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ESTIMATION OF TURBOPROP ENGINE PARAMETERS FOR VARIOUS FUELS

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Abstract

The analysis of work parameters of a turboprop engine fuelled by various fuels was done in the article. The turboprop engine model was presented in the beginning. The main feature of this model is description of the flow in the engine as semi-perfect gas model. By this way, the change of fumes chemical composition influence the gas properties as heat constant and isentropic index are determined. Next energy balance of a compressor and turbine was analysed and turbine pressure drop was evaluated. Finally, engine output power was determined. It was done for selected fuels, which could be applied in the aero engines. The results of analyse were presented in the tables and charts and discussed. Summary of the test results with the results for contemporary applied fuel allows drawing the conclusions about the turboprop engine performance change by various fuel application. Main of them refers to the point that higher combustion heat value of fuel and higher heat constant of fumes cause better engine work conditions By this way the hydrogen seems to be perspective fuel of future, because its combustion heat value is three times JET A-1 and by this way it is possible the engine fuel consumption will be lower.

Keywords: *Aircraft Engines, Fuels, Turboprop Engines,*

1. Introduction

The growth of crude oil consumption has been observed by the last decades. It is mentioned in the work [2] that half of world's crude oil has been consumed or it will happen soon and it should be undertaken some effort to ensure smooth transition to alternate fuels.

Similar situation concerns the air transport. Even though aircraft propulsions efficiency has grown significantly since introduction of commercial jet aircraft in the 1960s, the air travel growth of about 5% per year caused increase in air transport fuel consumption [2]. On the other hand air traffic growth strongly influence on the environment pollution [9, 10]. The tests of aero-engine emission [9] show the huge aircrafts impact of air pollution especially nearby them. By this way the airports and their nearby surrounding are mainly exposed to aircrafts adverse effects by large concentration of aircrafts operations [9].

As a consequence, the aviation industry is interested in alternative energy sources and alternative fuels. The key issues center of finding a sustainable source of energy for the future that will keep the operating cost and pollution emission at a reasonable level [2]. By this way the there are research about alternative energy sources for the aircraft propulsion like electrical motors with fuel cells and solar battery [7, 8] and new type of fuels, as bio-fuels or synthetic fuels [2, 15, 16]. Another way of fuel sawing and environment protection is turbojet engine cycle modification to make it more efficient like it is studied in works [3, 5, 6, 11, 13].

In these papers, the turboprop engine is used as an object of numerical test of different fuel application. It was built turboprop engine one-dimensional model for the study. The main feature of this model it is description of gas flowing through the engine as a semi-perfect gas model based on the work [1]. It allows analysing gas parameters as a function of its components and temperature. It is useful to describe properties of pure air and the combustion products of air and hydrocarbon fuels, where fumes is a mixture of the combustion products and air which hasn't took part in the combustion process.

There were done analyse for a typically applied in aviation hydrocarbon fuel and for few fuels, which aren't used, but could be apply in aviation such as methanol, ethanol, LPG, CNG, hydrogen etc. The semi-perfect gas model allowed determining specific heat and isentropic index for fumes produced by combustion of tested fuels. By this way, the changes of turbine work for different fuels were determined. In the analyse, it was assumed that total temperature in the high-pressure turbine inlet and pressure ratio of both compressors are constant. Hence, fuel consumption and the turbines pressure ratio were evaluated for analysed fuels. It allowed determining engine work parameters like engine output power and engine specific fuel consumption.

2. Turboprop engine model and assumption for analysis

The three-spool turboprop engine was assumed to analyse. Such structure represent PW120 turboprop engine, which parameters were used to this study. The scheme of the engine is presented in Fig 1. It consists in order of inlet, low and high-pressure centrifugal compressors, and combustion chamber, high and low pressure turbines, free power turbine and engine outlet.

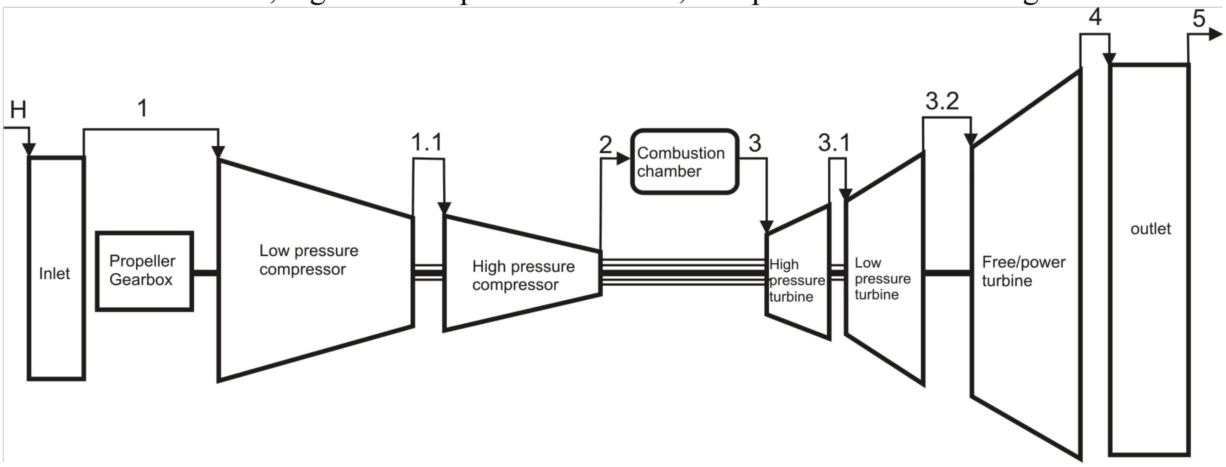

Fig 1. Three spool turboprop engine main components

It was assumed 0-1 D flow model in the engine gas-dynamic description typically applied for such analysis [4, 12]. Engine internal losses were assumed as pressure drop in the inlet, combustion chamber and outlet, thermal efficiency for combustion chamber, isentropic efficiency for engine turbomachinery and mechanical efficiency for power transmission between rotating elements. The value of these parameters was assumed based on data in the work [12].

Other assumptions were that the engine performance for various fuels was calculated for ground conditions. It was assumed constant temperature in the turbine inlet (TIT=1400 K) and constant compressor pressure ratio (π_C=12, 14). Air mass flow was assumed constant (m=6.7 kg/s). Pressure drop in engine outlet was fixed too. Data was taken from [12].

More important for analysis was semi-perfect gas model assumption. The air properties were described as a function of temperature. Fume parameters were described as a function of temperature and gas composition according formula given in paper [1]. By this way, it was possible to analysis the influence of different fuels for fumes composition and fumes properties as gas constant R, specific heat c_p and isentropic index γ.

Therefore, the mine turboprop engine performance parameters like output work of the power turbine were determined as:

$$W_{PT} = \eta_m \cdot \left(1 + \tau_{fuel}\right) c_{p\_m}\left(T_{32} - T_4\right), \tag{1}$$

turbine output power:

$$P_T = m \cdot W_{PT} \tag{2}$$

and specific fuel consumption was calculated as:

$$c_j = \frac{\tau_{fuel}}{W_{PT}}, \tag{3}$$

where fuel-air ratio was evaluated as:

$$\tau_{fuel} = \frac{c_{p\_m}\left(T_3 - T_2\right)}{\eta_B \cdot LHV}, \tag{4}$$

where:

η_m – mechanical losses mainly caused by engine gearbox,

τ_{fuel} – fuel air ratio,

m – air mass flow througt the engine,

c_{p_m} – mean gas heat constant for combustion process,

η_B – burner efficiency.

Main feature of model was semi-perfect gas model assumption. Based on the relations presented in paper [1] fumes properties were expressed as – specific heat of constant pressure:

$$\frac{c_{p,fum}}{c_{p,air}} = \frac{1 + \tau_{fuel}\left(X_0 + X_1 T + X_2 / T^2\right)}{1 + \tau_{fuel}}, \tag{5}$$

specific gas constant of fumes:

$$\frac{R_{fum}}{R_{air}} = \frac{1 + Y\tau_{fuel}}{1 + \tau_{fuel}} \tag{6}$$

and isentropic index:

$$k_{fum} = \frac{c_{p\_fum}}{c_{p\_fum} - R_{fum}}, \tag{7}$$

where:

n – number of specified atoms in one molecule of fuel,

c_p – specific heat capacity of constant pressure,

R – specific gas constant,

k – isentropic index,

τ_{fuel} – fuel air mass ratio,

T – temperature,

X_0, X_1, X_2, Y – characteristic numbers according below equations,

M – molecular weight,

indexes:

air – air,

fum – fumes,

fuel – fuel,

C, H, O – atoms of carbon, Hydrogen and oxygen.

$$X_0 = \frac{1}{M_{fuel}}\left(18.0566 n_C + 8.3485 n_H + 15.1616 n_O\right), \tag{8}$$

$$X_1 = \frac{0.00223 n_H}{M_{fuel}}, \tag{9}$$

$$X_2 = \frac{1077768.4 n_C}{M_{fuel}}, \tag{10}$$

$$Y = \frac{M_{air}}{M_{fuel}} \left(\frac{n_H}{4} - \frac{n_O}{2} \right), \tag{11}$$

For air $c_{p,air}$ was evaluated as a polynomial function of temperature. Specific gas constant and molecular mass were taken from [1].

For application of presented equations for fumes properties determination, it is necessary to know equivalent chemical formula of fumes. The formulas of fuels applied in analysis and its proprieties are presented in Tab. 1.

Tab. 1. Fuels main properties (elaborated based on [1, 17]

Fuel	Equivalent chemical formula	Density kg/m^3	Specific heat kJ/(kgK)	Lower heating values (LHV) MJ/(kg)	Molar mass kg/kmol
Ethanol	C_2H_6O	790	2.44	26.8	46.069
Methanol	CH_4O	790	2.53	19.92	32.042
Liquid hydrogen	H_2	70	1.44	120.0	2.016
CNG	CH_4	450	1.27	42	17.39
LPG	$C_{3,5}H_9$	550	1.253	45	15.67
Gasoline	C_7H_{17}	770	2.4	44	100
Diesel	$C_{14,4}H_{24,9}$	820	2.0	42.8	200
Kerosene	$C_{12,5}H_{23,5}$	850	2.0	42.8	173

3 Results of engine performance calculation

Results of engine output power, fuel-air ratio, and specific fuel consumption are presented in the Tab. 2. Start the analysis from fuel consumption it is seen fuel air ratio significantly decreasing of these parameters for hydrogen in comparison with classical aero-engine fuel – kerosene. For hydrogen, it is over 2.5-time lower fuel-air ratio than for kerosene. For methanol and ethanol is observed about two time grow of this parameter with compare to kerosene. Fuel-air ratio slightly changes for other fuels. Equation 11 shows that significant opposite influence on fuel-air ratio have fuel low heat value (LHV), while other parameters of combustion are constant. LHV values presented in Tab. 1 show LHV of ethanol and methanol is about two times lower than of kerosene and LHV of hydrogen is about 3 times higher than of kerosene.

Tab. 2. Results juxtaposition of the main turboprop engine parameters for various fuels

	Kerosene	Ethanol	Methanol	Hydrogen	CNG	LPG	Diesel
Power [kW]	1332	1409	1478	1332	1376	1321	1331
Fuel air ratio	0.0223	0.0365	0.0497	0.0088	0.0245	0.0213	0.0225
Specific fuel	0.4043	0.6255	0.8115	0.1601	0.4297	0.3891	0.4072

Specific fuel consumption changes in a similar manner as fuel-air ratio. Lower value is for hydrogen then for kerosene and higher value is for ethanol and methanol. Changes of that values plus power change for fuels versus kerosene in per cent are presented in Fig. 1.

It could be noticed that the growth of specific fuel consumption for methanol and ethanol is lower than fuel-air ratio. It is caused by engine output power, which grows up for methanol, and ethanol fuels compared it to the power of engine fuelled by kerosene. For hydrogen, it is not observed any change of power by compare to kerosene. By this way, the change of fuel air ratio and specific fuel consumption of engine fuelled by hydrogen compares to engine fuelled by kerosene is on the same level. LPG, CNG and Diesel fuels cause significantly less change of both discussed parameters. It should be noticed that LPG allow to reduce fuel air ratio and specific fuel consumption in comparison to Kerosene, but next two kind of fuels cause a few per cent growth of fuel consumption.

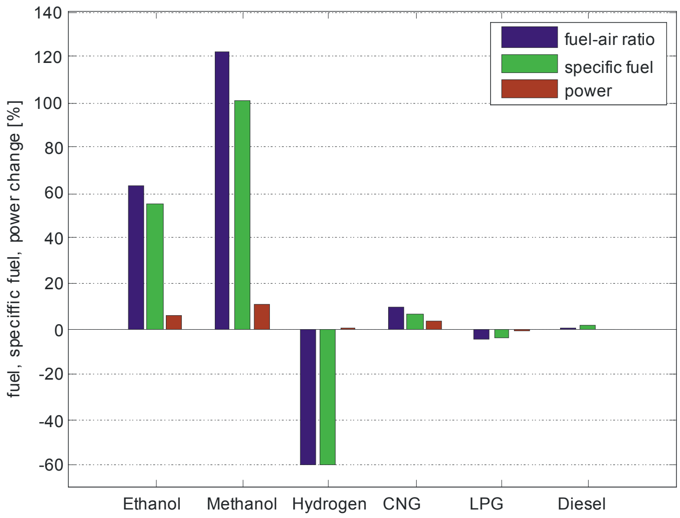

Fig. 1. Engine fuel consumption, specific fuel consumption and power for various fuels change into the engine fuelled by kerosene

Output power of the turboprop engine fuelled by the analysed fuels is another important engine parameter. Results presented in Tab. 2 show the power of engine fuelled by methanol and ethanol is higher than the one of fuelled by kerosene. The power of the turboprop engine fuelled by other fuels is on the similar level than for kerosene. The change of engine output power for other fuels compared to kerosene shows that methanol allows the power grow up about 6% and ethanol about 11%. The other fuels cause low change of output power compared to kerosene, so CNG gives higher power of about 3%. To explain obtained results it should be analysed the formula of output engine power. As it is clear from the equations 1 and 2 the engine output power depends on the temperature drop in the power turbine, fuel-air ratio and mean constant pressure heat value of gas in the turbine. Other parameters are not changed so significantly and they were assumed of stable.

Evaluated value of temperature and pressure drop in turbines is presented in Fig. 2. The bars of chart for high and low pressure turbine present that for methanol, ethanol, hydrogen and CNG temperature drop is lower than for kerosene. Compressor turbines pressure ratio for ethanol, methanol and CNG is on lower level than for kerosene too. Lower pressure drop in the compressor turbines causes higher overpressure in power turbine, which could be transferred into the output power. Comparison of output power results presented in Tab. 2 with pressure ratio of power turbine shows high consistency of both results. The highest-pressure ratio of power turbine achieves the engine fuelled by methanol 2.5. Evaluated output power for this engine is 1478 kW, while engine fuelled by kerosene has power turbine pressure ratio 2.36 and evaluated output power 1332 kW.

When lower pressure drop in compressor turbines is connected with lower temperature drop in these turbines, the effect of output power growth is reinforced. It could be observed for engines fuelled by methanol and ethanol. For hydrogen temperature drop in compressor turbines is lower than for engine fuelled by kerosene, but it is observed opposite situation with pressure drop in these turbines. Finally evaluated output power for engine fuelled bout kinds of fuel is on the same level.

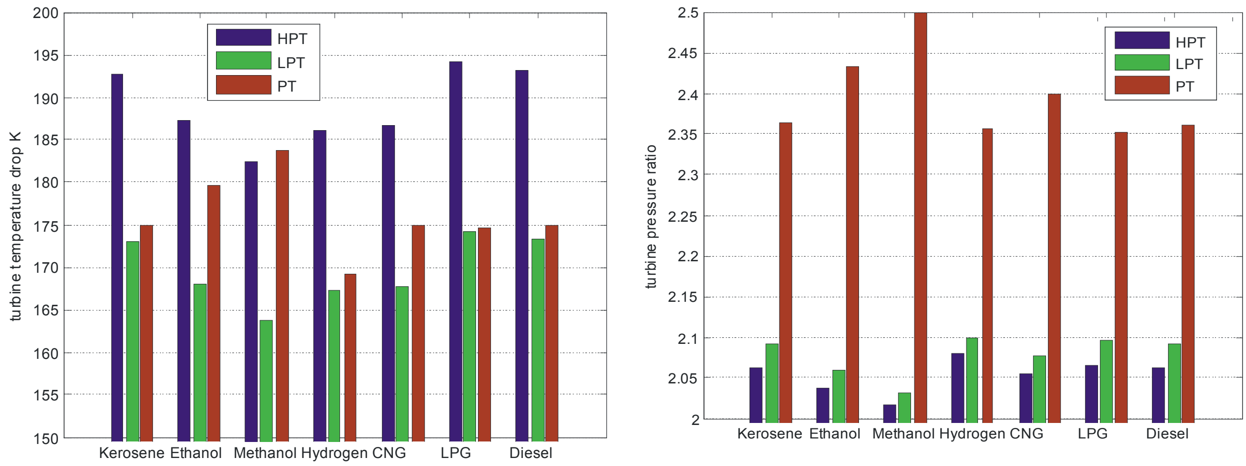

Fig. 2. Temperature drop and turbines pressure ratio of the engine fuelled by some kind of fuel (HPT – high-pressure turbine, LPT – low-pressure turbine, PT – power turbine)

To explain presented results it should be analysed relation between pressure and temperature drop in the turbine taking into account gas properties. For ideal turbine, it could be described by isentropic equation:

$$\tau_T = \pi_T^{\frac{\gamma-1}{\gamma}}, \qquad \pi_T = \tau_T^{\frac{\gamma}{\gamma-1}}, \tag{12}$$

where

τ_T – turbine temperature ratio,

π_T – turbine pressure ratio,

γ – average turbine isentropic index.

By this way for the same turbine pressure ratio, temperature ratio in turbine is higher while isentropic index is higher. On the other side for the same turbine temperature ratio, pressure ratio is higher while isentropic index is lower. Therefore, for compressor turbines while temperature drop is determined by compressor work balance, the lower isentropic index causes higher turbine pressure ratio. It could be noticed for engine fuelled by hydrogen, where high constant pressure heat value directly leads to low isentropic index (see Fig. 4). For engine fuelled by hydrogen compressor turbines presser ratio is higher than for other fuels even thought gas temperature drop in the compressor turbine is lower. Therefore, overpressure in the power turbine is less than in other of analysed engines what directly leads to lower power turbine temperature drop. For this engine similar level of output power to the one fuelled by kerosene is achieved by high value of constant pressure heat coefficient. Average constant pressure heat value and isentropic index of gas in analysed engine turbines is presented in Tab. 3.

4. Summary

Presented results indicate, that it is possible to improve engine performance by fuelled it by other kind of fuels than kerosene. When the goal is lower fuel consumption, applied fuel should be of higher low heat value. Low heat value of hydrogen is almost three time higher than other typical fuels like kerosene or Diesel fuel. Therefore, for engine fuelled by hydrogen fuel-air ratio is on significantly lower level. Specific fuel consumption of engine fuelled by hydrogen is the lowest among other of tested fuels. The results obtained for LPG except hydrogen give lower specific fuel consumption than for kerosene but the gain is significantly less.

Tab. 3. Average constant pressure heat value and isentropic index of gas in the turbines of the engine fuelled by some kind of fuel

	High Pressure Turbine		Low Pressure Turbine		Power Turbine	
	c_p [kJ/kg/K]	γ	c_p [kJ/kg/K]	γ	c_p [kJ/kg/K]	γ
Kerosene	1234.79	1.303	1205.65	1.312	1149.86	1.333
Ethanol	1254.14	1.297	1224.90	1.306	1167.27	1.326
Methanol	1269.58	1.292	1240.33	1.301	1181.16	1.321
Hydrogen	1295.20	1.285	1263.76	1.294	1205.78	1.312
CNG	1271.44	1.292	1241.27	1.301	1183.33	1.320
LPG	1227.08	1.305	1198.14	1.315	1143.05	1.335
Diesel	1232.61	1.304	1203.55	1.313	1147.86	1.333

The output power growth with comparison to kerosene has been obtained for ethanol, methanol and CNG. It has been discussed that high constant pressure heat value and lower isentropic index should be taken together in to account to determine turbine thermodynamic parameters changes. It has been shown that high gas heat value allows to decrease pressure drop in turbine cooperated with a compressor, but on the other hand low value of isentropic index causes higher-pressure drop in the turbine. Finally, power turbine overpressure is smaller and by this way engine, output power is smaller.

Presented analysis of various fuels influence the engine performance is the first step in the research and will be developed. Other important tests should concern evaluation of engine pollution and engine geometry modification to adopt it to work with different kind of fuel.

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