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GAS TURBINE PLANT ON THE BASIS OF THE CONVERTED AERO ENGINE WITH REGENERATION

Introduction

Gas turbine engines which has exhausted flight service life can be used for terrestrial objectives in the energetics. Turboprop (turboshaft) aircraft (helicopter) engine is the simplest to use as gas-turbine power plant, because in this engine, mechanical energy is transmitted on the outer shaft and can be used directly.

Such gas turbine power plant is indispensable for using in these cases, when:

– it is necessary to solve the problem of electrical and thermal energy, supply to a town or production plant - the modularity of the blocks allows to create any variants depending on the needs of its consumers;

– economic efficiency is important; modern gas turbines have efficiency up to 40% in simple cycle, high efficiency of plant provides the possibility of producing cheaper electricity and heat generation and short payback period;

– it is industrial development of new areas of people's lives and the natural features of these territories have great importance; operation of the plant is ensured in the range of ambient temperatures from –50 to +50 ºC when the adverse weather conditions like humidity, rain, snow effect (the level of stress and thermal condition of the aviation engine parts almost has no analogues among the products of mechanical engineering);

– it is necessary the automation of control plants; gas turbine stations based on aircraft engines is very maneuverable, and require a small time to start from cold condition to full load, can be automated and controlled remotely.

Crux of problem

Conversion of aircraft engines that have exhausted their assigned flight service life time is an actual problem for both Ukraine and other countries with a developed aviation transport infrastructure [7]. At the same time, for converted aircraft engines, the demand for a significant increase in fuel efficiency as compared to that which these engines have when they are used on aircraft, where the minimum engine weight requirement is put in the first place, is put forward.

The need to reduce the usage of fossil fuels have been increasingly part of our daily lives for both environmental and economic reasons.

Decreasing the consumptions without compromising the engine performance can be a difficult task, to approach this goal one of the reliable method is to use regeneration, Regenerator is placed after the turbine and before the propulsion nozzle to heat the compressed air before entering the combustor, reducing the fuel consumption.

In this paper an analysis of the PT6T turboshaft engine with regeneration will be performed. In other words, observations will be made on how a regenerator affect the thermal efficiency of this engine beside the turboshaft engine (PT6 family) has been chosen to redesign as a mobile power-plant with regeneration.

Due to the exceptional compactness, low weight, flexibility, high efficiency and availability of the outer shaft (through which the mechanical energy is transmitted to electrical device) make this turboshaft engine as a good choice to use for terrestrial purposes.

The aim of this work is to study the possibility of increasing the fuel efficiency of a converted aviation gas turbine engine when it is used as a drive for mobile electrical power plants.

The result of this paper can be used to perform the conversion of this type of engine with high efficiency and low fuel consumption as a mobile power-plant which can be installed on a truck to generate electricity for different purposes in different environmental conditions with different type of fuels.

Justification of the choice of engine

As a power drive for the mobile power plant the turboshaft engine PT6T-3D (PT6 family), Fig. 1, Fig. 2, which consists of two power sections coupled to a combining gearbox with a novel clutch system enabling both twin and single engine operation, was chosen [2; 3; 8].

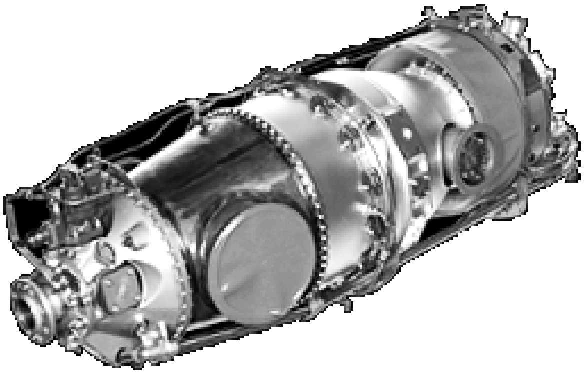

Fig. 1. Turboshaft engine PT6

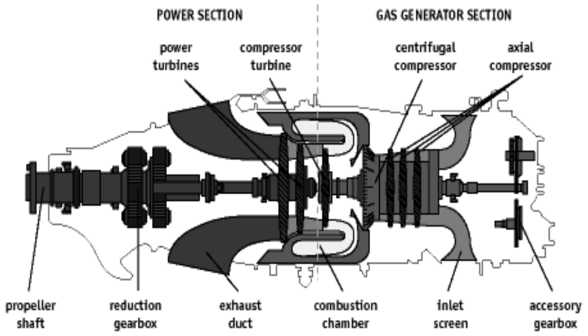

Fig. 2. PT6A cross section

The engine consists of two sections that can be easily separated for maintenance: a gas generator supplies hot gas to a free power turbine. A two-shaft configuration consisting of a multi-stage compressor driven by a single-stage compressor turbine and an independent shaft coupling the power turbine to the output shaft.

The starter has to accelerate only the gas generator, making the engine easy to start, particularly in cold weather. Air enters the gas-generator through an inlet screen into the low-pressure axial compressor.

The air then flows into a single-stage centrifugal compressor, through a reverse flow combustor, and finally through a single-stage turbine that powers the compressors. Hot gas from the gas generator flows into the power turbine.

The gas generator speed is around 36,000 rpm. For turboprop use, this powers a two-stage planetary output reduction gearbox, which rotates the power turbine at a speed of 1,900 to 2,200 rpm. The exhaust gas then escapes through two side-mounted ducts in the power turbine housing. The turbines are mounted inside the combustion chamber, reducing overall length.

Smaller gas turbines are rated with a higher operating speed — mainly because of thermo-dynamical reasons.

This is done in order to obtain better efficiencies. Due to the material-related maximum circumferential speed of the blades, the nominal speed of gas turbines with higher outputs is limited. Apart from these common models, which are often called ‘Industrial Gas Turbines’. These aero-derivative gas

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turbines come – as the name implies – from the aircraft construction industry, i.e. they have been derived from an aircraft engine and stand out for their more compact design compared to industrial gas turbines which are designed for conventional applications in power stations.

Characteristics of gas turbine plant on the basis of the converted one power section of PT6T-3D turboshaft engine (PT6A)

The turboshaft engine PT6T-3D which consists of two PT6A power sections is the engine for which studies and calculations of the main characteristics were performed.

The engine main components are a compressor which consists of 3-stage axial flow and 1-stage centrifugal compressor, combustors which has Annular reverse-flow with 14 Simplex burners and turbine that has 1-stage gas generator power turbine with 2-stage free power turbine (independent 'free' power turbine with shrouded blades Forward facing output for fast hot section refurbishment).

By performing thermodynamic and gas dynamic calculations we have recalculated the performance details of this engine as a gas turbine plant which are the followings:

- Maximum power output is around 670921 kW;
- Overall pressure ratio is 6.3;
- Air mass flow is approximately 2.5 kg/s;
- Specific fuel consumption is around 0.44 kg/kW/h.

The results of thermodynamic calculation of the basic cycle are given in the Table 1 and Table 2.

Table1

Working body parameters in main points of cycle

	Pressure, Pa	Temperature, K	Specific volume, m^3/kg
Compressor entrance	101300	288	0.815
Compressor exit	638190	486.6	0.218
Turbine entrance	638190	1363	0.612
Turbine exit	101300	806.64	2.285

Table 2

Thermal parameters in processes

	Process 1-2	Process 2-3	Process 3-4	Process 4-1
Change in internal energy	$1.425\cdot10^5$#	$6.288\cdot10^5$#	$-3.992\cdot10^5$#	$-3.721\cdot10^5$#
Change in enthalpy	$1.995\cdot10^5$#	$8.803\cdot10^5$#	$-5.589\cdot10^5$#	$-5.210\cdot10^5$#
Change in entropy	0#	$1.355\cdot10^5$#	0#	$-1.035\cdot10^5$#
Flow work	$1.995\cdot10^5$#	0#	$5.569\cdot10^5$#	0

Characteristics of gas turbine plant with regenerator

By comparing the temperature of the exhaust gas leaving the turbine with the temperature of the air leaving the compressor we have the possibility to use regeneration in this case. Schematic diagram of cycle with heat regeneration and its T-s diagram are shown in Fig. 3 and Fig. 4. Increase the efficiency of gas turbine plant can be carried out in various ways [5, 7] and in particular due to the thermal perfection of the GTU scheme by introducing regeneration of exhaust gas heat.

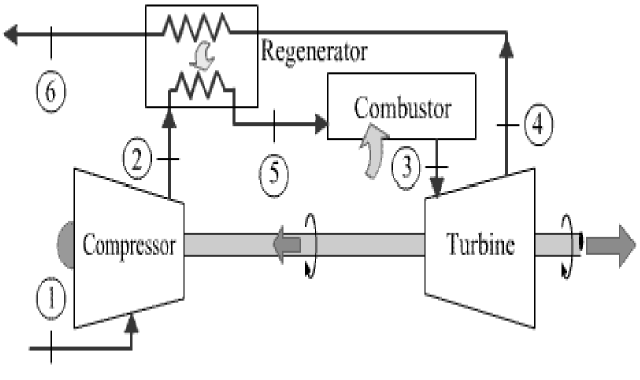

Fig. 3. Schematic scheme of the regenerative Brayton cycle

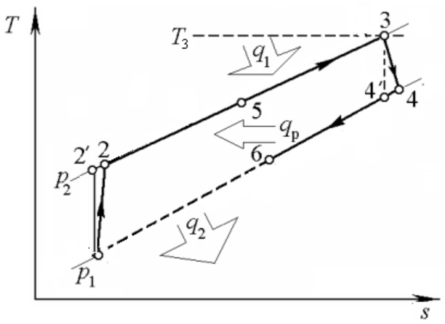

Fig. 4. T-S diagram of the cycle with regeneration

The analysis of the cycle parameters (see Table 1) shows the possibility of regenerative using of exhaust gas heat to reduce fuel consumption. In a simple plant the gases leaving the turbine have a temperature of 533 °C, the temperature of air leaving compressor is 213 °C.

The research of the regenerative cycle was carried out in two directions:

– evaluation of the efficiency of heat regeneration applying under the numerical values of the parameters of the existing plant;

– determination of the efficiency of the gas turbine plant operation at different values of the effectiveness of regeneration.

It should be noted that the difference between T_4 and T_2 reflects only thermodynamically possible relative fuel economy due to regeneration and do not take into account the actual working fluid parameters change during operation. Calculations were carried out for air temperatures of 10; 20 and 30 °C and temperatures of combustion products before the turbine of 1100, 1200 and 1300°C. Variation of T_2 with change of ambient temperature and variation of T_4 for different values of temperature before turbine were analyzed. In Fig. 5 it is shown the change of temperature difference ($T_4 - T_2$) versus the pressure ratio.

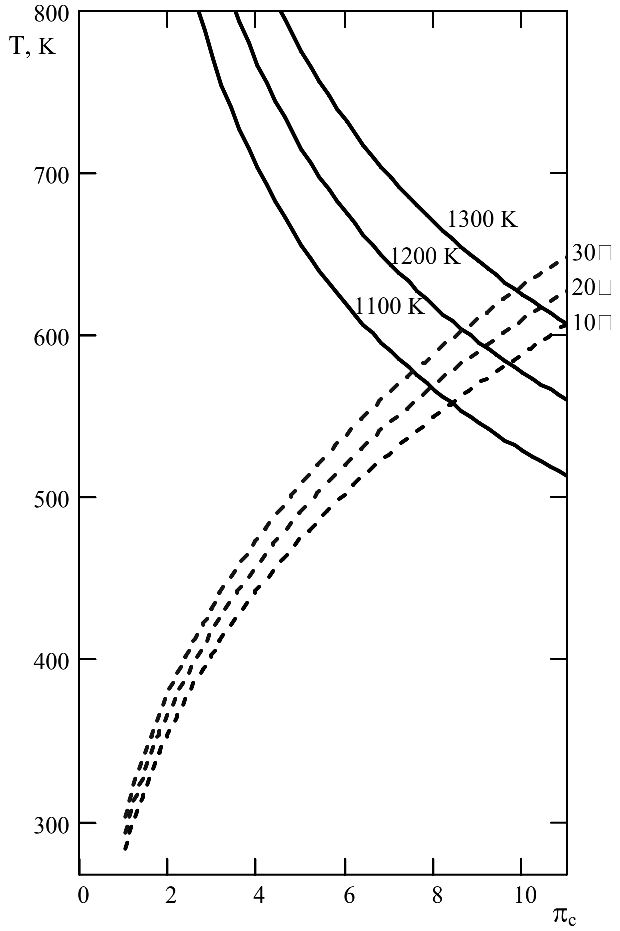

Fig. 5. Change of temperature difference versus the pressure ratio

The influence of the final temperature of the compression process on η_t makes the task of finding the optimal value of effectiveness of regeneration urgent question.

The cycle was modeled using the thermodynamic analysis for the simple gas turbine. In the studies of the effectiveness and parameters of GTU the following initial data were taken: temperature and pressure of the working fluid at the inlet to the compressor T_1 = 288 K and p_1= 0,10131 MPa, pressure ratio — π_c=6.3, T_3 = 1363 K , η_c = 0,86 — compressor isentropic efficiency, η_t = 0,9 — turbine isentropic efficiency, k — the ratio of specific heats for air, k_g — the ratio of specific heats for gas, σ_r = 0,85 — effectiveness of regeneration.

The air which is leaving the compressor is heated by exhaust gases in a counter-flow heat exchanger which is called recuperator and are usually constructed as shell-and-tube type heat exchangers using very small diameter tubes, with the high pressure air flowing inside the tubes and low pressure exhaust gas in multiple passes outside the tubes.

The thermal efficiency increases up to 0.419 due to regeneration since less fuel is used for the same work output. By drawing the dependence of thermal efficiency and pressure ratio we can see the differences in thermal efficiency η_{th} for the Brayton cycle with and without regenerator and as it is evident in Fig. 6 we realize that in lower pressure ratios (approximately from 2 to 6) the differences of thermal efficiency is considerable.

Table 3

Cycle parameters

	Cycle work, J/kg	Heat addition, J/kg	Thermal efficiency
With Regeneration	191893.54	486016.16	0.419
Without Regeneration	191893.54	430881.47	0.32

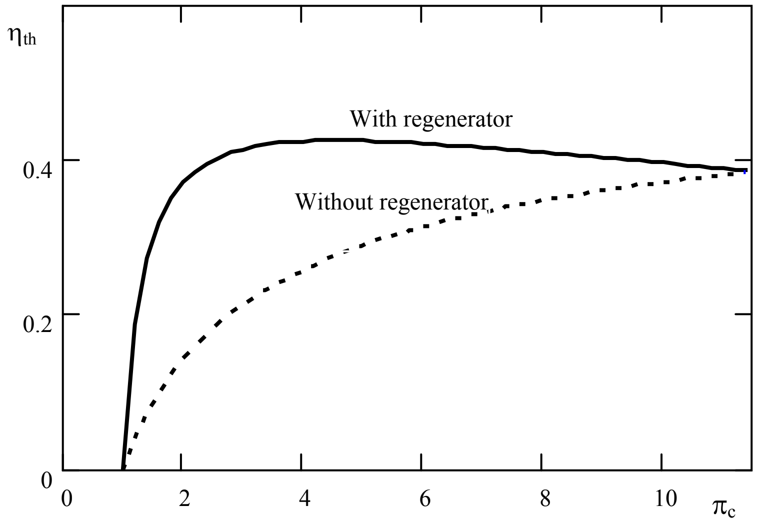

Fig. 6 Thermal Efficiency-Pressure Ratio dependence without regenerator and with regenerator

Analysis of a regenerative Brayton cycle

For given ambient conditions T_1 and p_1, compressor pressure ratio π_c and turbine inlet temperature T_3, the following procedure can be followed to estimate engine performance [1].

$$p_2 = p_1 \pi_c,$$

where π_c — pressure ratio; p_1 and p_2 — the compressor inlet and outlet pressure.

Because of the processes irreversibility, entropy generation takes place in processes 1-2 and 3-4, it takes into account by introducing the efficiency of the compressor η_c and turbine η_t.

The isentropic efficiencies of the compressor and turbine are

$$\eta_c = \frac{T_{2s} - T_1}{T_2 - T_1},$$

$$\eta_t = \frac{T_3 - T_4}{T_3 - T_{4s}}.$$

Inlet compressor temperature T_2 and inlet turbine temperature T_4:

$$T_2 = T_1 \left[1 + \frac{1}{\eta_c} \left(\pi_c^{\frac{k-1}{k}} - 1 \right) \right];$$

$$T_4 = T_3 \left[1 - \eta_t \left(1 - \pi_c^{\frac{k_g - 1}{k_g}} \right) \right].$$

The temperature at the end of regeneration T_5 is defined by the effectiveness of the regenerator σ_r:

$$T_5 = T_2 + \sigma_r (T_4 - T_2).$$

The compressor work:

$$w_c = c_p T_1 \left(\frac{\pi_c^{\frac{k-1}{k}} - 1}{\eta_c} \right),$$

where k — specific heat ratio for air, c_p — isobaric specific heat of air.

The turbine work:

$$w_t = c_{pg} T_3 \eta_t \left(1 - \frac{1}{\pi_c^{\frac{k_g - 1}{k_g}}} \right),$$

where k_g — specific heat ratio for gas (product of burning), c_{pg} – isobaric specific heat of gas.

The net work:

$$w_{net} = w_t - w_c =$$

$$= c_{pg} T_3 \eta_t \left(1 - \frac{1}{\pi_c^{\frac{k_g - 1}{k_g}}} \right) - c_p T_1 \left(\frac{\pi_c^{\frac{k-1}{k}} - 1}{\eta_c} \right).$$

Neglect the heat losses, which are usually small in the regenerator, it can be assumed that the heat given by the gas is equal to the heat received by the air. Heat input and heat output per cycle:

$$q_1 = c_p \left[(T_3 - T_2) - \sigma_r (T_4 - T_2) \right],$$

$$q_2 = c_{pg} (T_6 - T_1).$$

The cycle thermal efficiency

$$\eta_{th} = \frac{w_{net}}{q_1},$$

$$\eta_{th} = \frac{c_{pg} T_3 \eta_t \left(1 - \frac{1}{\pi_c^{\frac{k_g - 1}{k_g}}} \right) - c_p T_1 \left(\frac{\pi_c^{\frac{k-1}{k}} - 1}{\eta_c} \right)}{c_p \left[(T_3 - T_2) - \sigma_r (T_4 - T_2) \right]}$$

$$\eta_{th} = \frac{c_{pg} T_3 \eta_t \left(1 - \frac{1}{\pi_c^{\frac{k_g - 1}{k_g}}} \right) - c_p T_1 \left(\frac{\pi_c^{\frac{k-1}{k}} - 1}{\eta_c} \right)}{c_p \left[\left(T_3 - T_1 \left[1 + \frac{1}{\eta_c} \left(\pi_c^{\frac{k-1}{k}} - 1 \right) \right] \right) - \sigma_r \left(T_4 - T_1 \left[1 + \frac{1}{\eta_c} \left(\pi_c^{\frac{k-1}{k}} - 1 \right) \right] \right) \right]}.$$

Fig. 7 shows the effect of ambient temperature on thermal efficiency of gas turbine cycle with regeneration and without regeneration. Overall, in lower initial temperatures we have higher thermal efficiency in both cases. The character of the thermal efficiency change calculated at different values of the air temperature before the compressor is shown in Fig. 7. The graphs show that the thermal efficiency of the cycle with regeneration is more than that of the cycle without regeneration for all temperatures. It is seen that the cycle thermal efficiency decreases with increase ambient temperature. This is due to the increase in compression work. The decrease of thermal efficiency for cycle with regeneration is more than for cycle without regeneration.

The difference between thermal efficiency of gas turbine cycle with regeneration and thermal efficiency of cycle without regeneration decreases with air temperature increase.

The effect of operation conditions (ambient temperature) and regenerative effectiveness on the thermal efficiency were analyzed. Results are given in Table 4. Fig. 8 illustrates Increase of effectiveness of regeneration results in increase of the thermal efficiency of the gas turbine cycle. The thermal efficiency of gas turbine deteriorates significantly when the air ambient temperature rises.

The relation between **supplied heat** versus compressor pressure ratios for regenerative gas turbine cycle at different values of effectiveness of regeneration depicted in Fig. 9.

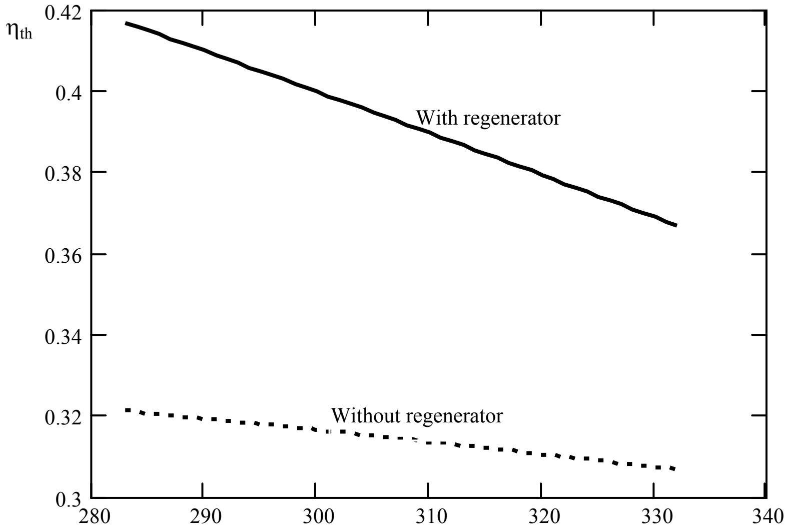

Fig. 7. Ambient temperature on thermal efficiency dependence

Table 4

Regenerative effectiveness on the thermal efficiency

T1	283 K			293 K			303 K		
σ_r	0,60	0,70	0,85	0,60	0,70	0,85	0,60	0,70	0,85
η_{th}	0.38	0.40	0.42	0.3	0.39	0.41	0.37	0.38	0.40

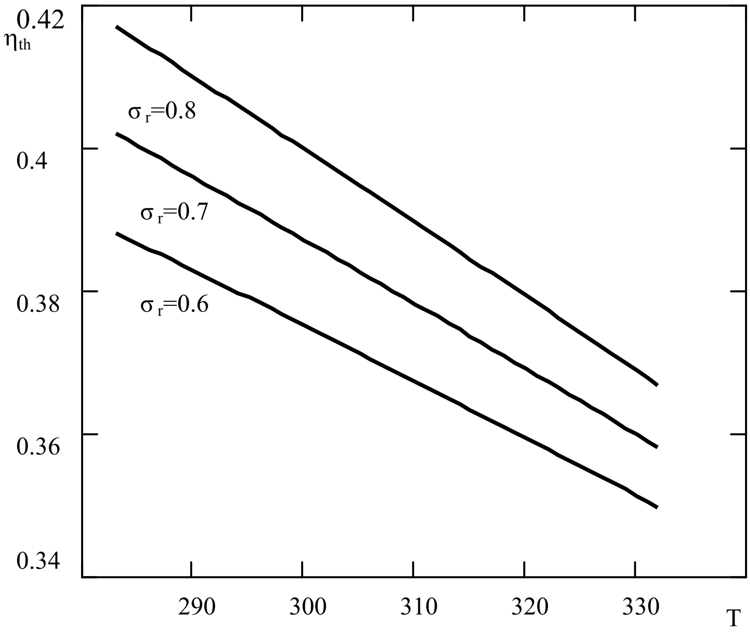

Fig. 8. Variation of thermal efficiency with change of ambient temperature and regenerative effectiveness.

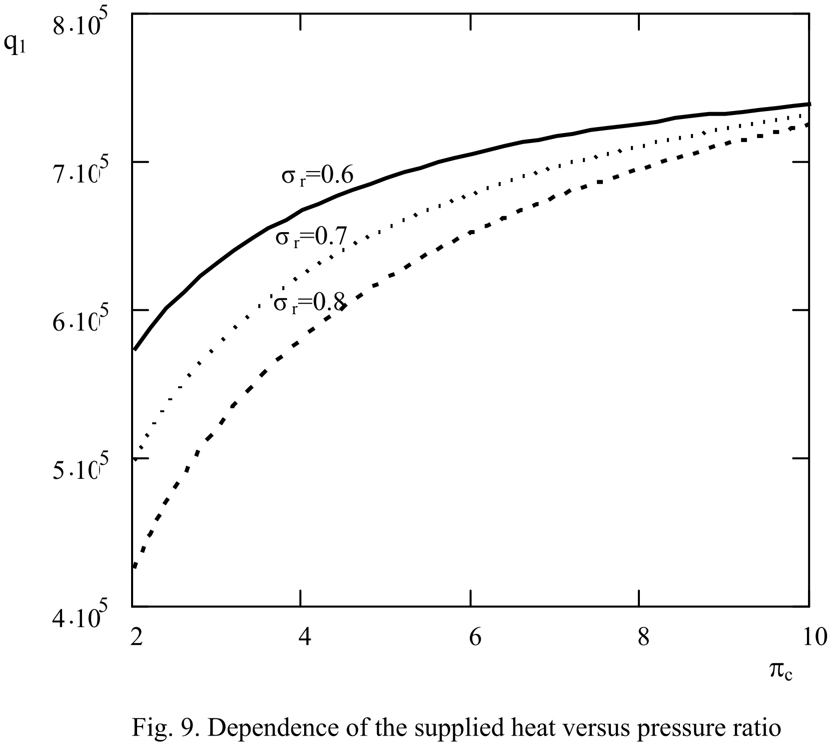

Fig. 9. Dependence of the supplied heat versus pressure ratio

Fig. 10 represents that high effective regenerator is much more suitable in lower pressure ratios due to the big differences in thermal efficiency, in our case (π_c = 6.3) a high effective regenerator is not economically appropriate.

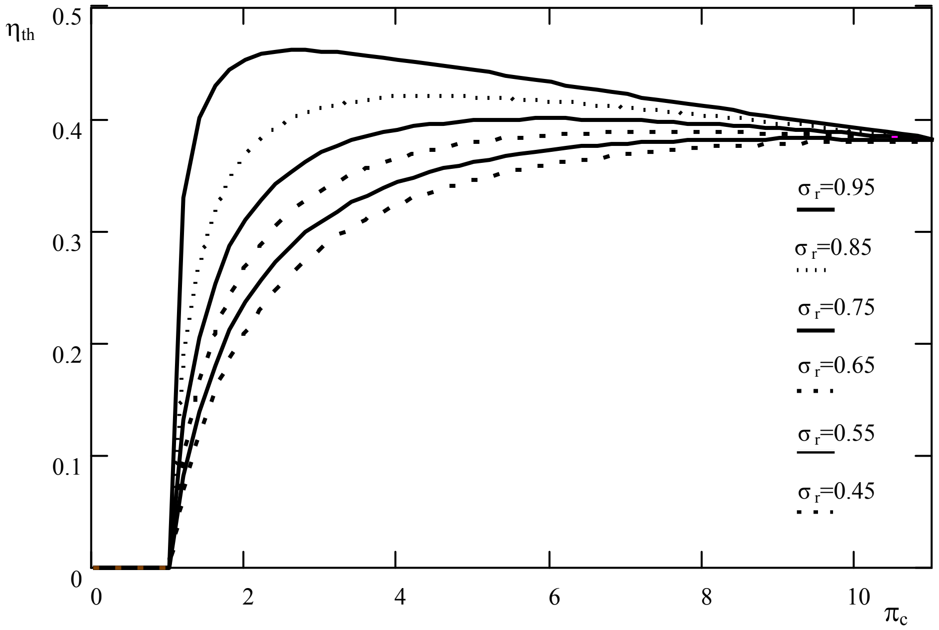

Fig. 10. Dependence of the supplied heat-compression ratio

Analyzing calculation and the obtained results of the study of gas turbine plants on the basis of the converted engine, we can do the following summary:

– The numerical analysis showed that the turboshaft engine PT6T can be used for mobile power-plant, and to achieve high efficiency parameters it is necessary to add heat regeneration into the design of plant;

– Adding regeneration to basic gas turbine cycle results in the increase of thermal efficiency of the cycle;

– The pressure ratio and inlet air temperature exert a major influence on the thermal efficiency of a basic and regenerative cycles;

– The efficiency of the regenerative cycle increases with the increase of compression ratio to 4.5, then efficiency decreased with increased compression ratio, but in simple cycle the thermal efficiency always increases with increased compression ratio;

– The increase of ambient temperature causes to decrease thermal efficiency, but the increase of turbine inlet temperature increases thermal efficiency;

– The value of parameters should be in the range from 4.5 to 6 for the pressure ratio and from 1100 to 1370 K for the temperature of the gas before the turbine.

Conclusion

One possible way of creation of highly efficient gas turbine plant for mobile terrestrial power generator based on aircraft engines, that exhausted flight service lifetime on aircraft, is shown in this article. This way assumes application of heat regeneration using the exhaust gas heat to reduce fuel consumption which is necessary to achieve the required level of gas temperature entering the turbine unit.

The calculations, carried out in the work, show that due to the use of the heat regenerator, the thermal efficiency value of a small-scale aviation engine with relatively low working process parameters can increase from 32 % up to 42 %.

As a result, for widespread turboshaft engine PT6T the rotational speed of the gas generator rotor can be reduced up to 36000 rpm which is far less than the limited value of this engine and also total gas temperature before compressor drive turbine can be maintained at an acceptable level (1100…1200 K), on the other word this engine is proper to be used as gas turbine plant for terrestrial mobile installations with long service lifetime.

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Гвоздецький І. І., Волянська Л. Г., Мохаммад Фархад

ГАЗОТУРБІННА УСТАНОВКА НА БАЗІ КОНВЕРТОВАНОГО АВІАЦІЙНОГО ДВИГУНА З РЕГЕНЕРАЦІЄЮ ТЕПЛА

Конвертація авіаційних двигунів, що вичерпали призначений льотний ресурс , є актуальною проблемою як для України, так і для інших країн, з розвиненою авіатранспортною інфраструктурою. При цьому для конвертованих авіаційних двигунів на одне з перших місць висувається вимога значного підвищення паливної ефективності в порівнянні з тією, яку мають ці двигуни при їх використанні на повітряних суднах, де на першому місці ставиться вимога мінімальної маси двигуна.

Метою роботи є дослідження можливості підвищення паливної ефективності конвертованого авіаційного газотурбінного двигуна при його використанні в якості приводу для мобільних електростанцій.

Як об'єкт дослідження було обрано турбовальний двигун сімейства PT-6T канадської фірми «PRATT &WHITNEY», що відрізняється компактністю конструкції і широко використовується у багатьох країнах світу.

Для реалізації цієї мети в даній роботі спочатку були виконані термодинамічний і газодинамічний розрахунки для базової моделі авіаційного двигуна, а потім ті ж розрахунки були проведені для конвертованого газотурбінного двигуна з різним ступенем регенерації тепла, після чого проведено порівняння термічного ККД в простому циклі і вдосконаленому циклі. Аналіз впливу регенерації тепла на коефіцієнт корисної дії двигуна проведено для кількох різних значень початкової температури в циклі і різних режимів роботи двигуна, що відрізняються ступенями підвищення тиску повітря в циклі. Цими розрахунками підтверджено доцільність застосування регенерації тепла газів, що виходять з двигуна, для підвищення термічного коефіцієнта корисної дії. Крім того, проведено розрахункову оцінку впливу температури повітря на вході в двигун на ефективність регенерації тепла, як одного з можливих способів підвищення термічного коефіцієнта корисної дії двигуна.

Ключові слова: газотурбінний двигун; термодинамічний розрахунок двигуна; регенерація тепла; мобільна електростанція; коефіцієнт корисної дії.

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GAS TURBINE PLANT ON THE BASIS OF THE CONVERTED AVIATION ENGINE WITH HEAT REGENERATION

Conversion of aircraft engines that have exhausted their assigned flight service life time is an actual problem for both Ukraine and other countries with a developed aviation transport infrastructure. At the same time, for converted aircraft engines, the demand for a significant increase in fuel efficiency as compared to that which these engines have when they are used on aircraft, where the minimum engine weight requirement is put in the first place, is put forward.

The aim of this work is to study the possibility of increasing the fuel efficiency of a converted aviation gas turbine engine when it is used as a drive for mobile electrical power plants.

The turboshaft engine of the PT-6 family of the Canadian company Pratt &Whitney, which is distinguished by its compact design and widely used in many countries of the world, was chosen as the object of study.

To achieve this aim, in the present work, thermodynamic and gas-dynamic calculations were first ly performed for the basic model of an aircraft engine, and then the same calculations were performed for the converted gas turbine engine with different degrees of heat regeneration, after which the thermal efficiency was compared in a simple cycle and in improved cycle. Finally, the analysis of the effect of heat regeneration on the efficiency of the engine was carried out for several different values of the initial temperature in the cycle and various engine operating conditions differing in the degrees of air pressure increase in the cycle.

These calculations confirmed the feasibility of using heat regeneration from gases flowing out from the engine to increase the thermal efficiency of cycle. In addition, the calculated assessment of the effect of air temperature at the engine inlet on the efficiency of heat regeneration, as one of the possible ways to increase the thermal efficiency of the engine.

Keywords: Gas turbine engine; Thermodynamic calculation of the engine; Heat regeneration; Mobile power station; Efficiency.

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ГАЗОТУРБИННАЯ УСТАНОВКА НА БАЗЕ КОНВЕРТИРОВАННОГО АВИАЦИОННОГО ДВИГАТЕЛЯ С РЕГЕНЕРАЦИЕЙ ТЕПЛА

Конвертирование авиационных двигателей, исчерпавших назначенный лётный ресурс, является актуальной проблемой как для Украины, так и для других стран, с развитой авиатранспортной инфраструктурой. При этом для конвертированных авиационных двигателей на одно из первых мест выдвигается требование значительного повышения топливной эффективности по сравнению с той, которую имеют эти двигатели при их использовании на воздушных судах, где на первом месте ставится требование минимальной массы двигателя.

Целью работы является исследование возможности повышения топливной эффективности конвертированного авиационного газотурбинного двигателя при его использовании в качестве привода для мобильных электростанций.

В качестве объекта исследования был выбран турбовальный двигатель семейства PT-6 канадской фирмы «Pratt Whitney», отличающийся компактностью конструкции и широко используемый во многих странах мира.

Для реализации этой цели в настоящей работе вначале были выполнены термодинамический и газодинамический расчеты для базовой модели авиационного двигателя, а затем те же расчеты были проведены для конвертированного газотурбинного двигателя с различной степенью регенерации тепла, после чего проведено сравнение термического КПД в простом цикле и усовершенствованном цикле. Наконец, анализ влияния регенерации тепла на коэффициент полезного действия двигателя проведен для нескольких различных значений начальной температуры в цикле и различных режимов работы двигателя, отличающихся степенями повышения давления воздуха в цикле. Этими расчетами подтверждена целесообразность применения регенерации тепла выходящих из двигателя газов для повышения термического коэффициента полезного действия. Кроме того, проведена расчётная оценка влияния температуры воздуха на входе в двигатель на эффективность регенерации тепла, как одного из возможных способов повышения термического коэффициента полезного действия двигателя.

Ключевые слова: газотурбинный двигатель; термодинамический расчёт двигателя; регенерация тепла; мобильная электростанция; коэффициент полезного действия.

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