Micro turbine engines for drones propulsion

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Abstract. Development of micro turbine engines began from attempts of application of that propulsion source by group of enthusiasts of aviation model making. Nowadays, the domain of micro turbojet engines is treated on a par with “full size” aviation constructions. The dynamic development of these engines is caused not only by aviation modellers, but also by use of micro turbojet engines by army to propulsion of contemporary drones, i.e. Unmanned Aerial Vehicles (UAV) or Unmanned Aerial Systems (UAS). On the base of selected examples the state of art in the mentioned group of engines has been presented in the article.

1. Introduction

Construction of contemporary micro-turbine engines (MTEs) as well turboshaft as turbojet ones is the result of about twenty years of development of that idea. Interesting is that the first designs were done by a group of enthusiasts of aviation model making. There was the need of finding of real engines, but made in micro scale, for propulsion of turbojet or turboprop aircraft models. The development of that area has been the object of particular interest of army. The idea of micro turbine engines application to the propulsion of small and medium size “professional” military Unmanned Aerial Vehicles (UAVs) is at present highly developed. Some of modeller engines have been used for special purposes in the technology demonstrator UAVs like for example X-56A built by Lockheed Martin and NASA [1].
On the base of market demand many specialized firm manufacturing different kinds of micro turbine engines have been established in the world. There are several concepts of construction of mentioned engines depending on the custom demands and available know-how. The selected examples of contemporary micro turbine engines, illustrating contemporary state of art within this area are presented below.

2. Types of Micro Turbine Engines (MTEs)

It is possible to distinguish several types of MTEs taking into account their construction and destination:

- turbojet MTE applied for propulsion by use of a thrust exclusively. There are two kinds of MTEs in this case:
  - with radial compressor and radial turbine,
  - with axial compressor and axial turbine (generally still experimental ones).
- turboshaft MTE applied for propulsion by use of the mechanical torque (power) delivered to the engine shaft (spool). In this case one can distinguish two kinds of construction:
  - single spool (single shaft) engines with gear box used for propulsion of helicopter drones,
  - two spool (dual shaft) engines for turboprop and helicopter aircraft drones.

The last ones are rarely used, but seem to be very "stylish" solution being the functional copy of full size engines. Cross section of a typical micro turbojet engine with radial compressor and axial turbine is presented in the figure 1. That is the example of construction of reverse flow combustion chamber. The compressor rotor is adapted from a serial produced car turbocharger. It is the often used solution, particularly by the amateur constructors, in the aim of manufacturing costs reduction.

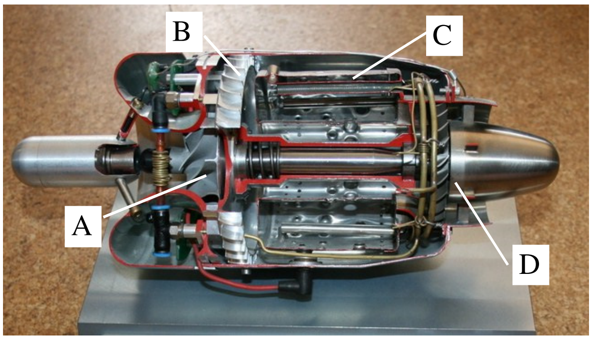

Figure 1. Cross section of a typical micro turbojet engine (MTE):
A - radial compressor rotor, B - diffuser,
C - flame tube, D - axial turbine [2].

The example of new, more advanced construction of turbojet MTE with single shaft 5-stage axial compressor and axial turbine is shown in the figure 2. Such two engines manufactured by Bladon firm, equipped with integral electric generators were applied to the battery charging of experimental Jaguar C-X75 hybrid car (2010) [3, 27].

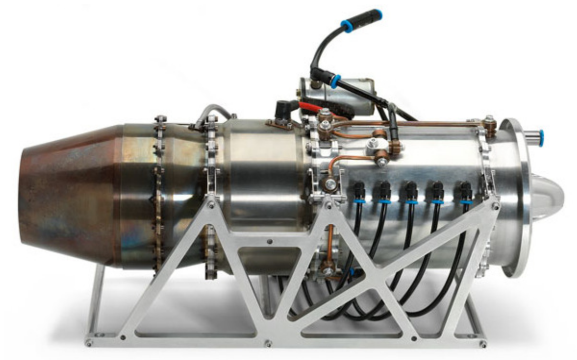

Figure 2. Turbojet MTE with 5-stage axial compressor and axial turbine made by Bladon firm [4].

View of the similar engine shaft with 6-stage axial compressor and axial turbine is presented in the figure 3. The coin visible at the shaft gives outlook on the total scale of the engine and required precision of making. Multistage axial compressor MTEs are contemporary still experimental, however it seems this kind of engines will be dominating in the micro turbojet applications in next several years.

Figure 3. Example of the turbojet MTE single shaft with 6-stage axial compressor and axial turbine [5].

The examples of single spool (single shaft) micro turboshaft engines (MTEs) applied for propulsion of helicopter drones are presented in the figures 4 and 5.

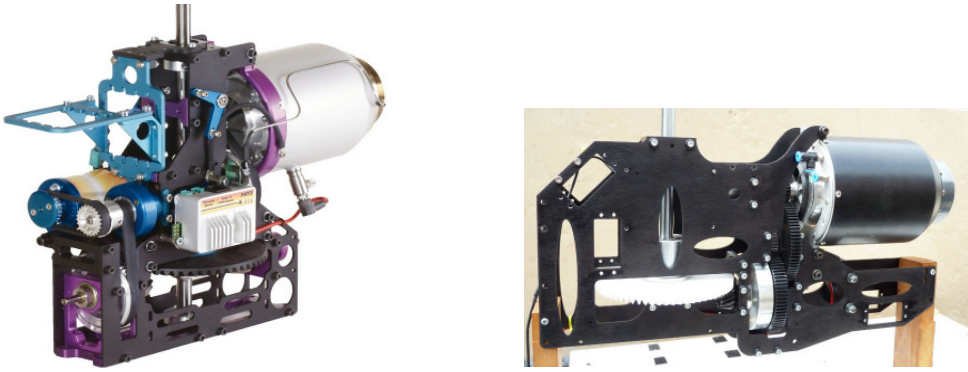

Figure 4. Single shaft MTE engine with gear box used for propulsion of helicopter drones: two different arrangements [6, 7].

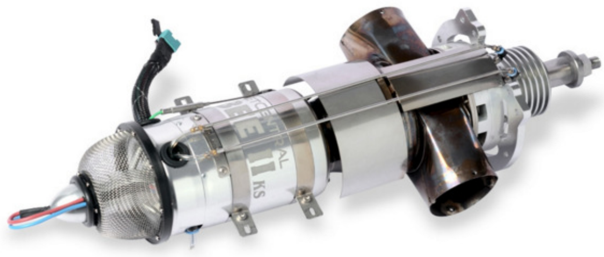

Figure 5. Single shaft engine with gear box used for propulsion of turboprop drones [8].

The dual shaft MTEs look similar to presented above single shaft arrangement, but have the free turbine (second shaft) for power delivery to the external system (helicopter gear box or propeller). The examples of dual shaft engines are presented in the figures 6 and 7.

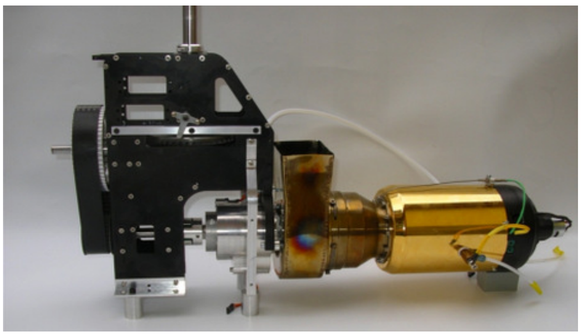

Figure 6. Taurus dual shaft MTE engine with gear box used for propulsion of helicopter drones [9].

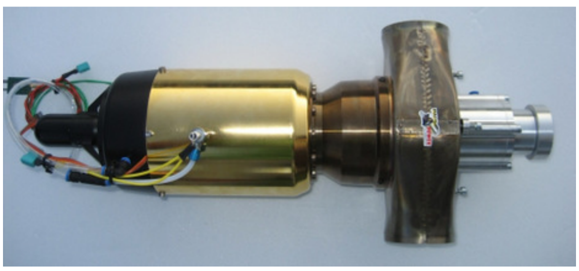

Figure 7. Taurus dual shaft MTE engine used for propulsion of turboprop drones [10].

3. Typical specifications of MTEs

3.1. Thrust range

There is no official classification for the micro turbojet engines. These engines are used mainly by modellers for propulsion of remotely piloted fixed wing aircraft and helicopters. Commonly used classification is the range of thrust generated by MTEs. Thrust values of such engines are included generally within the range of 50–250 N. The example of characteristic of thrust versus shaft rotational speed of micro turbojet engine is presented in the figure 8. The more thrust generating turbojet engines belong to the normal "adult" constructions, however sometimes for aircraft scaled models or flying mocks application of more powerful engines may be necessary.

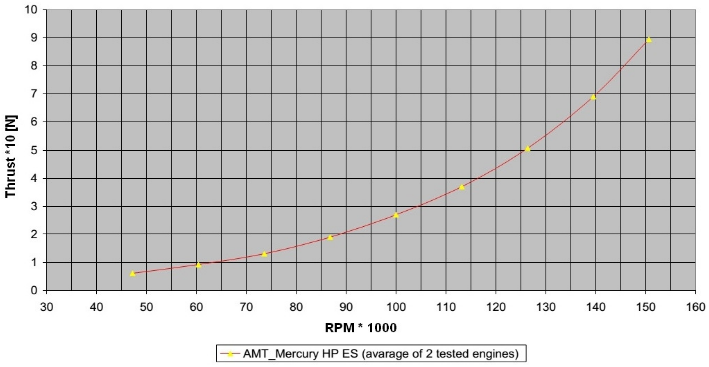

Figure 8. Thrust versus shaft rotational speed of AMT Mercury HP ES micro turbojet engine [11].

3.2. Shaft (spool) rotational speed range

The range of shaft rotational speed depends on the dimensions of an engine and required thrust value. The typical shaft RPM values are from about 35000 to 180000. The smallest MTEs have the idle speed of about 50000–95000 RPM. The biggest ones have idle speed of about 35000. The RPM of the maximum thrust (nominal RPM) are situated within the range from about 120000 to 240000 and are obtained at the maximum permissible engine speed [6, 7, 8, 9, 10, 11, 12, 16, 18, 24, 25, 26]. The ceramic shaft bearings are contemporary commonly used making possible relatively long maintenance interval up to even 50 hours. The earlier inspection is necessary in case of bearing noise or other reasons.

3.3. Compressor type

There is commonly used the single stage radial type of compressor (figure 9), as it was mentioned above. There are at least two reasons of such a concept: the simplicity of construction and possibility of adaptation, particularly in amateur designs, a standard compressor rotor taken from a car turbocharger. The professional MTEs elements are manufactured with use of advanced CAD and CNC machine tools including the contemporary tries of 3D printing application. The striving for obtaining more thrust and parallel a small diameter of an engine will be probably the impulse to wider application of multistage axial compressors. The previous technological problems of precise making of engine compressor and turbine elements are nowadays solved, so one can assume that it is only a problem of close future market demand.

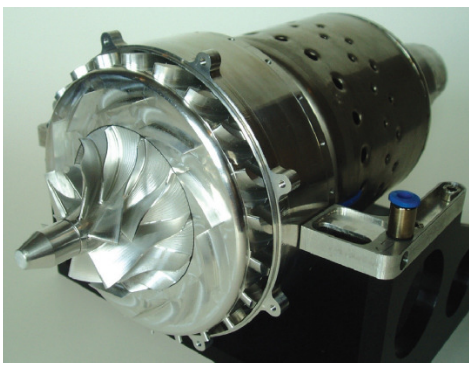

Figure 9. Hawk 100R micro turbojet engine without housing; visible compressor diffuser [12].

3.4. Pressure ratio
The single stage radial compressor is sufficient to obtain the value of pressure ratio appropriate for proper work of MTE combustion chamber. The average values of pressure ratio obtained in MTEs are from about 1.2 to 4.6 depending on the engine size and power demand. The highest value of pressure ratio while maintaining a small diameter of engine will require application of multistage axial compressor.

3.5. Combustion chamber type
The reverse flow combustion chamber with flame tube made usually of Inconel alloy is the common used solution. That construction enables providing the adequate conditions for proper preparing and combustion of the air-fuel mixture. Besides the reverse flow combustion chamber makes the whole engine shorter, more compact and as the result lighter. As low as possible weight of a turbojet engine is one of the essential parameters taken into account in aviation.

3.6. Turbine type
Two types of turbines are used in MTE: radial and axial ones. The radial type is a standard at present but one can forecast the axial turbine as a close future solution. Mentioned above development of the machining techniques will enable the free choice of combination of compressor and turbine types applied in a given case.

3.7. Exhaust Gas Temperature (EGT)
The maximal exhaust gas temperature of MTEs is limited by the thermal load of turbine rotor. The threshold is usually of about 830ºC. Because of need of keeping of the safety distance from that value, the real exhaust gas temperature does not exceed 800ºC. It is most often the value of about 700–760ºC (figure 10).

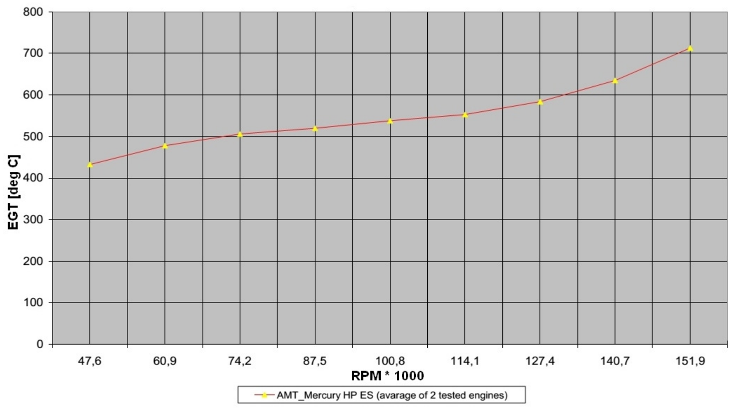

Figure 10. Exhaust gas Temperature (EGT) versus shaft rotational speed of AMT Mercury HP ES micro turbojet engine [11].

3.8. Fuel type
Micro turbojet engines are fed generally with kerosene-based fuel, i.e.: premium paraffin, kerosene, Jet-A1 or Diesel fuel. This is the reason why this kind of propulsion source is very interesting particularly for military, meeting the requirement of “single fuel in battlefield” concept. In the very begin of MTEs development, the LPG fuel was applied as the main fuel. At present LPG is used optionally as the start gas to support the engine start procedure.

3.9. Fuel consumption
Fuel consumption per minute of MTEs is relatively high when compared to the fuel consumption of piston engines. However taking into consideration the different way of power reception (mainly thrust)

and the engine power to mass ratio, the values of total fuel consumption (TFC) are acceptable. The TFC on idle run is usually of about 30–65 g/min and for the maximum thrust about 260–520 g/min, depending on the engine size and construction. The example of load characteristic of the Hawk 100R micro turbojet engine is presented in the figure 11 and for comparison the load characteristic of the second end of the size scale – Hawk 260R engine is presented in the figure 12.

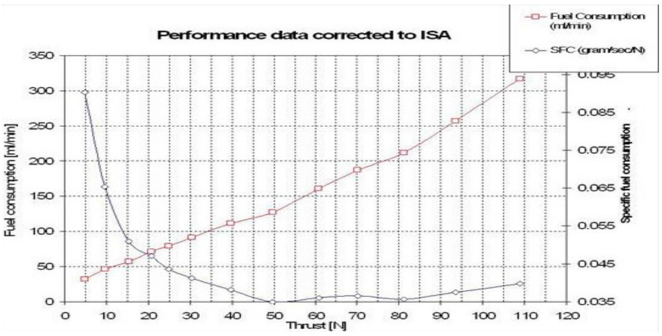

Figure 11. Load characteristic of Hawk 100R micro turbojet engine [13].

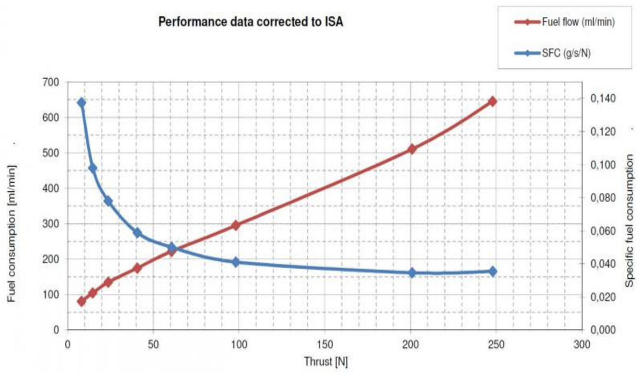

Figure 12. Load characteristic of Hawk 260R micro turbojet engine [14].

3.10. Lubrication
The bearings of micro turbojet engines are lubricated with the fuel-oil mixture. It is the open lubricating system but in the case of necessity of the engine weight diminishing, it is the only reasonable solution. Most frequently is used a two-stroke motorcycle or outboard oil but some manufacturers prefer a turbine oil.

The oil-fuel ratio depends on individual construction of a given engine and a kind of fuel applied (kerosene or diesel) and may amount to 1.5–5.0%. Generally the higher amount of lubricating oil is added to a kerosene-based lighter fuel.

3.11. Start system
There are three starting systems being contemporary in use: the air, propane-butane (Gas) and kerosene (Kero) system.

The air-start system is realized from outside of the MTE engine with use of the air stream directed into the engine air inlet on the compressor rotor (figure 13). The start procedure requires application of an external compressor but makes the engine lighter without a starter motor.

The autostart system (Gas or Kero) requires use of the integral electric starter motor (figure 14).

The propane-butane assisted starting was until recently the most widespread method. Propane-butane mixture (liquefied) has the good evaporating properties in a low ambient temperature making the easy flammable air-fuel mixture. This is the reason why gas fuel is used to support the start of MTE engines

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(figure 15). After reaching the temperature about 100ºC auto-start system changes the fuelling to kerosene what is the basic fuel.

Figure 13. Air-start system: left – AMT Pegasus HP (view without engine housing) [15]; right – Lambert T15 Kolibri [16].

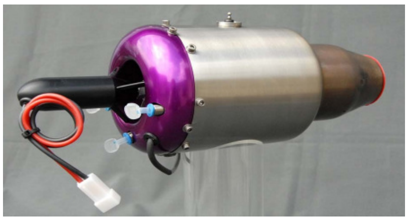

Figure 14. AMT Mercury HP electric start system (propane-butane or kerosene) [11].

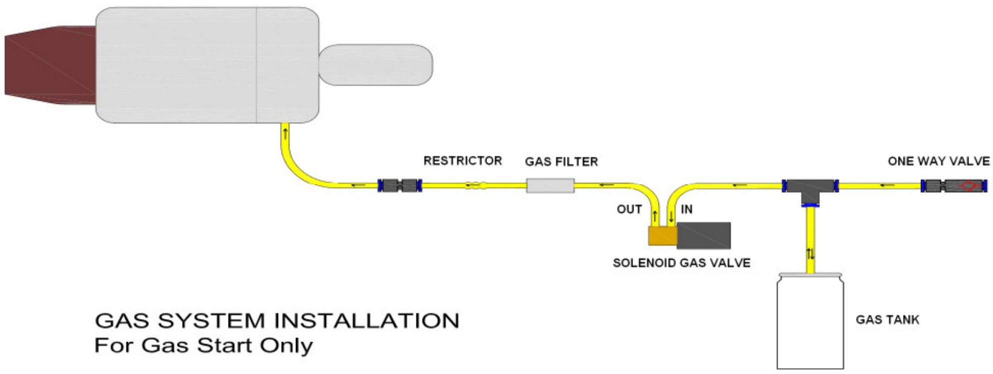

Figure 15. Gas (propane-butane) start system [17].

Kerosene auto-start system presented in the figure 16 is contemporary available due to the electronic control system (FADEC) what is the integral part of turbojet propulsion system. However the special care and attention must be paid, including a potential application of the CO_2 fire extinguisher.

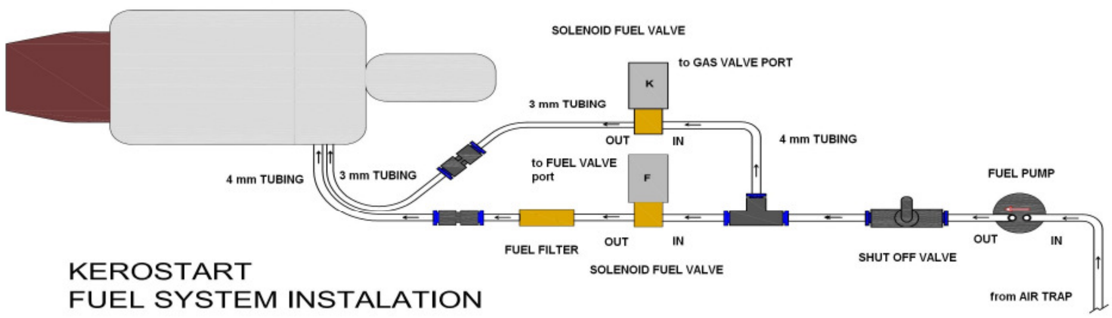

Figure 16. Kerosene auto-start system [17].

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3.12. Engine control

Contemporary MTEs are equipped with electronic control system enabling start and then proper run of engines. This control unit is called FADEC (Full Authority Digital Engine Control) in the same way as in "full size" aviation. The examples of the external view of FADEC electronic control units are presented in the figure 17. The scheme of fuel supply system controlled by FADEC ECU is presented in the figure 18.

Figure 17. Examples of FADEC electronic control units [12, 11, 18].

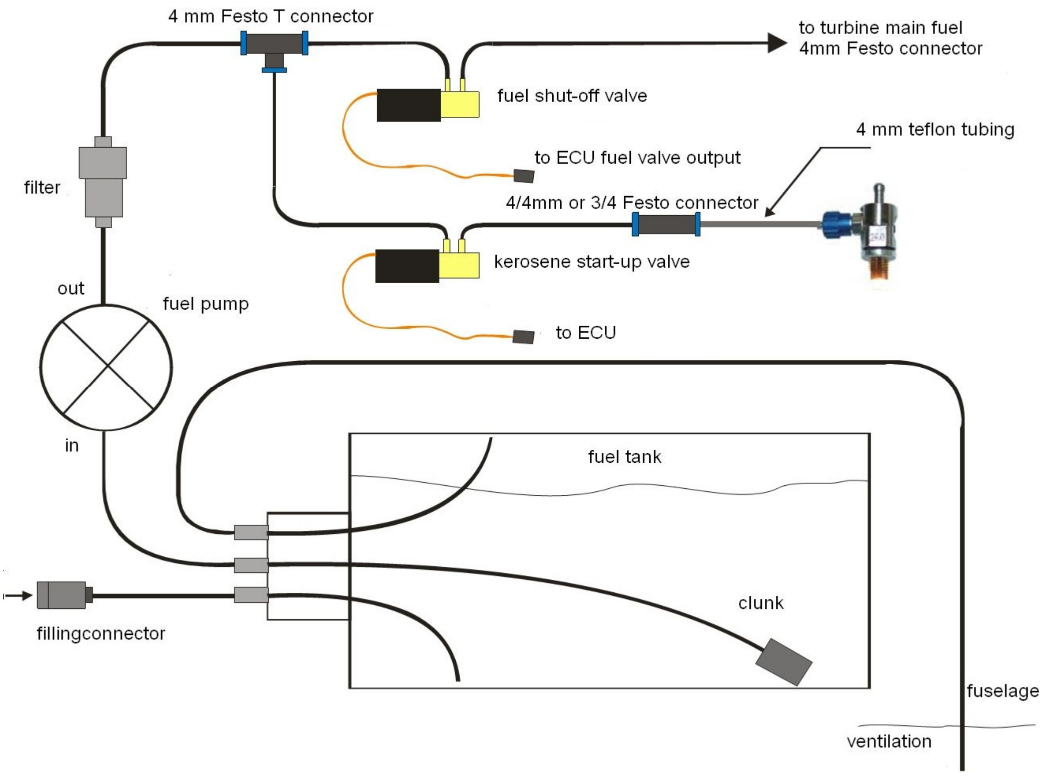

Figure 18. Scheme of fuel supply system controlled by FADEC ECU [6].

3.13. Performance (transient performance)

Transient performance is expressed by so called "spool time". It is the time of engine thrust response to the rapid "throttle" opening, measured from idle speed to maximum power (thrust) speed. As the example one can present Hawk 100R turbojet engine. For the factory settings the Hawk 100R spool time is about 4 s from idle to max power. It is however possible to apply custom regulation data and diminish the spool time to 2.5 s (figure 19). This effects in the spool time from half throttle (approximately 50 N of thrust to maximum thrust) in 0.5 s. This is a very valuable result enabling rapid manoeuvres of drone driven by such engine.

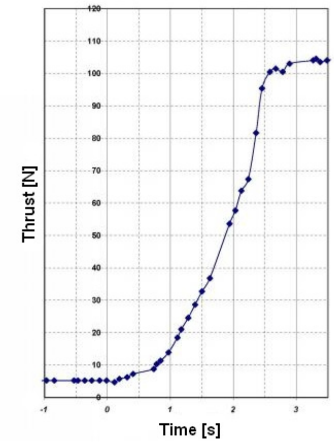

Figure 19. Hawk 100R turbojet engine transient performance – “spool time” [19].

3.14. Measures and weight

The development of technology enables to design small turbojet engines with high enough performance and durability. Particularly interesting are the smallest constructions because of the need of high precision of manufacturing.

The overall dimensions of micro turbojet engines are in the range approximately: housing diameter 90 – 120 mm, length 200 – 350 (450) mm (single-spool turboprop versions with gear box or two-spool turboprop).

The total weight with fuel supply, start and EC systems is in the range of about 1000 – 3200 g.

4. Examples of Micro Turbine Engines (MTE) specifications

Table 1. Technical specifications of chosen MTE engines [8, 20, 21, 22, 23, 28].

	Kolibri T15	Hawk 240R	Hawk 100R	Bee II Kero Start	Bee II Turbo Prop KS	Taurus 10
Idle thrust [N] / RPM	ca. 2 / 95000	8 / 39000	6 / 60000	3.6 / 55000	–	–
Maximum Thrust [N] / RPM	15 / 243000	240 / 132000	110 / 175000	70 / 185000	–	–
Maximum Power [kW] / RPM	–	–	–	–	9 / 180000	10 / 123000
Pressure ratio	2.2	1.2 – 4.6	1.2 – 3.8	–	–	–
RPM	95000 – 243000	39000 – 132000	60000 – 175000	55000 – 185000	55000 – 180000	33000 – 123000
Prop-shaft RPM range	–	–	–	–	6000 – 8000	9000 (max)
Exhaust Gas Temperature [°C]	max 680	400 – 760 (800)	390 – 760	500 – 700	500 – 700	550 – 750
Fuel consumption [g/min]	ca. 50 (max)	65 – 515	30 – 260	180 (max)	135 (average)	135 – 230
Fuel type	Kerosene JetA1 Petroleum	Kerosene Jet A1 Diesel (EN590)	Premium paraffin Kerosene Jet-A1 Diesel (EN590)	Kerosene Jet A1 Diesel (EN590)	Kerosene Jet A1 Diesel (EN590)	Jet A1
Spool time (idle to max. thrust) [s]	ca. 2.5	4.5	4	3	4.2	ca. 4
Lubrication (oil-fuel mixture)	5 [%] Aeroshell 500	1.5 [%] Two stroke outboard	1.5 [%] Two stroke outboard	2.0 – 2.5 [%] Two stroke synth. / 2.5 – 5.0 [%] Turbine synthetic	2.0 – 2.5 [%] Two stroke synth. / 2.5 – 5.0 [%] Turbine synthetic	5 [%] Turbine synthetic
Engine control	FADEC	FADEC	FADEC	FADEC	FADEC	FADEC
Start system	Propane-butane External Air	Propane-butane Full auto start	Propane-butane Full auto start	Kerosene Full auto start	Kerosene Full auto start	Kerosene Full auto start
Compressor	–	Radial	Radial	Radial	Radial	–
Combustion chamber type	–	Reverse flow	Reverse flow	Annular	Annular	–
Turbine type	–	Radial	Radial	Axial	Axial	–
Number of turbines	1	1	1	1	2	2

Engine diameter [mm]	55	108	108	82	86	109
Engine length [mm]	125	346	346	232	430	450
Engine weight [g]	200	1650	1650	880	2300	3200

5. Conclusions

Micro turbine (turbojet) engines (MTE) are the relatively new propulsion sources applied mainly to aircraft drones. However the level of technical advancement of these engines is contemporary very high and is worthy of special attention. The area of MTE engines has been until now "reserved" for amateur modellers but one can observe the more and more interest in such propulsion taken by professionals (the military or aviation R&D centres). The small measures and high value of thrust or power make the MTE engines the attractive alternative for drones' propulsion. Miniaturisation of turbojet engines is possible thanks to contemporary CAD and machining systems including the advanced 3D printing. The lack of reliable technical details of micro turbojet engines is understandable because of the know-how secret particularly in the strong market competition. The newest constructions of MTE engines dedicated to turboprops or helicopters are based on the aviation designs with free turbine. These engines are the most advanced and seems to be the most "elegant" source of propulsion possessing all the best features of speed-torque characteristic of two-spool engines.

References

[1] Dutczak J 2014 *Combustion engines for propulsion of contemporary drones*, (Kraków: Silniki Spalinowe i Ekologia, Wydawnictwo Politechniki Krakowskiej) pp 63-82
[2] http://pfmrc.eu/uploads/monthly_09_2012/post-697-0-22752100-1346612586.jpg
[3] http://www.jaguar.com/about-jaguar/concept-cars/cx75.html
[4] https://www.gov.uk/government/case-studies/bladon-jets-innovative-mobile-and-low-cost-generator-takes-off
[5] http://www.gtba.co.uk/pgallery/index.php?spgmGal=Axial&spgmPic=2#spgmPicture
[6] www.cat-ing.de/turbines, Bedienungsanlaitung JetCat PHT2 ECU 6.0 2016
[7] http://www.jet-italia.it
[8] http://www.jetcentral.com.mx/products/turbo-prop-ks/
[9] http://www.pahlhelicopter.com/index_htm_files/470.png
[10] http://www.pahlhelicopter.com/index_htm_files/472.png
[11] www.amtjets.com/, Mercury HP gas turbine specifications, January 2008
[12] http://www.hawkturbine.com, Hawk Turbine RCJI 2006/2007
[13] http://www.hawkturbine.com/Fuelfigures.htm
[14] http://www.hawkturbine.com/FuelFiguresxxx.htm
[15] http://4.bp.blogspot.com/-N_U95pECvYg/T_1VkXRMz8I/AAAAAAAAAKU/T_Hu8OrhROg/s320/ac.jpg
[16] http://www.lambert-modellturbinen.de/assets/images/Kolibri2_s.jpg
[17] Jet Central, Bee II Operation and Maintenance Manual, February 2012
[18] Jet-Italia, Speed13-Pulse17-Kaiman19-Lion22-Atom25, Istruzioni e Garanzia, Rev1 2015
[19] http://www.hawkturbine.com/Performance.htm
[20] http://www.hawkturbine.com/Technicalspec.htm
[21] http://www.hawkturbine.com/Technicalspecxxx.htm
[22] http://www.jetcentral.com.mx/products/bee-ii-ks/
[23] http://www.pahlhelicopter.com/index_htm_files/Taurus%20Daten_2012
[24] http://www.frankturbine.de
[25] www.jets-munt.com/
[26] www.bf-turbines.de
[27] http://www.caranddriver.com/news/jaguar-c-x75-concept-auto-shows
[28] http://www.modellbau-peters.de/kolibri-turbine-t15-ohne-autostart.html#product_tabs_additional_tabbed