Journal of KONES Powertrain and Transport, Vol. 19, No. 2 2012

MODELING AND ANALYSIS OF JET ENGINE WITH COOLING TURBINE

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Abstract

The problems of the turbojet engines with a cooling turbine modelling are discussed in the paper. The cooling systems of the contemporary jet engines are briefly described in the first part of the paper. Than the models of various turbine, cooling systems are presented and discussed. The main scope of the paper is the turbine cooling system consisted of internal convection cooling and external film cooling of turbine blades. This cooling system is commonly used in contemporary military and civil turbojet engines. The model of the internal-external cooling turbine incorporated in the overall jet engine model is presented and discussed. Some simplifying assumptions are discussed. Then the results of the jet engine calculation taking into account the proposed model are presented in the tables. The results are compared with results obtained by simple model of the jet engine with cooling turbine. The simple model is commonly applied for 1D turbojet engine analysis. Based on this analysis, some aspects of the turbojet engine calculation with reference to different models applied for description of the turbine cooling process are presented and discussed. The analysis allowed formulating some conclusions, which are presented in the final part of the paper. One of them is that proposed model of cooling turbine allows to calculate of coolant mass flow, while the simple models of cooling turbine require the assumption of coolant mass. By this way the calculation results accuracy by the use of simple model, strictly depend on the proper assumption of coolant mass flow.

***Keywords:** jet engine, modelling of jet engine, modelling of jet engine with cooling turbine*

1. Introduction

An accuracy of modelling of turbojet engine thermo and gas-dynamic processes depends on stage of advance of engine analysis. The lower model accuracy (ideal engine model) could be used for trend investigation of engine thermodynamic parameters change [2, 7, 10]. The mass flow change in the engine is frequently negligible in this model.

Preliminary analysis of the turbojet engine cycle involves more accurate model but without many details, which are unknown on this level of engine study. More accurate engine model is built for engine detailed design, where all engine components are precisely specified and dimensioned [10].

When the existing engine model is built, it is possible to build detailed model. In dependence on its application, it could be 1D, 2D or 3D model [2, 10]. 3D models are more accurate but involve a lot of time to build them, very good computers and a lot of time for the calculation process. Generally 3D model analysis is time consuming and more expensive.

By this way very often for determination of engine performance, not so much detailed model could be used. The results calculated by this model are enough accurate, but the time and cost of model preparing and calculation is significantly lower.

To determine turbojet engine performance and in the preliminary engine analysis the 1D model is commonly applied [2, 10]. The problem is what stage of simplification should be done to achieve enough accurate data calculation. This paper focuses on the problem of turbine cooling system modelling. Some examples of contemporary engine models built for preliminary analysis are presented and discussed in the paper. Then the results of calculation of the single spool turbojet engine with cooling turbine modelled by different ways are presented and compared. Finally, the conclusions of leaden investigations are presented.

2. Turbine cooling systems of contemporary turbojet engines

The contemporary turbojet engines for increasing its performance should have high maximal temperature of thermodynamic cycle. That is achieved by the high temperature level of gas inflow to the turbine. The gas temperature in the turbine inlet is about 1700–1870 K [9–11]. This is significantly higher than the turbine materials permits.

The increasing of material work temperature causes decreasing of its durability [1]. A diagram of durability of different alloys working in high temperature vs. working temperature is presented in Fig. 1. Results show significant decreasing of materials durability with the temperature rise. On the other hand the working temperature of nickel based alloys, commonly used as a material for turbine, are significantly lower than the temperature of hot gases flowing through the turbine.

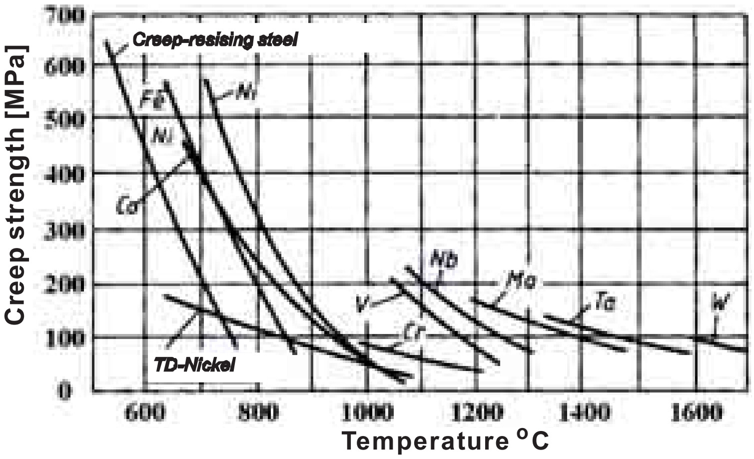

Fig. 1. Creep strength vs. temperature of nickel and cobalt based alloys and high-alloy steel by 100 hours [1]

The gas temperature inflow the turbine (turbine inlet temperature TIT) influences the turbine cooling system (see Fig. 2). For TIT lower than 1300 K, the turbine without the blade cooling system is acceptable. When TIT is between 1300 K and 1560 K, the internal convection cooling system is required. The higher level of TIT requires the mixed internal-external blades cooling system (convection and film cooling).

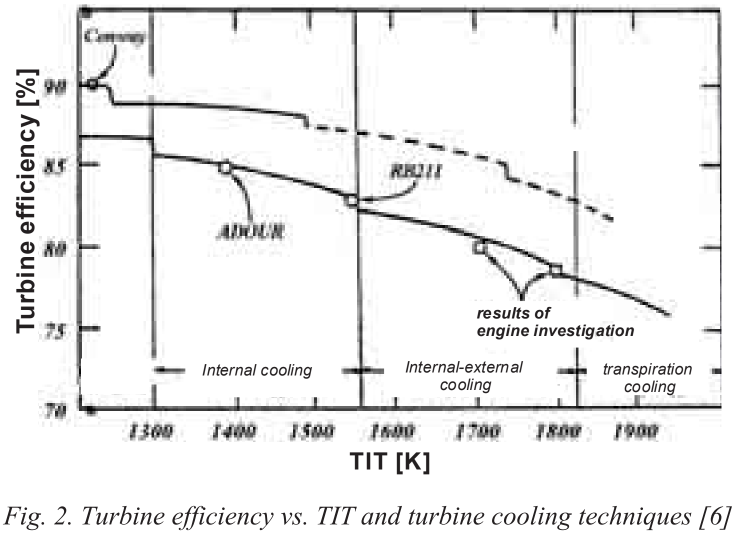

Fig. 2. Turbine efficiency vs. TIT and turbine cooling techniques [6]

Contemporary aero engines are characterized by high maximal temperature of their cycle. So turbine inlet temperature is very nearly 1800 K. Obviously the contemporary aero engines have one and more frequently two or three turbines with several stages. Turbine inflow gas temperature TIT depends on turbine location. Higher level of inflow gas temperature is in the turbine near the combustor so-called high-pressure turbine. If turbine is more far away of the combustor then TIT is lower, but very often it is still so high and requires application of cooling system.

The cooling system application lowers efficiency of turbine work process (see Fig. 2). It is caused by several factors connected with blade cooling, but mainly it is an effect of the inflow of coolant to mainstream flow and mixing process of these two streams. As it is shown in Fig. 2 more advanced cooling system and higher TIT cause significant decreasing of turbine efficiency.

To improve of turbine efficiency the cooling air should has similar pressure to mainstream of flow passing through the turbine [9]. By this way the location of cooling air bleedings are in various places of the compressor. For typical NASA's energy efficient engine (E^3) bleeding of first turbine stage coolant is located after the compressor and the next stages of turbine are cooled by air bleeding after fifth and 7th compressor stages [9]. This requires pipes supplying cooling air from appropriate place of compressor to the turbine stages. Air bleeding from compressor decrease power, which should be supplied to the compressor.

3. Models of turbojet engine with cooling turbine for preliminary analysis

The turbojet engine modelling for preliminary analysis, generate some problems of choice of engine simplification level. The information about engine is very small, and many details of engine are unknown. This generate problem to develop a more accurate model. By this way the inaccuracy of engine calculation should by established.

The analysis of existing turbojet engine models for preliminary study shows, that two approaches are represented [2, 3, 10, 11]. The first one is omitting of cooling system [4, 7, 8, 10], and the second one is including of cooling system bat with assuming its significant simplification of cooling process modelling [5, 6, 9, 11]. The cooling process is modelled by mixing of cooling air with mainstream of hot fume [8, 10]. The energy balance of two mixing stream is used to determine the change of turbine outlet gas stream energy. In this approach the cooling air energy in the mixing process is equal the compressor bleeding gas energy. This mean the processes of heat transfer among cooling air and engine hot elements (turbine) are omitted. The model takes into account mass flow change in the engine by extracting and adding coolant. Therefore, this model is much more advanced than the one without cooling and allows for more exact turbojet engine analysis. The accuracy of calculation strongly depends on proper coolant mass flow assumption. It needs statistical evaluation of cooling air mass flow as a function of hot fume temperature and other factors, which influence it. The other problem is an efficiency of cooling turbine. It should be assumed by statistical analyses of similar existing engines.

More advanced models of cooling turbine are presented in the papers [6, 9, 11]. In theses model processes of convection and film cooling are respected. By analysis of cooling air heat transfer with engines elements the temperature of air inflow to turbine mean stream is determined. It is done by calculation of turbine heat dissipated by coolant and turbine blade protection by air film, when the film cooling system is applied. Model is more complicated because it requires the assumptions of some parameters of heat transfer process in turbine elements. By this way it needs more detailed model of turbine (we should predict the turbine scheme, number of stages, cooling process).

The description of some topics in this model is not a problem for existing engines, but when the hypothetical engine model is built the data of turbine parameters should be assumed on the basis of similar engines data. The model allows to determine of cooling air amount. It makes that the results of the engine analysis are more accurate than the results of presented earlier models [6, 9, 11]. The development of modelling and computational computer programs allows us to apply this model to preliminary analysis of the turbojet engines. Some detailed information about this model is presented in the next paragraph.

4. Model of turbojet engine with cooling turbine

The application of proposed model requires to divide the turbine by separated blade rows. It is required to consider the cooling of each blade row separately too (see Fig. 3). The simplification of analysis is that coolant is drawn from the compressor outlet and enters the blade passages. For convection cooling the coolant leaves from the end of the blade or the trailing edge. For combined convection and film cooling it exits through holes in the blade surface and endwalls. For each type of flow, a mass flow-averaged exit state can be determined by,

$$\dot{m}_{exit} = \dot{m}_{m\_inflow} + \sum \dot{m}_{c\_inflow} , \tag{1}$$

where:

$\dot{m}_{m\_inflow}$ – mass flow of main stream inflow,

$\dot{m}_{c\_inflow}$ – mass flow of cooling streams inflow,

$\dot{m}_{exit}$ – mass flow of exit stream.

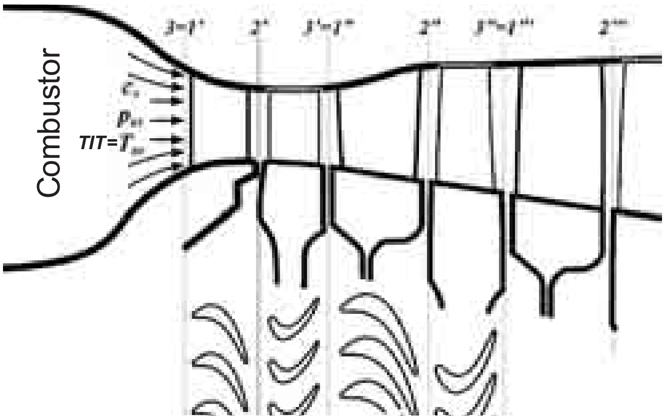

Fig. 3. Turbine model assumption for precise analysis of turbine cooling process

For each stationary blade row, a mean enthalpy balance can be determined by,

$$\dot{m}_{exit} h_{0,exit} - \dot{m}_{m\_inflow} h_{0,m\_inlet} - \sum \dot{m}_{c\_inflow} h_{0,c\_inflow} = 0 . \tag{2}$$

For each rotating blade row, a mean enthalpy balance can be determined by,

$$\dot{m}_{exit} h_{0,exit} - \dot{m}_{m\_inflow} h_{0,m\_inlet} - \sum \dot{m}_{c\_inflow} h_{0,c\_inflow} = P_{ri} , \tag{3}$$

where:

$h_{0,exit}$ – stagnation enthalpy,

P_{ri} – power of i rotating blade row.

Mass of coolant for each blade rows can be determined from heat transfer equation:

$$Q = m_c c_{pc} \left(T_{0c} - T_{0c,inflow} \right), \tag{4}$$

where

Q – heat transferred to the coolant,

$T_{0c,inflow}$ – absolute temperature of coolant inflow to the blade row,

T_{0c} – absolute temperature of coolant inflow to the main stream from blade row. Calculation of it requires knowledge of the mean internal heat transfer coefficient, which is difficult to predict accurately. The problem is solving by introducing an internal flow cooling efficiency defined by:

$$\eta_{c,int} = \frac{T_{0c} - T_{0c,inflow}}{T_{m,int} - T_{0c,inflow}}, \tag{5}$$

$\eta_{c,int}$ – is treated as a known empirical parameter, whose value is typically 0.6-0.8 and reflects the level of the internal cooling technology [11],

$T_{m,int}$ – it is temperature of the internal blade surface (see Fig. 4). It is determined from heat conductivity equations.

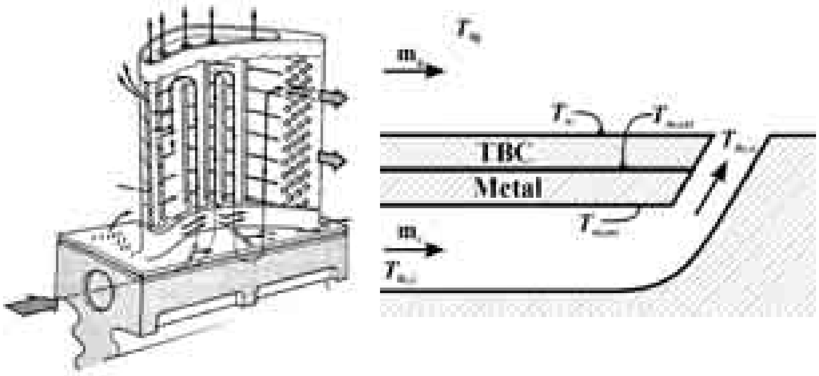

Fig.4. Model of heat transfer among hot gas, turbine blade and coolant [11].

For blades with thermal barrier coating (TBC) it could be determined by:

$$Q = \frac{\lambda_{TBC}}{t_{TBC}} A\left(T_w - T_{m,ext}\right), \tag{6}$$

$$Q = \frac{\lambda_m}{t_m} A\left(T_{m,ext} - T_{m,int}\right), \tag{7}$$

where:

λ – thermal conductivity of blade material and TBC,

t – thickness of material and TBC,

A – total cooled external surface area of blades in row.

On the other hand, the heat transferred by coolant is equal of heat transferred by mainstream of hot fumes. It could by written as:

$$Q = \alpha_g A\left(T_{aw} - T_w\right), \tag{8}$$

α_g – mean external heat transfer coefficient,

T_{aw} – mean adiabatic wall temperature. In the absence of film cooling it equals the mainstream recovery temperature. This in turn, is approximately equal to the inlet absolute temperature for stators, and the inlet relative total temperature for rotors, denoted by T_{0g}. When film cooling is present T_{aw} could be evaluated from film cooling effectiveness equation:

$$\varepsilon_f = \frac{T_{0g} - T_{aw}}{T_{0g} - T_{0c}}, \tag{9}$$

where ε_f is treated as a known parameter equal typically 0.2-0.4 [11].

The combination of presented equations, and elimination of Q allows us to present the cooling process by:

$$\frac{m_c c_{pc}}{\alpha_g A} = \frac{T_{aw} - T_w}{T_{0c} - T_{0c,inflow}},$$
$$Bi_{TBC} = \frac{t_{TBC}\alpha_g}{\lambda_{TBC}} = \frac{T_w - T_{m,ext}}{T_{aw} - T_w}, \tag{10}$$
$$Bi_m = \frac{t_m \alpha_g}{\lambda_m} = \frac{T_{m,ext} - T_{m,int}}{T_{aw} - T_w},$$

where:
Bi – Biot number,

Adaptation of the presented cooling turbine model involves dividing the turbine by the stages, because the cooling process should by analyzed for each blades row separately. In the turbine stages calculation assumed average turbine stage loading coefficient ψ=1.75-1.85 [6], where:

$$\psi = \frac{P_i}{m_g U^2}, \tag{11}$$

where:
U – mean angular velocity.

Another problem is an evaluation of the external surface area of cooled blades in row. For simplification it could be evaluated as a function of axial flow area A, which could be evaluated from continuity equation as:

$$A = \frac{m_g}{\rho c_x}, \tag{12}$$

ρ – gas density,
c_x – axial gas velocity.

In calculation the external surface area of blade was assumed as three-time axial flow area.

4. Comparison of different engine model calculation results

In this chapter the results of three approaches for the turbojet engine modelling are presented. First engine model was done with omitting cooling process although the engine requires cooling of the turbine. Another model takes into consideration simple model of turbine cooling process, when the cooling process was modelled by mixing of hot fumes with coolant but omitting the heat transfer. The last one was more accurate model of cooling which was widely presented in the earlier chapter.

The analysis was done for single spool turbojet engine. It was assumed compressor pressure ratio π_s=32, turbine inlet temperature TIT= 1600K, mass flow rate 50 kg/s. The ambient condition was assumed p_0=10^5 Pa, T_0=287 K, flight speed V=0.

For more accurate engine model calculation the blades turbine material was assumed as IN 100, which allow maximum material temperature about 700-850^{o}C. Blades were coated by thermal barrier Zr-La, which maximum work temperature is 1500^{o}C.

The material temperature limit was taken in to the consideration during evaluation of coolant mass flow. Coolant mass flow rated in this approach was taken to the low precision cooling engine model calculation.

For cooling process analysis a thickness of blades wall was assumed 0,8 mm and the thickness of TBC was assumed 0.34 μm. The parameters of heat transfer were assumed: conductivity of material λ= 25 W/m/K, conductivity of TBC λ= 1,7 W/m/K , mean external heat transfer coefficient for stator blades $\alpha_g = 566\ \mathrm{W/m^2/K}$, mean external heat transfer coefficient for rotor blades $\alpha_g = 531\ \mathrm{W/m^2/K}$, film cooling effectiveness $\varepsilon_f = 0.25$.

The results are presented in three columns in Tab. 1. Column A it is the engine without cooling, column B it is the engine with low precision cooling turbine model and column C it is the engine with more precise engine model of turbine cooling, which is presented, in 3th chapter. The results of turbine parameters calculation by precise engine model is presented in Tab. 2.

The presented results of the turbojet engine calculation show that results for cold engine sections are similar for three presented models. The differences start from calculation of the combustor and depend on the applied model. Calculation of mass of fuel supplied into the combustor is largest for simpler model. It is caused by greater mass of air inflow into the combustor, and for achievement of established TIT it requires more fuel.

Tab. 1. Results of turbojet engine calculation for different model of turbine cooling

		A	B	C
Stagnation pressure after compressor [MPa]		3.17	3.17	3.17
Stagnation temperature after compressor [K]		802	802	802
Power of compressor [MW]		26.73	26.73	26.73
Combustor air mass inflow [kg/s]		50	46.67	46.67
Mass of fuel [kg/s]		1.183	1.104	1.104
Mass of gas inflow to the turbine [kg/s]		51.18	47.77	47.77
Turbine inlet	Stagnation pressure [MPa]	3.0	3.0	3,0
	Stagnation temperature [K]	1600	1600	1600
Turbine outlet	Stagnation pressure [MPa]	0.623	0.501	0,482
	Stagnation temperature [K]	1163	1110	1063
	Gas mass flow [kg/s]	51.18	51.1	51,1
Thrust [kN]		50.68	46.75	45.57
Specific thrust [Ns/kg]		1014	935	911
Specific fuel consumption [g/daN/s]		0.233	0.236	0.242

Anywhere engine model with omitting turbine cooling (simpler model) allows calculating more optimistic results of engine performance. Higher pressure and temperature of fumes outlet the turbine cause better engine work parameters. Calculated thrust and specific thrust is higher and specific fuel consumption is lower than the results calculated for engine with included the turbine-cooling model. The differences of results depend on the turbine cooling process simplification. The much more differences are between results evaluated by simple engine model and more detailed engine model (column A and C). The differences in trust and specific thrust calculation are about 10% and the difference in specific fuel consumption evaluation is about 5%. The results presented in column B are similar to results in column C. It could be caused by the fact that amount of coolant was calculated in the exact turbine-cooling model in the first step and then the same value was used in the simple model with turbine cooling.

Table 2 presents the results of some parameters calculation in turbine. The results were calculated by the exact cooling turbine model application. Presented analysis allows to evaluate the parameters after each blade rows of turbine. By control gas temperature this model allows to evaluate the cooling mass flow supplied to each blade rows. It allows to predict the cooling system for each blade row. However, the accuracy of evaluation depends on the correctness of the assumed cooling turbine parameters, i.e. the heat transfer coefficients and area of the cooled blade rows surface.

The exact turbine analysis shows that first two stages require convection-film cooling systems. The third stage could be cooled by internal method only. The total mass of coolant supplied into the turbine evaluated on 3.33 kg/s, what is 6.6% of air mass inflow the engine.

Tab. 2. Results of exact cooling turbine analysis

Turbine stages			3
Turbine power [MW]			27.01
Stage 1	Stator	coolant mass flow [kg/s]	0.51
		cooling type	int.- ext.
		outlet temperature [K]	1590
		outlet pressure [MPa]	2.917
	Rotor	coolant mass flow [kg/s]	0.54
		cooling type	int.-ext.
		outlet temperature [K]	1411
		outlet pressure [MPa]	1.697
Stage 2	Stator	coolant mass flow [kg/s]	0.53
		cooling type	int.-ext.
		outlet temperature [K]	1402
		outlet pressure [MPa]	1.653
	Rotor	coolant mass flow [kg/s]	0.65
		cooling type	int.-ext.
		outlet temperature [K]	1217
		outlet pressure [MPa]	0.901
Stage 3	Stator	coolant mass flow [kg/s]	0.50
		cooling type	internal
		outlet temperature [K]	1209
		outlet pressure [MPa]	0.880
	Rotor	coolant mass flow [kg/s]	0.600
		cooling type	internal
		outlet temperature [K]	1063
		outlet pressure [MPa]	0.482

5. Summary and conclusions

The three approaches for the turbojet engine modelling for preliminary design are presented in the paper. The more simple engine model but not ideal engine model, assumed the irreversible internal processes in the engine component and semi perfect gas model, but omit the turbine cooling process is first. This model allows to calculate more optimistic engine performance. Its advantages are simple engine description without many details unknown during preliminary analysis, easy modification of engine parameters and possibilities of calculation of different engine variants. Disadvantages are not so accurate results, which are overstate for contemporary turbojet engines, which require cooling turbines.

The second one is classically used in calculation engine model with simple analysis of cooling process. The cooling process is described by cooling air mixing with hot fumes in the turbine. It omits heat transfer among hot gas, elements of the turbine blades and cooling air. Cooling air is bleeded from the compressor and supplied to the turbine. The energy balance equation is used for calculation energy drop by mixing processes. The results of engine calculation with this model application depend on the correctness of the assumption of amount of coolant flow, and turbine efficiency drop. Model is similarly simple as presented earlier and very good for preliminary engine analysis, but results of calculation are more accurate on condition the coolant mass is correctly assumed.

The third model is more precise. Cooling process is described more detailed with consideration of turbine blades cooling types and heat transfer among hot and cold stream and the blades material. The results of engine analysis are more pessimistic than evaluated by earlier presented models, but they should be closer to the real engine investigation results [11]. The model needs specification of heat processes characteristics and dimension of turbine elements. In the preliminary design some details of turbine elements are unknown, and could be assumed by statistical data analysis. By this way the difficulty of the presented model application is proper assumption of these parameters like blade material thermal characteristic, blades area and thickness, TBC occurrence, etc. On the other hand, presented model allows determining the mass of coolant.

The problem of model application for preliminary design depends on quantity of unknown details of the engine structure. For trend analysis of engine parameters change it is enough the simple model but with turbine cooling process respect for engines of high TIT. This allows precisely evaluate engine performances, and to build and use this model is not so difficult. For engine performance and structure analyses as a first stage of activity before detailed engine design, the more accurate engine model should be used. It could be the first stage of the engine structure detail specification.

References

[1] Chodorowski, J., Ciszewski, A., Radomski, T., *Materiałoznawstwo lotnicze,* Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa 2003.

[2] Górski, J., Orkisz, M., *Wpływ modelu czynnika roboczego na parametry obiegu lotniczego silnika turbinowego*, IV Sympozjum Naukowe: Problemy techniczno-eksploatacyjne w kształceniu pilotów, Dęblin 1999.

[3] Guha, A., *An efficient generic method for calculating the properties of combustion products*, Proceedings of the Institution of Mechanical Engineers, Part A, Vol. 215, Is. 3, Londyn 2001.

[4] Guha, A., *Performance and optimization of gas turbines with real gas effects*, Proceedings of the Institution of Mechanical Engineers, Part A, Vol. 215, Is. 4, pp. 507-512, Londyn 2001.

[5] Horloc, J., H., et al., *Limitation on Gas Turbine Performance Imposed by Large Turbine Cooling Flows*, Journal of Engineering for Gas Turbines and Power, ASME Trans., Vol. 123, July 2001.

[6] Japikse, D., *Advanced topics in turbomachinery technology*, PLS No 2, Concepts ETI Inc. Norwich, Vermont 05055, USA 1986.

[7] Jakubowski, R., Orkisz, M., *Comparison analyze of single spool turbojet engine inner characteristics taking different gas model*, 29th International Conference on Combustion Engines, KONES 2003, Wisła 2003.

[8] Jakubowski, R., Orkisz, M., *Ocena charakterystyk eksploatacyjnych jednoprzepływowego turbinowego silnika odrzutowego z wykorzystaniem metody bilansu energetycznego*, 27th International Scientific Conference on Combustion Engines, KONES 2001, pp. 268-279 Jastrzębia Góra 2001.

[9] Je-Chin Han, Sandip, Dutta, Srinath, V. Ekkad, *Gas turbine heat transfer and cooling technology*, Taylor & Francis, 646, New York 2001.

[10] Orkisz, M., at al., *Podstawy doboru turbinowych silników odrzutowych do płatowca*, Biblioteka Naukowa Instytutu Lotnictwa 18, Warszawa 2002

[11] Young, J. B., Wilcock, R. C., *Modelling the Air-Cooled Gas Turbine*, Joumal of Turbomachinery, Vol. 124, pp. 207-222, 2002.