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COMPUTER MODELING OF POWER GENERATION GAS TURBINES, ISSUED FROM TURBOJET OR TURBOFAN AIR PROPELLERS

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Technological transfer from aeronautic area to power sector leaded to development of a new class of medium scale power gas turbines, using as "gas generators" engines issued from turbojet and turbofan propellers. The assembly is designing on coaxial shifts, without mechanics gears between them, but coupled by the gas flow. The lack of mechanical link between shafts permits having: ***a)*** *modular design and* ***b)*** *high and variable rotation speeds at the high pressure shaft(s). The first feature allows an easier and quickly maintenance, by replacing the gas generator. The high speed reduces the dimensions and the investment amount. In the same time it allows, for the same air / gas flowing areas, longer working profiles and higher isentropic efficiencies of rotating machines, respectively higher thermal efficiency. The variable speed improves the partial load GT performances. Consequently, using the aero-derivative turbojet / turbofan design could insures, in the same time, high efficiencies, low investment prices and a good reliability and availability*

The paper, based on a numeric model of gas turbine's cycles, conceived for stationary nominal load, uses procedures achieved and validated in our chair. The author's targets are determining: ***a)*** *the equivalent Brayton cycle and their main thermodynamic and energetic data (temperatures, pressures, expansion ratios, efficiencies, specific works)* ***b)*** *the repartition of gas's expansion between the HP turbine(s) - witch drive the compressor(s) – and the Low Pressure (LP) turbine, witch drive the electrical generator, respectively* ***c)*** *the parameters at the LP turbine input. The numerical data were taken from producers directories and refer to usual medium power gas turbines. The obtained results are in concordance with references data. They show that LP turbines, driving the generators have significantly lower parameters than the usual heavy duty turbines. The conclusions could be applied, mainly, for choosing the higher thermodynamic parameters at the gas generator and coordinate their design with the LP power gas turbines.*

Key words: Power Generation, Aero-Derivative Gas Turbines, Turbojet, Turbofan, Brayton Cycle, and Computer Modeling.

1. Introduction. Problem formulation.

Technological transfer from aeronautic area to power sector leaded to

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development of a new class of medium scale power Gas Turbines, using as “gas generators” engines issued from turbojet and turbofan propellers [1]. The easiest way to transform an aircraft propeller in a stationary gas turbine is adapting a turbojet engine by replacing the exhaust nozzle with a LP gas turbines witch drive the electrical generator [2] - see figures 1 and 2. For turbofan propellers, because of their design witch includes already two shafts, more changing are necessary and the design is more complex[3] [3], but the main idea remains the same.

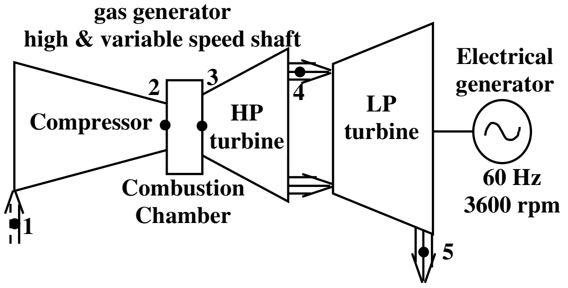

Fig. 1. Aero-derivative turbojet power engine.

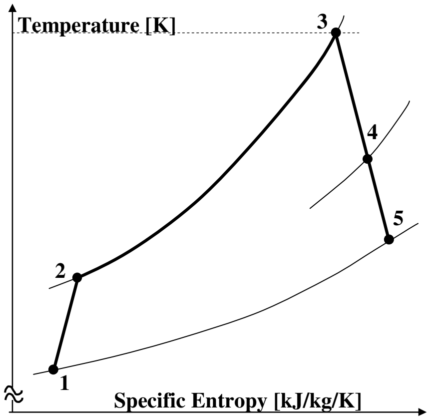

Fig. 2. Temperature – entropy diagram.

In both cases the assembly is made on coaxial shafts with different rotation speeds, without mechanics gears between them, but coupled by the gas flow. The lack of mechanical coupling between shafts offers: **A)** High rotation speed for the compressor(s) and HP turbine(s). It reduces the dimensions and the investment amount, by: **A_1)** diameters decrease; **A_2)** peripheral speeds raise; **A_3)** increase of compression ratio per stage, at the compressor, and expansion ratio per stage, at the turbine; **A_4)** decreasing the number of stages. For the same air / gas flowing areas the active length of the working profiles increases, allowing higher isentropic efficiencies for the compressor, “$\eta_{i\,K}$”, and turbine, “$\eta_{i\,T}$”, respectively higher efficiency. **B)** Variable rotation speeds to the high pressure shaft. That improves the partial load GT performances. **C)** An easier maintenance, made in short time, by replacing the gas generator.

The paper treats about medium power aero-derivatives gas turbines with nominal generator terminal’s output 20÷50 MW. The main target is that, starting from directories data, to establish by numerical modeling: **1)** the repartition of gas’s expansion between turbines and **2)** the input parameters in the LP turbine.

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[3] The power GT assembly could have in this case three shafts. The firsts two of them having high and variable rotation speed include the LP compressor, the HP compressor, the HP turbine (witch drive the HP compressor) and the intermediate pressure turbine (driving the LP compressor). The third include the LP turbine and the electrical generator.

2. Brayton equivalent cycle modeling, starting from directories data.

Usually, the producer’s gas turbines directories offer only commonly data, as: generator nominal output **“P_g”**; heat consumption, **“$q_{sp}=3600*P_{t\,f}/P_g$”**, ($P_{t\,f}=D_{fuel}*LHV$ is the thermal flow rate achieved by fuel burning); compression ratio **“$\varepsilon_K=p_2/p_1$”**; gas exhaust flow, **“D_5”** and temperature, **“t_5”**. Table 1 indicates such data, in ISO condition[4], about 6 aero-derivatives natural gas fuelled gas turbines, designed by GE[5] for 60 Hz market[6] [4].

Table 1

Directory data and directly computed data for 6 representative aero-derivatives gas turbines

No	Directory data						Directly computed data	
	GT model	P_g	q_{sp}	ε_K	Gas exhaust			
					flow	temp	η_{el}	e_{sp}
		kW	kJ/kWh	-	kg/s	^{0}C	%	kJ_{el}/kg
1	LM 6000 PC[7]	43 471	8 554.0	29.1	127.95	440.0	42.086	339.75
2	LM 6000 PD	42 336	8 760.3	29.3	126.05	452.1	41.094	335.87
3	LM 2500 RC[8]	33 394	9 230.8	23.0	91.60	524.2	39.000	364.56
4	LM 2500 RD	33 165	9 252.9	23.0	91.10	525.0	38.907	364.05
5	LM 2500 PH	27 763	8 847.6	19.4	75.85	494.2	40.689	366.03
6	LM 2500 PE	23 292	9 822.1	19.1	69.20	533.15	36.652	336.59
Statistical data processing results	MAX	43 471	9 822.1	29.3	127.95	533.15	42.086	366.03
	AVERAGE+σ	41 825	9 533.2	28.3	121.80	534.96	41.688	366.26
	AVERAGE	33 904	9 078.0	23.8	96.96	494.78	39.738	351.14
	AVERAGE-σ	25 982	8 622.7	19.3	72.12	454.59	37.788	336.02
	MIN	23 292	8 554.0	19.1	69.20	440.0	36.652	335.87
	STDEV (σ)	±7 922	±455.2	±4.496	±24.84	±40.18	±1.9501	±15.12

Knowing the directory data allow: **a)** statistical processing and **b)** directly determining: electrical efficiency, **“$\eta_{el}=P_g/P_{t\,f}=3600/q_{sp}$”**, and the specific energy per kg of flue gas, **“$e_{sp}=P_g/D_5$”**. The directories do not give information about: air mass flow, **“D_1”**, fuel mass flow, **“D_{fuel}”**, CC air excess, **“α_{CC}”**, CC efficiency, **“η_{CC}”**, CC relative pressure losses, **“$\Delta p_{CC\,rel}=(p_3-p_2)/p_2*100$ %”**, the higher temperature, **“t_3”**, the isentropic efficiencies (**$\eta_{i\,K}$, $\eta_{i\,T}$**), or mechanical and generator efficiencies **“η_{mec}”**, and **“η_{gen}”**. Because of great number of variables and transcendent equation involved, the study was elaborated through numerical simulation. We used methodologies, functions and procedures designed and validated in our chair. The model exposed in this paper is applicable only for stationary design regimes.

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[4] Without pressure losses at air input and gas output, and for p_1=1.013 bar, t_1=15^{0}C, and φ_1=60%.

[5] GE design GT cover, directly or by licenses, over 60 % from the market.

[6] All the data refers to situation without mechanical gear between the LP turbine and the generator.

[7] The LM 6000 power GT are issue from the CF6-80C2 turbofan engine.

[8] LM 2500 models are conceived starting from the CF6 turbojet propeller.

In order to determine **1)** the Brayton equivalent cycle[9], and **2)** the energy balance of the gas turbines, the authors conceived a supple numerical model and the associated software [5]. It starts from directories data and takes into consideration the elementary real gases thermodynamic properties and the burning equations. The numerical tests demonstrate that the model offers enough exactly results and plausible figures for the "hidden data". The main obtained results, for $\Delta p_{CC\ rel}$=7 %, typical for aero engines, are given in table 2[10]. The model and software offer and other valuable data as: t_2, the peak coordinates, of the curves $\eta_{el} = f(\varepsilon_K)$ and $e_{sp} = f(\varepsilon_K)$,[11] the ratio between the mechanical power consumed by compressor and the mechanical power of the turbine(s), **"$P_{i\ K}/P_{i\ TG}$"**, and others.

Table 2

Software computed data for the analyzed aero-derivatives gas turbines

No	GT model	Numerical modeling computed data								
		η_{CC}	$\eta_{iz\ K}$	$\eta_{iz\ T}$	t_3	η_{mec}	η_{gen}	α_{CC}	D_1	D_{fuel}
		%	%	%	^{0}C	%	%	-	kg/s	kg/s
1	LM 6000 PC	99.77	91.20	90.09	1 145.3	99.28	99.29	3.51640	125.88149	2.06851
2	LM 6000 PD	99.76	90.50	89.33	1 157.0	99.27	99.28	3.47258	123.98691	2.06309
3	LM 2500 RC	99.56	89.60	88.42	1 200.1	99.20	98.17	3.02891	89.88527	1.71473
4	LM 2500 RD	99.51	89.60	88.35	1 201.2	99.19	98.17	3.02587	89.39295	1.70705
5	LM 2500 PH	99.75	92.20	90.95	1 138.3	99.13	98.08	3.14973	74.48359	1.36641
6	LM 2500 PE	99.42	89.00	87.79	1 158.6	99.07	97.98	3.08417	67.92738	1.27262
Statistical data processing results	MAX	99.77	92.20	90.95	1 201.2	99.28	98.29	3.51640	125.88149	2.06851
	AVERAGE+σ	99.78	91.54	90.35	1 194.1	99.27	98.28	3.43608	119.77471	2.03394
	AVERAGE	99.63	90.35	89.16	1 166.7	99.19	98.16	3.21294	95.25960	1.69874
	AVERAGE-σ	99.48	89.16	87.96	1 139.4	99.11	98.04	2.98981	70.74449	1.36353
	MIN	99.42	89.00	87.79	1 138.3	99.07	97.98	3.02587	67.92738	1.27262
	STDEV (σ)	±0.15	±1.19	±1.20	±27.3	±0.08	±0.12	±0.2231	±24.5151	±0.3352

3. Tuning the numerical model for aero-derivatives GT.

The above mentioned model is a generally one. It does not identify, for the aero-derivatives GT, the repartition of flue gas expansion between the HP and the LP turbine. In order to solve this aspect and determine the thermodynamic parameters at the LP turbine input, we adapted the model and the software, adding a search routine. The intermediate pressure, $p_4 \in [p_3 \div p_5]$, is determined putting the condition that the useful mechanical work of HP turbine(s) cover the consumption of compressor(s) and the mechanical losses of high rotation speed shaft. Knowing

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[9] The Brayton cycle of the GT without high temperature buckets cooling, witch realizes the same power and the same efficiency as the real one.

[10] As in table 1, the input data and computed ones were statistically processed.

[11] It is generally know and accepted that, for given extreme temperatures t_1 and t_3, the evolution with ε of main indicators, η_{el} and e_{sp}, follows curves with maximal values, having coordinates $\varepsilon_K(e_{sp\ max})$ / $e_{sp\ max}$, respectively $\varepsilon_K(\eta_{el\ max})$ / $\eta_{el\ max}$, with $\varepsilon_K(e_{sp\ max}) < \varepsilon_K(\eta_{el\ max})$.

p_4 and the isentropic efficiency of the turbine, $\eta_{i\,T}$, allows determining $t_4 \in [t_3 \div t_5]$.

With the tailored software we performed two kind of numerical modeling:

A) In the first step we examined a wide range of input data, $\varepsilon_K \in [12 \div 60]$, with three clusters of values (for high, average and low components performances), issued from data processing of previous software results.

B) In the second step the calculations were made bit by bit, for each ε_K, t_3, η_{CC}, $\eta_{i\,K}$, $\eta_{i\,T}$, η_{mec}, and η_{gen}, of six analyzed gas turbines.

The input data and the peak coordinates are exposed in table 3 and 4.

Table 3

Input data and optimal computed data for different sets of GT components performances

Sets of GT components performances	Input data						Optimal computed data			
	η_{CC}	$\eta_{iz\,K}$	$\eta_{iz\,T}$	t_3	η_{mec}	η_{gen}	$\varepsilon_K(\eta_{el\,max})$	$\eta_{el\,max}$	$\varepsilon_K(e_{sp\,max})$	$e_{sp\,max}$
	%	%	%	^{0}C	%	%	-	%	-	kJ_{el}/kg
High	99,75	92,2	90,95	1.200	99,25	98,29	54,3753	45,86141	17,3121	413,3825
Average	99,6	90,35	89,15	1.165	99,19	98,16	41,4983	41,59219	15,4262	368,6553
Low	99,4	89	87,8	1.140	99,1	98	34,5252	38,54947	14,1616	337,3088

Table 4

Input data and optimal data for analyzed aero-derivatives GT components performances

No	GT model	Input data						Optimal computed data			
		η_{CC}	$\eta_{iz\,K}$	$\eta_{iz\,T}$	t_3	η_{mec}	η_{gen}	$\varepsilon_K(\eta_{el\,max})$	$\eta_{el\,max}$	$\varepsilon_K(e_{sp\,max})$	$e_{sp\,max}$
		%	%	%	^{0}C	%	%	-	%	-	kJ_{el}/kg
1	LM 6000 PC	99,77	91,20	90,09	1.145,3	99,28	98,29	43,3571	43,0381	15,5131	369,305
2	LM 6000 PD	99,76	90,50	89,33	1.157,0	99,27	98,28	41,4071	41,8414	15,3495	366,851
3	LM 2500 RC	99,56	89,60	88,42	1.200,1	99,20	98,17	41,8661	40,9216	15,7315	379,748
4	LM 2500 RD	99,51	89,60	88,35	1.201,2	99,19	98,17	41,7964	40,8464	15,7334	379,774
5	LM 2500 PH	99,75	92,20	90,95	1.138,3	99,13	98,08	46,8563	44,5028	15,8913	375,005
6	LM 2500 PE	99,42	89,00	87,79	1.158,6	99,07	97,98	35,9832	38,8779	14,5299	347,271

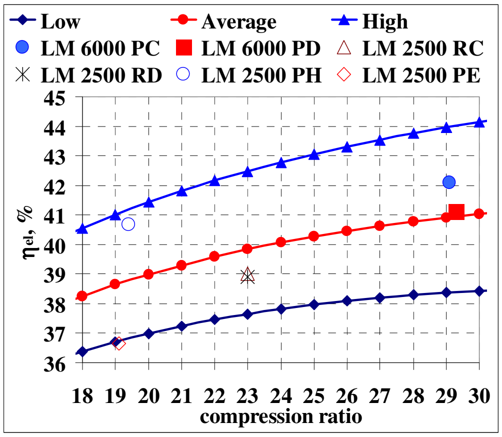

Fig. 3. η_{el} versus ε_K.

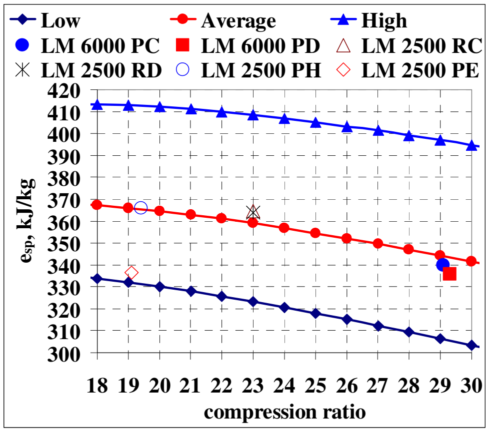

Fig. 4. e_{sp} versus ε_K.

With the additional computed data, not written in tables, we build the charts from figures 3 to 10. The curves were building based on data achieved from the first step of numerical modeling, for $\varepsilon_K \in [12 \div 60]$ and the sets of components performances. The points represents directory or computed data for the analyzed gas turbines. In all these graphs the ε_K abscissa was limited to achieve values of compression ratios of LM gas turbines, $\varepsilon_K \in [18 \div 30]$.

Figures 3 and 4 show that, for the investigated area, η_{el} increase with ε_K and e_{sp} decrease with ε_K. The analyzed gas turbines compression ratios are choused after the canon $\varepsilon_K \in [\varepsilon_K(e_{sp\,max}) \div \varepsilon_K(\eta_{el\,max})]$. The difference is that the LM 2500 turbojet engines have ε_K nearer $\varepsilon_K(e_{sp\,max})$, while LM 6000 turbofan ones have bigger ε_K, closer to $\varepsilon_K(e_{sp\,max})$. Those choices explain the higher e_{sp} of LM 2500 engines and the better efficiencies of LM 6000 ones.

The figure 5 shows that the CC air excess increases with ε_K and diminish with the growth of maximal temperature t_3. For the analyzed gas turbines $\alpha_{CC} \in [3.05 \div 3.55]$. The mechanical work consumed by the compressor increases with ε_K up to 2/3 from $P_{i\,TG}$ (figure 6). That's why (see figure 7) the power resulting from the flue gas expansion in the HP turbine is: **a)** for LM 2500 turbojet engines 1.1 to 1.3 times bigger than the electrical generator output, respectively **b)** for LM 6000 turbofan more than 1.5 times bigger than the generator one.

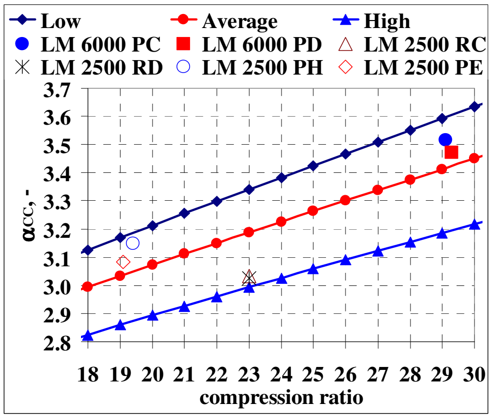

Fig. 5. α_{CC} versus ε_K.

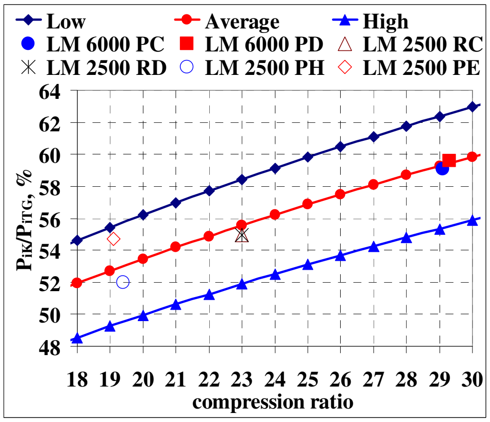

Fig. 6. $P_{iK}/P_{i\,TG}$ versus ε_K.

The most interesting and peculiar results refer to intermediate parameters at the HP turbine output and LP turbine input, p_4 and t_4. The figures 8 and 9 show the following. **A)** The intermediate pressure evolution, versus ε_K, follows curves with maximal values. For lower / intermediate GT components performances, the peak values of p_4 are attained on the graphical represented interval, $\varepsilon_K \in [18 \div 30]$, being lower than 5.25. For higher performances the curves are still increasing on the represented interval. Outside this interval, the maximal p_4 value achieve up to 6, for $\varepsilon_K \cong 38$, after that it decreases. Consequently on low expansion ratios, the LP turbine might be fabricated in 3 subsonic stages. **B)** The intermediate temperature t_4 increases with t_3 rising and decreases at ε_K growth.

On the other hand ε_K is a way for increasing the electrical efficiency of gas turbines. In this design the method will keep almost the same pressure and will decrease the temperature at the input of the LP turbine, which drive the generator. For all the analyzed aero-derivatives gas turbines t_4 is inferior to 840 °C. That permits accomplishing the LP gas turbine without air cooling, on condition to use high temperature materials.

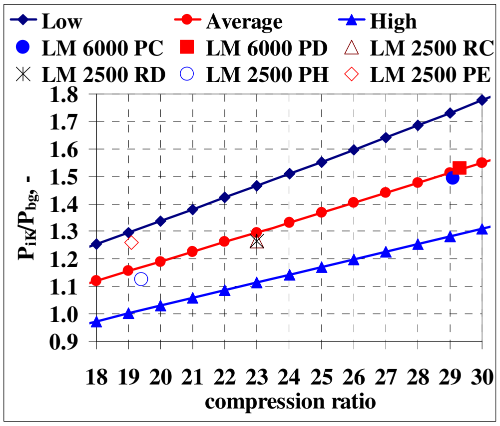

Fig. 7. P_{iK}/P_{bg} versus ε_K.

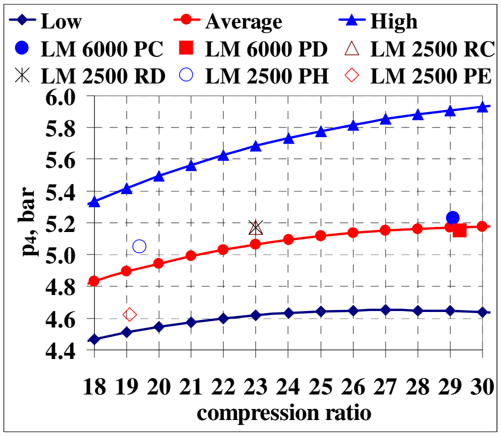

Fig. 8. p_4 versus ε_K.

The last constraint appears to be the most important design restriction for the aero-derivatives power gas turbines.

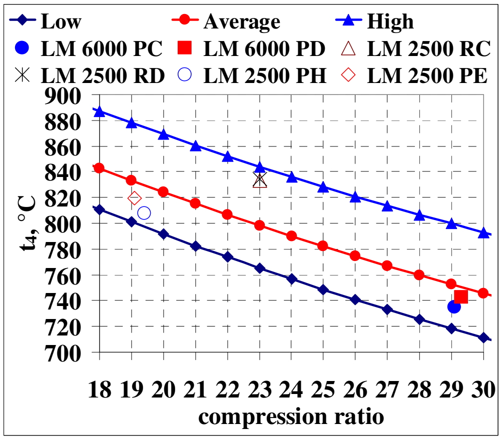

Fig. 9. t_4 versus ε_K.

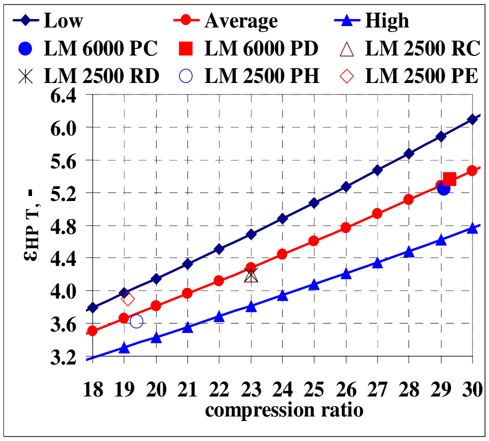

Fig. 10. The ratio $\varepsilon_{HP\,T}/\varepsilon_{LP\,T}$ versus ε_K.

The expansion ratio in the HP turbine, $\varepsilon_{HP\,T}=p_3/p_4$, - see figure 10 - have a linear augment with ε_K. Together with the results about the variation of p_4 and t_4

with ε_K, this last feature involve that the ε_K increase, for electrical efficiency of aeroderivative gas turbines improving, will augment, mainly, the price of “gas generator”. Keeping almost the same pressure and decreasing the temperature at the input of the generator driving LP turbine, the price of these one will remain almost the same, even for higher parameters at gas generator.

4. Conclusions

The new class of medium power aero-derivative gas turbines, employing as “gas generators” turbojet and turbofan propellers, could offer, in the same time, high efficiency, low investment price, and a good reliability / availability. The paper, based on a numeric model of gas turbine’s cycles, conceived for stationary nominal load, uses procedures achieved and validated in our chair. With this model, and starting from directories data, the author’s were establish for chosen aeroderivative medium power gas turbines, and for common records: **a)** the equivalent Brayton cycles and their main thermodynamic and energetic data (temperatures, pressures, expansion ratios, efficiencies, specific works) **b)** the repartition of gas’s expansion between the HP and LP turbine, respectively **c)** the parameters at the LP turbine input. The obtained results are in concordance with references data. They show that LP turbines, driving the generators, have significantly lower parameters than the usual heavy duty turbines. It allows to LP section having a simple structure, without air cooling. Even for higher temperatures at the CC, if the compression ratio increases to, the parameters at the LP turbine input could remain in the same field of suitable values. The conclusions could be applied mainly for choosing the couple of higher thermodynamic parameters, pressure / temperature, at the gas generator, and coordinate their design with the LP power gas turbines.

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