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Military vehicle options arising from the barrel type piston engine

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Abstract

The article reviews knowledge about requirements for engines in state-of-the-art unmanned aerial vehicles and tanks. Analysis of design and operational parameters was carried out on selected turboshaft and piston engines generating power in the range of 500 - 1500 kW (0.5 - 1.5 MW). The data was compared with the performance of innovative, barrel type piston engines, which are likely to become an alternative drive solution in the target vehicle groups.

Keywords: military UAV, tanks, turboshaft engines, piston engines, barrel type piston engines

1 Introduction

This article consolidates knowledge on options and capabilities arising from use of the barrel type piston engine in military vehicles.

Firstly, the article presents engines already in use in military drones. Then, we look at issues concerning engines that are used in tanks. After assessing present-generation drone and tank engines, we compare them with barrel type piston engines.

The progress and evolution of unmanned aerial vehicles have raised their profile and importance in the military. Drones play vital roles, complementing those of manned combat aircraft. They perform missions of various types such as persistent intelligence, surveillance, target acquisition and reconnaissance (ISTAR). The autonomy of unmanned aerial vehicles (UAVs), which allows them to carry out missions without endangering human assets, is highly valued but the key feature is their flight endurance and range.

Most UAVs whose power drive unit generates power between 0.5MW – 1.5MW are equipped with piston or turboshaft engines. The two constructions differ in many ways. One major difference is specific fuel consumption, which correlates with engine efficiency. The piston engine outperforms the turboshaft engine in terms of efficiency, meaning that piston engines can deliver enhanced range and endurance. This is beneficial in missions requiring a stopover for refueling and particularly useful for unmanned supply, observation and maritime missions.

In contrast, land combat vehicles have significantly different drive unit requirements. High mobility enables the vehicle to rapidly change location after detection. To this end, the torque curve as a function of the rotational speed of the shaft is of decisive importance.

The complexity of tank engines adds an additional layer of requirements, impacting the reliability and durability of the power unit, and they come with related manufacturing and operating costs.

In military land vehicles, the engine should be as small as possible; the space saved can be used for other purposes.

As with UAVs, low fuel consumption is desirable in combat land vehicles, as logistics issues have always posed major problems throughout military history.

The barrel type engine is proposed as an alternative drive unit for both UAVs and land combat vehicles. Requirements of air and land units are met by innovative construction. More details about solutions used in engines of this type are presented in Section 4 of this article.

2 Millitary UAVs

UAVs now form a standard element in the military mix. Escalating demand for UAVs has driven intense research and development. Technological advancements have dramatically broadened drone capabilities and endurance, with one high altitude pseudo satellite now able to stay aloft for months [1]. While UAVs are unlikely to fully replace manned combat aircraft, at least in the foreseeable future, their autonomy decreases mission cost and ensures crew safety.

Military type UAV [2]:

- Combat UAVs
- Endurance UAVs
- High autonomy UAVs
- Medium autonomy UAVs
- Reconnaissance UAVs
- Rotorcraft UAVs
- Transport and utility UAVs
- Cruise missiles.

Endurance UAVs and cruise missiles are powered by different kinds of drive unit and fall outside the remit of this article.

Combat UAVs can carry armament and sensor packages. Due to their multitasking ability, they have an advantage over smaller reconnaissance drones. This group of UAVs is mainly used in airstrikes.

Drones use sensor packages to gather data for long periods over extensive operating ranges, often above rough terrain far from base. In special situations, UAVs are used as a measure that can be more easily written off; hence drones are sent to places that are too dangerous for helicopters or attack aircraft, thereby ensuring crew safety.

Reconnaissance, and high and medium autonomy UAVs, are intended for strategic research and data gathering in foreign territory. During design, a maximalist-minimalist approach is used. This means that a UAV is equipped with several high-performance systems and multiple devices with a smaller range of capabilities. Airplanes were originally used for this type of operation, but despite flying at high altitudes they were still liable to interception. Unmanned high-altitude platforms can be smaller and more difficult to detect and do not put pilots at mortal risk.

Rotorcrafts are used in places with limited space for take-off and landing. In contrast to conventional aircraft, they can operate in tight spaces and hover precisely. They move at lower speed and have a more complex structure than fixed-wing UAVs. The complexity of the rotorcraft results in higher cost of construction.

Military transport and utility drones are used in logistics. Every military operation depends on a steady supply of matériel. The use of UAVs for transport purposes reduces the human risk involved in ambushes or attacks on land transport. They also reduce the risks inherent in all road transport, such as accidents caused by driver fatigue and error.

In the next section, we present examples of drones powered by turboshaft or piston engines, generating power in the range of 0.5 - 1.5 MW.

2.1 Honeywell TPE331-10

A turboprop engine (military designation: T76), originally designed in 1959 by Garrett AiResearch and certified in 1965. The series now includes 18 engine models and 106 configurations. The engine has been produced since 1999 by Honeywell Aerospace. The engines power output ranges from 575 to 1650 shp (0.429 to 1.23 MW)[3].

Figure 1: Honeywell TPE331-10 [3]

Version TPE331-10T (Fig. 1) generates a maximum of 0.671 MW power and is used in MQ-9 Reaper. Works on the successor of the MQ-1 Predator began in 2005. The U.S. Customs and Border Protection, and Department of Homeland Security required an unmanned aerial vehicle for patrol operations, while the US Army was interested in a multipurpose long-range UAV.

In the meantime, a contract was signed for design and construction of the MQ-9 Reaper search and attack drone (Fig. 2). In 2007, the first Reaper squadron was created by the US Air Force, which then operated over Iraq. In 2008 the drones were used in combat operations over Iraq and Afghanistan.

Figure 2: MQ-9 Reaper[4]

The first Reaper concept used the Predator as a test platform. First, a version equipped with a turbofan engine and a version with an enlarged airframe

MQ-9 Reaper		
Lenght	11.0	m
Span	20.1	m
Height	2.1	m
Empty weight	2 220	kg
Fuel weight	1 815	kg
Armament weight	1 360	kg
MTOW	4 760	kg
Performance		
Maximum speed	370	km/h
Range	1 852	km
Service ceiling	15 240	km
Endurance	28	h
Armament		
Up to four AGM-114 Hellfire air to ground missiles		
Two 227 kg GBU-12 Paveway II laser-guided bombs		

equipped with a turboprop engine was tested. The second version is used at NASA under the name Altair. In contrast to the standard Reaper, Altair is unarmed and includes an advanced avionics package required by measurement and research equipment.

The MQ-9 Reaper served mostly in Afghanistan and Iraq, where it used bombs and missiles to attack enemy vehicles, using precise guidance [2].

2.2 Turbomeca Ariel 2N

Turboshaft engine, certified in December 2014, is the newest addition to the Ariel 2+ family. Ariel 2N generates take-off power of 0.53 MW. Its maximum power, via the OEI-30, approaches 0.75MW [5].

Figure 3: Turbomeca Ariel 2N [5]

Relative to its predecessor Ariel 2C, it features a new axial compressor, a new HP compressor diffuser, new HP turbine blade material, and a new-generation, dual-channel FADEC linked to an upgraded fuel system [5]. Turbomeca Ariel 2N (Fig. 3) drives the Eurocopter AS565MBe Panther, which is a medium-weight, multipurpose twin-engine helicopter, adapted to work in all weather conditions. The helicopter can be operated onboard of ships or at sea completing a full range of maritime missions.

The engine was designed for new helicopter concepts such as the Korean military helicopter LAH. Ariel 2N was used in the Tactical Robotics Cormorant (formerly AirMule) (Fig.4). It is a compact, unmanned, single-engine, VTOL (Vertical Take-Off and Landing) aircraft that was constructed in Israel for the needs of the Lebanon conflict. The first flight is dated to January 2009. The project assumed a quick and efficient mode of transporting wounded from the combat zone and delivering supplies in a crowded, urbanized area. It is also intended to be used in large-scale logistics operations when supplying huge combat teams in the field or transporting personnel requiring transfer to the rear.

The vehicle reduces the vulnerability of fighting units to mines and roadside improvised explosive devices. It eliminates fatigue of drivers or pilots and allows high-risk operations to be undertaken without endangering the lives of crew [2].

Cormorant uses an innovative system of internal rotors consisting of two large downward facing rotors that keep the ship in the air and two smaller drive-direction rotors. There are no rotating parts outside the drone outline to ensure the safety of people in its vicinity.

In case of engine, rotor, or transmission emergency a parachute system is automatically activated to safely bring the ship to ground.

Figure 4: Tactical Robotics Cormorant [6]

Cormorant is equipped with two laser altimeters and radar systems for navigation and target designation

Table 1: Cormorant Specification

Tactical Robotics Cormorant		
Length	5.2	m
Width	3.5	m
Rotor diameter	1.8	m
Height	2.3	m
Empty weight	771	kg
Maximum payload weight	635	kg
Performance		
Maximum speed	180	km/h
Endurance	5	h
Service ceiling	3 600	m

as well as GPS and inertial navigation systems. It is controlled manually from the ground station or, if necessary, the UAV can be operated autonomously.

Urban Aeronautics, which owns Tactical Robotics, also runs projects with aircraft equipped with Arriel 2N adapted to highly urbanized areas. Plans include an autonomous ambulance, taxi, private transport and a mobile office.

2.3 Honeywell T53-17A-1

Designed in Lycoming Turbine Engine Division in Stratford, Connecticut, by a team headed by , who was the chief designer of the world's first turbojet engine, WWII Junkers Jumo 004. In July 1952 Lycoming was awarded a contract from Air Force Air Materiel Command to develop a turbine set engine with a free turbine, designated LTC1 (military designation T53-L-1). The first T53-17A-1 (Fig.5) was delivered in 1959 and was certified in June 1966. It is currently produced by Honeywell Aerospace [7].

Figure 5: Honeywell T53 Cutaway view [7]

The T53 front-wheel-drive coaxial drive system was the widely accepted American standard for turbo-shaft engine design and gave Lycoming a start in the aircraft gas turbine industry. It was a key technology contributing to the increased mobility of military aviation during the Vietnam War. The engine was used in Bell UH-1 Iroquois (Huey) and AH-1 HueyCobra helicopters and Grumman OV-1 Mohawk airplanes. Kaman K-MAX (Fig.6) is a representative of drones equipped with Honeywell T53-17A-1.

Figure 6: Kaman K-MAX[8]

It is an optionally piloted vehicle that can be piloted autonomously or with a human pilot on board.

Kaman K-Max is a synchropter with two counter-rotating rotors in a Flettner arrangement. Due to this solution, the rotors do not collide with each other and compensate for their torque. This eliminates the need for a tail rotor and associated power transmission mechanisms. In this way, the problem of conventional helicopters is eliminated, and the drone does not tend to spin in place (K-MAX).

The specific structure of the helicopter is adapted to the tasks of a flying elevator. By the structure of the fuselage, the pilot has excellent sideways and downward visibility, which is useful during loading and lowering operations. The entire load is carried by the external hook under the fuselage, so the helicopter is only loaded with its weight and fuel during take-off and landing. The use of these solutions allowed to achieve the ratio of payload to the MTOW of 57%.

In 2011-2014, the drone was used in Afghanistan, where the key was to transport cargo, completely resistant to IED attacks, to ensure regular supplies to military units. During this time, one PRO K-Max model crashed as a result of bad weather conditions and the swing of the suspended load. Despite the accident in Afghanistan, the program was considered a success and the drone itself proved that it can successfully function in difficult operating conditions.

The concept seems so proven and promising that the US Marines declared the use of PRO K-Max unlimited and indefinitely. Numerous countries are currently interested in this concept. To the best of our knowledge works are underway to increase the UAVs' capabilities. Current research includes the automation of

Table 2: Specification Kaman K-MAX

Kaman K-MAX		
Length	15.8	m
Rotor diameter	14.71	m
Height	4.14	m
Empty weight	2 334	kg
Maximum payload weight	2 722	kg
MTOW	5 443	kg
Performance		
Maximum speed	185.2	km/h
Operational speed	148.2	km/h
Range with payload	396.3	km
Range without payload	494.5	km
Service ceiling	4 600	m
Crew		
Optionally one pilot		
Fuel		
Fuel capacity	831	l
Jet A consumption	252.9	kg/h
Endurance	161	min

risk avoidance systems and the possibility of redirection and reprogramming of first-person view and UAV tasks in flight.

3 Tanks

The effectiveness of tracked combat vehicles is determined by three basic factors [9]:

- armament, including damage, target detection, and firing precision,
- resistance to bullet impacts and the effects of other enemy attacks,
- mobility to quickly change positions to avoid detection and enemy strike.

Most combat vehicles are currently equipped with compression-ignition engines and only a few are powered by turboshaft engines. Moreover, work is underway on new technologies for electric combat vehicles of the future. Their implementation depends on technical and economic factors.

As combat vehicles have a wide range of tasks to perform, their power units must meet multiple, specific requirements, such as:

- high values of torque, overall power and unit power of the engine (ratio of engine torque and power to dimensions and engine weight),
- high driving force when starting the vehicle,
- low fuel consumption,
- high durability and reliability.

Engine torque density (power density) is important, because large power units require a larger armored space, thus increasing vehicle weight and adversely impacting traction properties. Hence, concepts of integrated drive units are used that combine engine, air intake and exhaust gas exhaust systems, and the powertrain. Such solutions significantly reduce the volume of the drive units and the armored volume of the vehicle.

High driving force is required to rapidly change position and overcome terrain obstacles. Driving force is very important in the functionality of a vehicle's driveshaft rotational velocity. Since piston engines have torque discontinuity at low rotational speeds, they can only be loaded after exceeding a certain minimum rotational speed. This significantly extends the time needed for the vehicle to accelerate after it is detected by the enemy. The piston engine also suffers from loud running, making the vehicle easier to detect.

Lower fuel consumption is related to a lower burden on the logistics supply chain. The transport of large amounts of fuel for the needs of fighting troops constitutes 40% of transported supplies [9].

3.1 MTU MB 873 Ka 501

The MTU company produces a series of twelve-cylinder, V-type 90° diesel engines MB 870. The MB 873 Ka 501 (Fig. 7), which generates 1.1 MW (1500hp), drives the Leopard II. The engine accelerates a 67 500 kg vehicle to a speed of 72 km/h. It is equipped with two turbochargers with an intercooler, a liquid-cooling system and a Renk HSWL 354 gearbox. The engine and drive transmission systems are separated from the crew by a firewall.

Figure 7: MTU MB 873 Ka 501 [10]

The Leopard 2 is a main battle tank manufactured from October 1979. It is the first tank belonging to the third generation of tanks. Various versions have served in the armed forces of Germany and 12 other European countries, as well as several non-European nations, including Canada, Chile, Indonesia, Singapore and Turkey. The Leopard 2A5 and its newer versions have angled arrow-shaped turret appliqué armour together with digital fire control systems with laser rangefinders, advanced night vision and targeting equipment, and a fully stabilized main gun and a coaxial machine gun.

Figure 8: Leopard 2A7+[11]

The newest model, Leopard 2A7+(Fig. 8) was introduced to the public at the Eurosatory in 2010. The Leopard 2A7+ is designed to operate in low intensity and high-intensity conflicts. The tank protection has been increased by modular armour; the frontal protection has been improved with a dual kit on the turret and hull front, while 360° protection against RPGs and mine protection increase the survivability of the tank in urban operations. It can fire programmable HE munitions and the turret mounted MG3 has been replaced with a stabilized FLW 200 remotely controlled weapon station. Mobility, sustainability and situational awareness have also been improved [11].

The tank is adapted to overcome difficult terrain. Leopard 2 can drive through water 4 meters deep using a snorkel or 1.2 meters without any preparation. It can climb vertical obstacles over one meter high.

3.2 Avco Lycoming AGT-1500

Turbine engines used to drive land combat vehicles constitute a minority in the group of engines used in this type of vehicle. Currently, two models of tanks are equipped with turboshaft engines: M1 (AGT1500 engine) and T80 (GTD1000 engine). These engines have maximum torque with the drive turbine rotor stopped, which enables high acceleration from rest. However, the turboshaft engine also has disadvantages, including high fuel consumption in transient operating states or when idling. This is due to the steep overall efficiency curve of the engine. Added to this is the need for fine filtration of several times more air than a piston engine. High sensitivity to environmental conditions (pressure, temperature and humidity) may worsen their parameters. The turbine engine itself is relatively small, but its overall volume is increased by the use of large air filters and of heat exchangers to reduce fuel consumption. As a result, the armored volume of the vehicle increases significantly.

Figure 9: Avco Lycoming AGT-1500[12]

The Honeywell AGT1500 (Fig. 9) is a gas turbine engine from the 1960s. It is the main powerplant of the M1 Abrams series of tanks. The engine was originally designed and produced by the Lycoming Turbine Engine Division in the Stratford Army Engine Plant. In 1995, production moved to the Anniston Army Depot after the Stratford Army Engine Plant closed. Engine output peaks at 1.12 MW, with 3754 Nm of torque at that peak which occurs at 3 000 rpm. The maximum torque of 5355 Nm is reached at 1 000 rpm. The engine can use a variety of fuels, including jet fuel, gasoline, diesel and marine diesel.

This unusual drive unit for tanks has advantages like the torque curve peaks at the lowest rotational speeds, providing high acceleration. The turbine can also be easily started at low temperatures, has a relatively simple structure and relatively quiet operation, especially when compared with the MTU MB 873 Ka 501 diesel engines. This is why Abrams tanks have earned the sobriquet “Whispering Death”.

On the other hand, the turbine needs large amounts of fuel and air. The large air filters (the air filtration system has a total volume of 0.68 m^3) need replacing often – in dusty Middle East conditions they sometimes had to be changed every day.

High air requirements also make it difficult to overcome water obstacles. Only a small percentage of Abrams tanks are deep wading, capable of overcoming water obstacles, and the risk of a serious failure

Table 3: Specification Leopard 2A7+

Leopard 2A7+		
Width	3.76	m
Height	2.64	m
Length	10.97	m
Fuel capacity	1200	dm3
Protection	Modular armour Dual-kit on the turret and hull front 360° protection against RPGs mine protection	
Crew	4 people	
Combat weight	67 500	kg
Performance		
Maximum speed	72	km/h
Range	340	km
Armament		
Rheinmetall 120 mm smoothbore gun L/55 Two machine guns MG3		

in the event of flooding of the hull roof is significant. There are known cases of permanent immobilization of the tank when driving through water-filled ditches - the splashing water damaged the engine so much that it was impossible for the crew to remove the defect (and even maintenance vehicle crew failed).

The engine also requires large amounts of fuel - JP-8 aviation fuel. According to data from comparative tests conducted in Sweden in the 1990s, the Abrams consumed an average of 148 liters of fuel per 10 km. For comparison, the Leopard 2I with the MTU MB873 engine of the same power consumed only 72 liters per 10 km (the routes covered were 3800 and 3730 km, respectively, the total fuel consumption was 56,488 and 26,874 liters).

Figure 10: M1A2 Abrams [13]

Table 4: Specification Abrams

Abrams M1A2 SEP		
Width	3.75	m
Height	2.4	m
Length	9.77	m
Fuselage length	7.92	m
Fuel Capacity	1 900	dm3
Protection		
Depleted uranium inserts in hull and turret Chobham armor, increased turret armor Additions of ARAT ERA, slat armor		
Crew	4 person	
Combat weight	66 800	kg
Performance		
Maximum speed	68	km/h
Range	425	km
Armament		
105 mm M68A1 cannon 120 mm M256A1 smoothbore One machine gun M2HB 12.7 mm Two machine guns M240 7.62 mm		

The engine itself has a relatively low lifetime of only 700 hours. The TIGER program was started in the years after 2005, doubling the turbine's lifetime. Nevertheless, 1400 hours of operating time is not competitive.

The M1 Abrams is a third-generation American main battle tank designed by Chrysler Defense. Production started in 1980. The existing M1 tanks are constantly being modernized, and older versions of the vehicle are upgraded to the modern M1A1SA, M1A1FEP, and M1A2SEP standards. The M1A2 (Fig. 10) includes an independent thermal sight for the tank commander and the ability to, in rapid sequence, shoot at two targets without the need to acquire each one sequentially. The M1A2 SEP has upgraded third-generation depleted uranium armor components with graphite coating [13].

3.3 GTD-1250

The gas turbine is the main powerplant of a T-80U MBT. It is a development of GTD-1000T and GTD-1000TF engines that were installed on the previous tanks of the T-80 line.

The engine is implemented in a triple-shaft scheme, with two independent turbochargers and a free propulsion turbine with a built-in conicocylindrical reducer, and is kinematically connected to two planetary gearboxes. The engine monoblock comprises the core engine, the air filter, oil tanks, and transmission radiators, fuel filters and the driving gear components. The monoblock is attached to the hull in three points, two stirrups in the rear and one roof-attached support in the front. The turbine has an adjustable nozzle system that provides for braking with the engine, reduces the turbine's rotation speed and prevents overrunning when the gears are changed. The engine can use jet fuels, diesel and low octane gasoline fuel. Engine startup is automated by two electric motors fed by accumulators or GTA-18 auxiliary power units.

Figure 11: T-80 [14]

T-80 (Fig. 11) is a Russian, third-generation, main battle tank. The project was created in the design office of the Kirov Works in Leningrad. It was the world's first mass-produced tank equipped with a gas turbine. The first one rolled off the assembly line in 1976. The T-80 is still produced at the plants in Omsk, Russia, and Kharkiv, Ukraine. The tank is a construction based on the T-64 tank. Since 1985 there is a newer variant: T-80U equipped with the GTD-1250 turbine. In parallel with the T-80U and Russia in general, the Morozov Bureau in Ukraine developed a diesel-powered version: T-80UD. It is powered by the 6TD, a 6-cylinder charged, opposed-piston, multi-fuel, two-stroke diesel engine generating 737.5 kW of power. The replacement gave higher fuel efficiency and a longer cruising range. The 6TD support systems make it possible to operate the tank at a temperature of up to 55 °C and to cross water obstacles of 1.8 m in depth [14].

Table 5: T-80/T-80U Specification

T-80/T-80U		
Width	3.4 /3.6 (T-80/T-80U)	m
Height	2.2	m
Length	9.9/9.65 (T-80/ T-80U)	m
Fuselage length	7.4(T-80) 7.0 (T-80U)	m
Fuel Capacity	1 100 1 840 with additional containers	dm3
Protection	500 Turret: 550(T-80) 780(T-80U)	mm
Crew	3 person	
Combat weight	42 500(T-80) 46 000(T-80U)	kg
Performance		
Maximum speed	70	km/h
Range	500	km
Armament		
125 mm 2A46-2 smoothbore gun 7.62 mm PKT machine gun 12.7 mm NSVT antiaircraft machine gun		

4 Barrel type engines

They are a kind of axial, counter-rotating engine. What distinguishes this type of engine are (i) cylinders that are parallel to the shaft axis and (ii) the mechanism of converting the reciprocating motion of pistons into the rotation of the output shaft in barrel engines. The combustion chamber is located between two pistons in the cylinder. This piston arrangement optimizes the shape of the combustion chamber - giving the largest possible volume and the smallest surface area of the combustion chamber. Figure 12 presents a concept of eight cylinders in a barrel type engine.

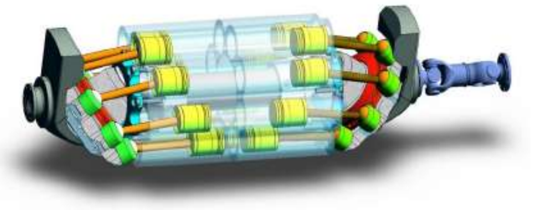


Figure 12: Concept of barrel type engine

The shape enhances the thermal efficiency of the process - more heat is generated (in proportion to volume) and heat losses are minimized (in proportion to heat exchange surface). An additional advantage of OPEs is the lack of a cylinder head, a main source of heat loss. Moreover, it reduces the emission of unburned hydrocarbons and CO, which are produced mainly on the cooled head.

Engines with opposite pistons do not require poppet valves, significantly reducing the engine failure rate and facilitating engine maintenance. Barrel engines provide full axial symmetry, greatly simplifying engine construction and thus facilitating low-cost, large-scale production. The level of vibration is also reduced, giving quieter operation. Another advantage of the parallel alignment of the cylinder axis and the shaft axis is the small frontal surface, which is desirable for fixed-wing aircraft in particular.

4.1 PAMAR engines

PAMAR engines are a type of opposed-piston, axial engines, referred to as barrel engines. Those engines operate in a two-stroke cycle with uniflow scavenging, which provides better conditions in the combustion chamber. The construction of PAMAR engines includes solutions that improve mechanical efficiency and thermodynamic efficiency.

Enhanced mechanical efficiency is obtained by an unusual shaft drive. In barrel engines, the sliding motion of pistons is converted into rotary motion of the shaft in various ways. This is usually done using a special plate – a swash plate or wobble plate mechanism (Fig. 13).

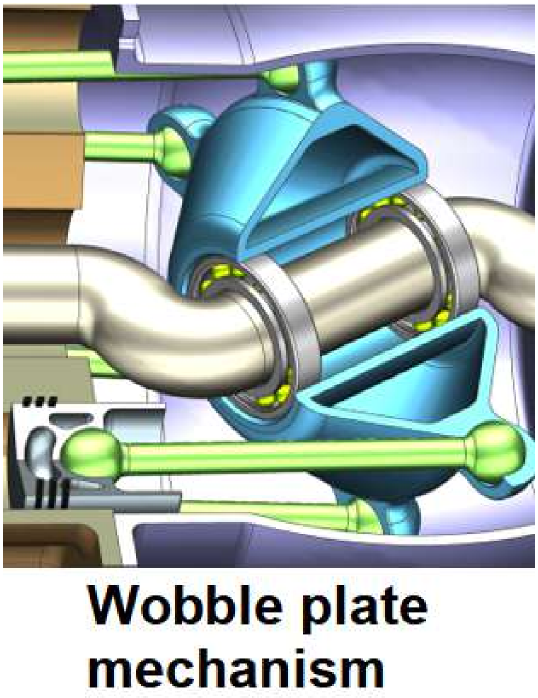


Figure 13: One type of barrel engine plate

The values of connecting rod deviation angles from the cylinder axis are smaller in wobble plate engines compared to conventional engines with a crank mechanism. As a result, the value of the piston side force reduces. Moreover, lower angles provide the possibility of obtaining higher stroke to bore ratios. In constructions based on bevel gears or crosshead, the lateral force acting on the piston may be as much as 50% lower than in a classic engine.

The kinematics of the wobble plate mechanism require the use of spherical plain bearings in the connecting rod-piston and connecting rod-wobble plate (Fig 14). This type of bearing is characterized by a much higher load capacity than common slide bearings and the piston pin.

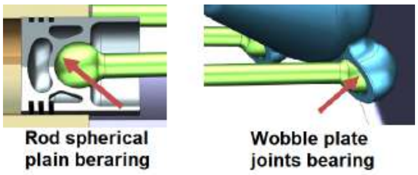


Figure 14: Bearings in the wobble plate mechanism

PAMAR engines achieve high thermodynamics efficiency inter alia due to the characteristic barrel shape of the axial engine with the small frontal area, which is especially important for fixed-wing aircraft. From a thermodynamic point of view, axial symmetry can enable the same filling, lubrication, and cooling conditions for all cylinders. This simplifies the process of controlling optimal engine operation.

With the purpose of reaching the efficiency limit set by the second law of thermodynamics, modifications seek to reduce the heat exchange between the working medium and its surrounding parts, i.e., mainly piston crown, poppet valves, cylinder head, and cylinder liner. In common construction, the strength of a material is the limit. As the temperature peak during the combustion process is up to 2500 K, there is a need to cool the most thermally loaded parts of the engine. Heat dissipation to the cooling system is a waste of energy which, to some extent, could be converted into useful work. The situation in opposed piston engines is different, the engine timing based on the piston movement meaning that it is unnecessary to cool or drive additional poppet valves. A significant advantage is also the lack of a classic cylinder head.

PAMAR engines are characterized by a high stroke to bore ratio value. As a result, the engine has a lower knocking tendency. The possibility of controlling the opening of the intake and exhaust ports by opposed pistons creates ideal conditions for uniflow scaveng-

Table 6: PAMAR engines compared to presented drone engines

Engine Details	TPE331-1		A-1	PAMAR 3
Length [mm]	1087.60		9	1 400
Width [mm]	532.90		4	300
Height [mm]	676.15		2	400
Frontal area [mm2]	361 386	315 732	303 705	120 000
Dry weight [kg]	152	134	249	190.4
Maximum power output [kW]	940	750	1 119	340
Frontal area / Maximum Power [mm2/kW]	384.5	421	271.4	352.9
Maximum torque [Nm]	844	1 193	2 305	1 200
Specific fuel consumption [g/kWh]	325	376	351	197

Requ

The

Table 7: Comparison Arrius 2F and AE440

Engine	Dry weight [kg]	Shaft power [kW]	Specific fuel consumption [g/kWh]	Fuel weight [kg]
Arrius 2F	104	335	550	335
AE440	197	330	235	242

ing. This type of scavenging delivers the greatest efficiency.

Table 6 highlights that in PAMAR 3 the benefits in terms of engine specific fuel consumption and maximum torque far outweigh the disadvantages with regard to engine weight. Moreover, PAMAR 3 was not designed for weight optimization. PAMAR 3 has a comparable value of factor frontal area to maximum power with turboshaft engines.To better illustrate the idea of using piston engines as replacements for turbine engines [15], we used the example of the Eurocopter EC120 Colibri helicopter. The basis of the drive unit is the Turbomeca TM 319 Arrius 2F turboshaft engine, which generates 376 kW power during take-off and a maximum continuous power of 335 kW. The first test flight equipped with a HIPE AE440 compression-ignition engine powered by aviation fuel took place on November 5, 2015. The collected data in Table 4.2 below on the above-mentioned engines was used for simplified analysis:

Assuming the same mass of the craft during take-off, the excess mass of the piston engine was reduced by the deficit of fuel in the helicopter's tanks. Then we made a graph showing the mass of fuel during the flight.

The graph above Fig. 15 shows that a turboshaft helicopter with 38% more fuel has shorter flight endurance by over three hours. During a real test flight with a diesel engine, the helicopter doubled its nominal range.

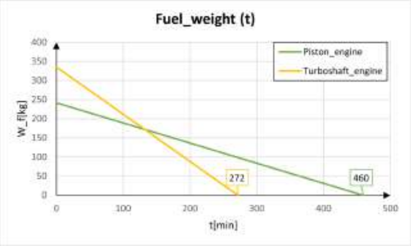


Figure 15: Fuel mass vs. flight time graph

Table 8: PAMAR engines compared to presented tank engines

Engine Details	AGT-1500	GTD – 1250
Length [mm]	1 685	1 491
Width [mm]	990	1 042
Height [mm]	846	888
Engine volume [dm3]	1 356.27	1315.86
Dry weight [kg]	1 134	1050
Maximum power output [MW]	1.118	0.920
Specific power [kW/kg]	0.985	0.876
Power density [kW/dm3]	0.824	0.699
Specific fuel consumption [g/kWh]	300	305
Maximum torque [Nm]	5 355 at 0 RPM	4 395 at 0 RPM

Returning to the PAMAR construction, those engines are also adapted to varying engine loads by Variable Compression Ratio (VCR), Variable Angle Shift, and Variable Port Area. The first system can be used in tanks. The system used in PAMAR engines will not be described in detail, as it will be the subject of a patent in the next few years. The solutions used in PAMAR allow the compression ratio to change very smoothly from 1:10 to 1:20 while the engine is running. Due to the VCR, it is possible to use different fuels i.e., gasoline, diesel, methanol, biogas, and gas fuel with low caloric value. More details on this topic can be found in [16].

Table 8 highlights that in PAMAR 5 the benefits in terms of engine volume, specific fuel consumption and maximum torque far outweigh the disadvantages with regard to engine weight. It is noteworthy that PAMAR 5 was designed for distributed generation with, e.g., an adiabatic combustion chamber, advanced VCR, and three other variable systems that significantly increase weight. The range of the engine's maximum power output depends on the fuel used; the lowest value is predicted for gas fuels with 6 MJ/kg gross calorific value and the highest value is predicted for diesel fuel with double turbocharge.

4.2 Project progress

The team has already developed four engines, and the fifth is currently under construction. The know-how accumulated during work on the first two prototypes with a volume of 50 cm^3 (PAMAR-1) and 600 cm^3 (PAMAR-2) was used to build a larger, more advanced version of the engine with a volume of 3 dm^3 (PAMAR-3) developed in the period 2007-2009. The research included different geometrical configurations, fuels, ignition and injection types. The results of testing the PAMAR-3 engine on the dynamometer exceeded the authors' expectations. So far, mechanical efficiency of $\eta_m = 89\%$ and overall efficiency of $\eta_o = 44\%$ (on gasoline) have been achieved. These values are unprecedented for such small piston engines. All theoretical and numerical analyses carried out by the team have shown that barrel engines have a chance to become a breakthrough solution when increasing efficiency and minimizing harmful emissions is essential.

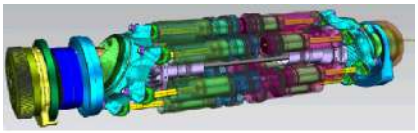
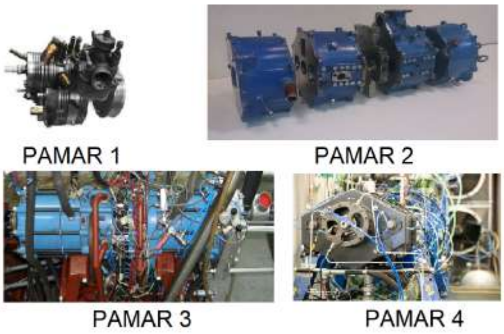


Figure 16: PAMAR 5 engine concept

Within the framework of the GENEKO project, the PAMAR 5 (Fig. 16) engine with a capacity of 24 dm^3 is being built, and the fourth generation engine with a capacity of 1.8 dm^3 (PAMAR 4) is being tested. These tests are mostly aimed at testing the variability systems. Figure 17 shows all PAMAR engines built.



PAMAR 1 PAMAR 2 PAMAR 3 PAMAR 4

Figure 17: PAMAR engines

Our work has led us to the conclusion that drones in the set range of drive unit power are dominated by turboshaft engines. The foremost cause is a significant increase in weight with the power of the piston engine. Powering aircraft with a lighter and shapelier engine is more beneficial than designing a large fuselage to accommodate an engine with a large frontal area. The current trend is to use partially retractable turbofan engines to reduce the thermal footprint.

Piston engines are still the basic technology for driving combat vehicles. They are becoming increasingly technologically advanced, and the possibility of creating whole families of engines from segments of a refined "single cylinder" significantly reduces production costs. These engines are equipped with high-pressure injection systems that facilitate optimal combustion control and significantly increase the power and speed of the engines. The commonly available materials for their construction are also reflected in the moderate price.

Our findings suggest that turboshaft engines will not return for the propulsion of land combat vehicles. However, it is very possible that the modern turbine engine LV 100, developed to replace the previously used ADT 1500, may be an answer, but its implementation is delayed. To the best of our knowledge, until such time as the fuel consumption problem is resolved, turboshaft engines will be a minority in land vehicles.

Barrel type engines might be the answer. Due to their design solutions, the engines combine the advantages of conventional piston engines and turboshaft engines. High overall efficiency, low nominal rational shaft speed, high overall torque, small frontal area and the possibility to use various types of fuel are desired features of modern military vehicles.

5 Nomecnlature

UAV - Unmanned Aerial Vehicle,

FADEC - Full Authority Digital Engine Control,

OPE - Opposed-Piston Engine,

IED - Improvised Explosive Devices

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