THE TURBINE INLET TEMPERATURE AND COMPRESSOR PRESSURE RATIO, THE SIAMESE TWINS OF THE GAS TURBINE ENGINES

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DOI: 10.19062/2247-3173.2016.18.1.53

Abstract: *When we read the technical data of any kind of gas turbine engines in most cases besides the performance data we get two important data, namely the Turbine Inlet Temperature (TIT) and Compressor Pressure Ratio (CPR) usually for take-off rate of power. But considering a certain TIT there is a range of CPR which is suitable for this TIT. This range of CPR depends on the TIT itself but the engine component efficiencies also has effect on the possible CPR. In this paper we intended to examine how this range of CPR can be determined, the range itself, how it is affected by the component efficiencies and the operational point of today existing turboshaft engines between the minimum and maximum possible CPR-s. To answer these questions we developed a gas turbine thermal mathematical model.*

Keywords: *take-off operational point, turbine inlet temperature, compressor pressure ratio, specific net work output, thermal efficiency*

1. INTRODUCTION

To achieve the above mentioned results we theoretically determined the possible terms of minimum and maximum CPR-s considering a certain TIT. Surely we have to tie the CPR extremes to some kind of optimum points of the gas turbine engines.

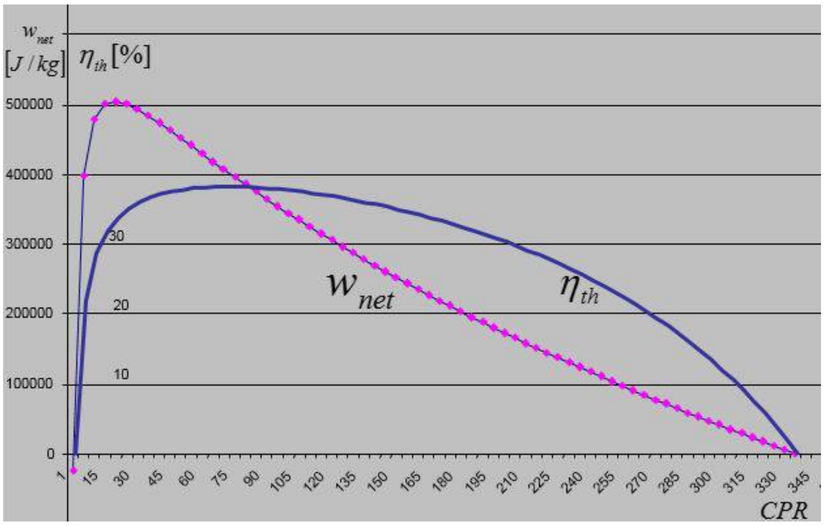


FIG. 1. The Specific Net Work Output and Thermal Efficiency of a gas turbine cycle as a function of Compressor Pressure Ratio [1]

We can presume that the Specific Net Work Output (SNWO or w_{net}) and Thermal Efficiency (TE or η_{th}) of the gas turbine engine cycles, both of which are primary performance indicators and suitable for the evaluation of any kind of gas turbine engines, can define these extremes. It is quite clear that their maximum value are at different CPRs, but lower CPR than that of the CPR of maximum SNWO and higher CPR than that of the CPR of maximum TE is illogical because out of this range both of them decrease, see Fig.1.

2. BUILDING UP THE THERMAL MATHEMATICAL MODEL

To build up the thermal mathematical model we used three basic equations of gas turbine engine cycles (1), (2), (3). All three energy transfers to or from the cycle are the function of CPR, considering given "T_0-T_3" temperature range and component efficiencies [1]. Where "T_0" is equivalent of the International Standard Atmosphere temperature at Main See Level.

Important to note, that the gas properties are also functions of CPR through the actual temperature range of compression or expansion.

$$w_c(\pi) = \left(c_{pa} T_0 / \eta_m\right) \cdot \left(\pi^{(\kappa_a - 1)/\kappa_a \cdot \eta_{polc}} - 1\right) \tag{1}$$

$$w_e(\pi) = c_{pg} T_3 \left(1 - 1/(\sigma\pi)^{((\kappa_g - 1)\eta_{pole})/\kappa_g}\right) \tag{2}$$

$$q_{in}(\pi) = \left(c_{pb} / \eta_b\right) \cdot \left(T_3 - T_0 \pi^{(\kappa_a - 1)/\kappa_a \cdot \eta_{polc}}\right) \tag{3}$$

This equations are suitable to determine the chosen performance indicators, namely the SNWO and the TE.

$$w_{net}(\pi) = w_e(\pi) - w_c(\pi) \tag{4}$$

$$\eta_{th}(\pi) = w_{net}(\pi) / q_{in}(\pi) \tag{5}$$

here: $w_{net}(\pi)$ - SNWO [J/kg]; $\eta_{th}(\pi)$ - TE [-]; $w_c(\pi)$ - specific compression work [J/kg]; $w_e(\pi)$ - specific expansion work [J/kg]; $q_{in}(\pi)$ - specific input heat [J/kg]; π - CPR [-]; T_0 - intake inlet temperature [K]; T_3 - TIT [K]; κ_a - adiabatic exponent for compression [-]; κ_g - adiabatic exponent for expansion [-]; c_{pa} - isobaric specific heat for compression [J/kgK]; c_{pg} - isobaric specific heat for expansion [J/kgK]; c_{pb} - isobaric specific heat for combustion [J/kgK]; σ - pressure loss for the whole engine (air intake, combustor, exhaust pipe, others) [-]; η_{polc} - polytrophic efficiency of compression [-]; η_{pole} - polytrophic efficiency of expansion [-]; η_m - mechanical efficiency including power off take [-]; η_b - combustion efficiency [-].

SNWO ($w_{net}(\pi)$) is the desired output of the thermodynamic cycle. In accordance with the second law of thermodynamics the mechanical work is always less than the input heat and in addition the friction in the real gas turbine elements causes some more heat loss. This heat is dissipated as wasted heat into the environment.

TE ($\eta_{th}(\pi)$), in general, energy conversion efficiency is the ratio between the useful output of a device and the input, in energy terms. For thermal efficiency, the input ($q_{in}(\pi)$) to the device is heat, or the heat content of the fuel that is consumed.

In accordance with (4) and (5) the real gas turbine engine cycles, at given "T_0-T_3" temperature range and component efficiencies, have two optimums, namely the maximum of the SNWO and TE, but the related CPRs are significantly different from each other. In accordance with it, it is impossible to produce the maximum SNWO and the maximum TE in the same time. Using this programme, described in this paper, the user can determine the CPRs of the maximum SNWO and the maximum TE and their actual value.

To determine these special CPRs related to the above mentioned engine properties, equations (4) and (5) needs to be analysed as functions, looking for their local extreme. In this case it is the local maximum we are looking for and can be found by using the first derivative test. SNWO and TE maximums are, where their first derivative is zero, see (6) and (7).

$$w_{net}(\pi) \text{ is maximum, where}: w_{net}'(\pi) = 0 \tag{6}$$

$$\eta_{\mathrm{th}}(\pi) \text{ is maximum, where}: \eta_{\mathrm{th}}'(\pi) = 0 \tag{7}$$

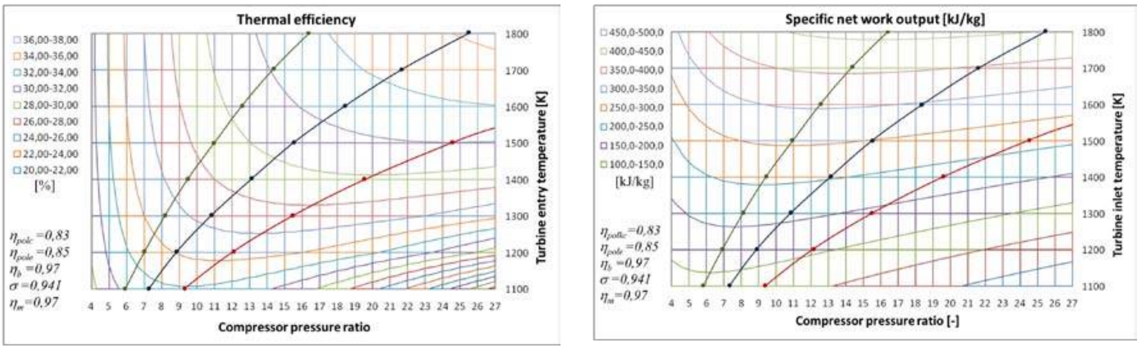
The model produces:

- The characteristic curves in TIT versus CPR diagram for any kind of combination of engine component efficiencies;
- Calculates the distinguished CPR values;
- It takes into consideration the change of compressor polytrophic efficiency as a function of blade length giving possibility to evaluate its effect on the distinguished CPRs, TE and SNWO;
- It provides the analyses and evaluation of existed turboshaft engines.

To process the above listed examinations, Microsoft Excel was used with Visual Basic programming. Microsoft Excel Worksheet provides the communication platform of the created Visual Basic programme [3].

3. TE AND SNWO CHARACTERISTICS IN CPR VERSUS TIT DIAGRAM

In Fig. 2 (a) the TE curves can be shown from 20 to 36%, while in Fig. 2 (b) the SNWO curves from 100 to 500 kJ/kg. In both cases the component efficiencies are shown in the bottom left corner. Three curves from left to right represent the CPRs of the maximum SNWO (green), maximum TE (red) and as a compromise between them as the maximum value of their multiplication (blue). The two curves (green and red) really gives the possible range of CPR at this given component efficiencies and at any TIT.



(a) (b)

FIG. 2. The TE and SNWO curves in TIT versus CPR diagram [1]

In accordance with it these charts give general information at a certain component efficiencies what TE and SNWO can be expected and what the possible range of CPR. The model can produce that for every variety of component efficiencies and losses.

What is clearly visible that at a given TIT and at low CPRs both examined engine properties worsen heavily. It can be proven by simple mathematical deduction. Neglecting the deduction we have to recognise that both functions are rational functions with vertical asymptotes, where at decreasing CPR both functions go to infinity.

4. IDEAS ABOUT THE POSSIBLE OPERATIONAL POINT

Presuming, the designers in most cases can work with given engine components, which mostly determine the component efficiencies and turbine entry temperature. In this case the only thing they can vary, is the CPR. Of course, the CPR must not be out of the above defined limits, namely the CPR of maximum SNWO and TE. At a low TIT and consequently low SNWO it is reasonable to position the take-off operational point close to the lower eligible CPR. It is even more justified if the raise of CPR causes significant deterioration of compressor polytrophic efficiency, because in this case the lower compressor polytrophic efficiency can consume the hoped advantage of higher TE. At higher turbine entry temperature, consequently higher SNWO there is larger space for the designers to play with the CPR. One reason that a small drop of the SNWO, from a relatively high value, is not so painful like at originally low SNWO. In addition at this range the deterioration of SNWO at increasing CPR is not so significant like at lower TIT. Consequently, we presumed, that at older turboshaft engines with lower TIT the take-off operational point is positioned in the first part of possible CPR range, between the green and blue line, by Figure 1 and 2. At newer engines with higher turbine entry temperature it is more likely tending to the upper limit of CPR even accepting the deterioration of compressor polytrophic efficiency, however it decreases this upper limit of CPR. In the next part of paper we check these ideas analysing some existing turboshaft engines.

5. ANALYSES OF EXISTING TURBOSHAFT ENGINES

First step for the above mentioned analyses is to collect all possible available performance data of some existing turboshaft engines [3,4,5,6,7,8,9,10]. Of course, there are numerous turboshaft engines, but the companies are not eager to share too much data. Choosing the turboshaft engines we preferred the middle category considering their shaft power. There is only one exception. This one is the LM 2500 turboshaft which is used rather as an industrial and marine gas turbine with much larger size and shaft power comparing to the chosen helicopter turboshaft engines.

During the evaluation I concentrated for five important data:

- Shaft power of take off RPM (P_{shaft});
- TIT (T_3) (or any other temperature in hot section);
- CPR (π);
- Engine mass flow rate $(\dot{m})$;
- Specific fuel consumption (SFC) or thermal efficiency (η_t).

Shaft power, SFC and CPR was almost always available. The TIT caused the strongest uncertainty as either missing or clearly deformed data. It did not thwart the examination but weaken the verification of results. During the evaluation process the shaft power and the compressor pressure ratio were the two fixed data in the process. The mass flow rate and specific fuel consumption were the two data I used to smooth the model using TIT and component efficiencies as variables. I continued changing the variables until both above mentioned data $(\dot{m}; SFC)$ of the model and the existing engine became equal, which was the requirement to accept the final results of model. As I mentioned earlier, the turbine entry temperature in some cases were confusing. Finding exact data was easier in case of two Russian (ex-Soviet) helicopter engines, TV2-117A and TV3-117, because of their available maintenance manuals. Their turbine inlet temperature only slightly differed from the result of the model. From this conformity I concluded that in case of missing TIT or when it is clearly out of reasonable range I accept the result of thermal model. To be honest I did not try to achieve totally precise results analysing the existing turboshafts. The reason was the relatively large number of analysed engines. To collect all engine data would have been time consuming and sometimes futile. The second reason was that my main object was rather to present how this thermal model works practically.

Table 1. Results of the engine analyses

	TV2-117A	**TV3-117VM**	**T58-GE-100**	**MTR 390E**	**T800-LHT-801**	**RTM 322-01/9**	**LM 2500**
P_{sh} *[kW]*	1103	1699	1118	1043	1166	1799	24000
T_3 *[K]*	1168	1250	1269	1627	1444	1507	1504
$\dot{m}$ *[kg/s]*	6,8	8,75	6,35	3,6	4,53	5,79	70,3
π_{wh}-$\pi_{\eta t}$ π_{op} *[-]*	6,24-9,97 6,6	7,18-12,2 9,45	6,52-10,22 8,4	9,45-16,73 14	8,92-16,41 15	10,36-20,81 14,7	12,38-29,64 18
Poz. [%]	9,58	45,28	50,73	62,48	81,19	41,56	32,58
η_{pole} *[-]*	0,848	0,846	0,824	0,815	0,849	0,857	0,872
η_{polc} *[-]*	0,824	0,824	0,798	0,774	0,808	0,822	0,858
η_t *[%]*	22,58	25,66	22,59	27,83	29,85	32,26	36
w_{net} *[kJ/kg]*	162,3	190,8	176	303,47	257,3	310,8	341,451

here: P_{sh} – shaft power [kW]; $\dot{m}$ - mass flow rate [kg/s]; π_{wh}-$\pi_{\eta t}$ – CPRs of the SNWO and TE maximums at a given turbine entry temperature [-]; π_{op} – take off operational point (CPR) [-]; *Poz. [%]* – position of the operational point between the CPRs of the SNWO and TE maximums [%]; *SFC* – Specific Fuel Consumption [kg/kWh].

Considering the above mentioned operational points (CPRs) it is well demonstrated, that all the operational CPRs are between the SNWO and TE maximums but these positions does not show any significant order, which would allow to draw any deeper conclusions. Their positions are in percentage of the whole CPR range and can be seen in line 5 of Table 1 (*Poz. [%]*).

CONCLUSIONS

Having gone through the analysis process we got other interesting results about the turboshaft engines. It is clear that the helicopter engines (Table 1), like the other fields of aviation have gone through huge evolution. The increased CPR, TIT, and the FADEC system (used by all new engines) improved their performance, although much less than we experience in other gas turbine engine categories. The main reason is that the average turboshafts provide about 250–2500 kW shaft power with 2–12 kg/s air mass flow rate. Accordingly their compressors are relatively small, which causes short rotor blade length, especially in rear stages (or last centrifugal stage). This effect has been heightened by the development trend to increase the SNWO decreasing the engine dimensions and weight. This fact considerably penalizes mainly the compressor polytrophic efficiency [2]. It is the reason that in some cases compressor and turbine polytrophic efficiency of a newer engine is not significantly higher, what is more sometimes lower comparing to an older engine. It means the CPR is usually not higher than ~15, and the resulted maximum TE is less than 32%, while at bigger (new) gas turbine engines (where air mass flow is over 30 kg/s) the TE is usually over 40%. Good example is the LM 2500, which TE does not achieve 40%, but its TE is considerably higher than the efficiency of the much smaller turboshafts.

The better component efficiencies and the high CPR and TIT of the new generation RTM-322-01/9 presents the best overall features. This is clearly shows us that good performance indicators cannot be achieved only by increasing the CPR and TIT. To keep the component efficiencies, especially compressor polytrophic efficiency as high as possible, has the same importance.

Of course, increasing the TIT and CPR without higher or even sometimes with lower element efficiencies, higher SNWO and TE can be achieved. Without being precise, about 100 K TIT and 2.5-3 CPR raise gives (absolute) 2% TE and 50 kJ/kg SNWO increment. That is the situation today in turboshaft category. Analyzing the performance of turboshaft engines, chosen one category (by shaft-power) we experience that the higher SNWO and TE is mainly coming from the higher TIT and CPR. It is almost a catch-22. Considering the same shaft-power output getting higher SNWO the result is smaller and smaller engine (lower mass flow rate is needed) preventing to achieve (significantly) higher engine element efficiencies or sometimes resulting even lower values [2].

The advantage of this thermal mathematical model that for any variations of the engine element efficiencies and TITs the changes of TE, SNWO and the related CPRs can be followed and vice versa being known the estimated element efficiencies and the desired TE and SNWO the user can determine the necessary TIT and CPR [1].

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