutions. These engines have been compared to the Turbomeca Marboré, a typical turbine engine built in a 1A+R-1 design configuration. This comparison highlights the differences and similarities between full-size turbine engines and micro engines. When comparing the thrust and specific fuel consumption curves of the SW300 and Marboré engines, it becomes evident that their compressor rotors are geometrically similar. The SW400, however, differs from the other designs, as its relative thrust curve exhibits a gentler slope compared to the other engines. This indicates that the SW400 is likely designed around high mass flow rates. This engine was designed following the principles of the fanjet philosophy (Fig. 22).

5. Summary

A promising future is seen for microjet engines. Over the last quarter-century, significant potential for modernization has been demonstrated. To begin, the classification of microjet engines should be reevaluated. This classification can be simplified into three categories based on thrust criteria:

– Micro: ≤ 44.5 daN
– Small: ≤ 445 daN
– Full-size: > 445 daN.

This division is determined not only by thrust but also by the internal structure of the engines, which allows for the integration of a closed (lossless) oil system [7]. It is also possible for turbine engines to be classified based on the mass flow rate of air through the engine duct. This criterion is considered stricter compared to thrust, as thrust is derived from the flow rate, pressure, and temperature of the working fluid. The airflow rate is highly influential in determining the dimensions of the flow channel, as well as in affecting the feasibility of rotor installation, including the selection of the oil system type. An alternative classification can be proposed with three categories:

– Micro engines with an airflow rate of up to 1 kg/s
– Small engines with an airflow rate of up to 10 kg/s
– Turbine engines (full size) with air flow rate exceeding 10 kg/s.

Engines in the first group are primarily characterized by the simplification of fuel and oil systems [1]. In the case of small engines, including APU units, full-sized fuel and oil systems are used, with clear technological oversizing observed due to the implementation of connector joints. For turbine engines in the third group, such limitations are not encountered. This often leads to imprecise recommendations, which can mislead an inexperienced reader.

Certain proportions are considered important for modern micro-class engines in relation to their thrust. Ratios that have been observed include:

– Fuel consumption: 1/30 of the thrust
– Engine weight: 1/10 of the thrust (T/W ratio).

These proportions are regarded as valuable for preliminary UAV calculations and for determining dimensions during iterative design processes. It can also be assumed that if a micro engine is not equipped with a fanjet-type turbine, its characteristics will qualitatively resemble those of small-class turbine engines with the same design configuration (Fig. 22). Due to the fact that micro gas turbine engines have been implemented in military systems, an increase in the overall volume of such designs on the market is to be expected, with a clear distinction between civilian and military markets [8]. It is anticipated that the performance of the next generation of these engines will improve by no more than 15% while maintaining the same external dimensions [6, 18]. Further improvement will require the rotor configuration to be changed from 1R-1 to 1A+R-1.

Nomenclature

BLDC	brushless DC motor
DC	direct current motor
EGT	exhaust gas temperature
K	engine thrust
LPG	liquefied petroleum gas
SFC	specific fuel consumption
T/W	thrust to weight ratio
W	engine weight

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Michał Czarnecki, DEng. – Faculty of Mechanical Engineering and Aeronautics, Rzeszów University of Technology, Poland.
e-mail: *czarn@prz.edu.pl*