Utilization of Low-Potential Energy Through to the Use in Aircraft Fuel System

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Abstract: The article discusses the possibility of improving the main characteristics (efficiency, specific thrust) of a gas turbine engine by using liquefied natural gas (LNG) as fuel. This possibility is considered on the example of using as fuel instead of aviation kerosene on PS-90A and NK-93 engines. The parameters of the engine were determined at various stages in the cruise flight mode when operating on kerosene and LNG. The parameters evaluating the fuel consumption of the engine are calculated and compared for both fuels. The performance characteristics for kerosene and LNG were evaluated in the system of the Tu-330 subsonic transport aircraft. Energy losses during storage of cryogenic fuel on board the aircraft are estimated.

Keywords: liquefied natural gas, gas turbine engine, power plant.

1. INTRODUCTION

The use of LNG as an alternative fuel for aviation is based on the possibilities of its production in various regions of the country with virtually no serious damage to the consumption of natural gas by industry and the public. LNG is more environmentally friendly and safe to use, and also makes it possible to provide such technical characteristics of aircraft that are not achievable with traditional petroleum fuel [1]. Cryogenic fuels have higher energy performance, have high environmental quality, and their use will allow you to move on to new stages in the development of the aircraft industry.

Currently, modifications are being made to the Tu-330 cargo aircraft using LNG as fuel: the Tu-330-LNG military transport aircraft and the Tu-330T-LNG tanker aircraft, in which PS-90A dual-circuit turbojet engines can be used as a power plant NK-93.

Since a sufficient amount of energy is spent during liquefaction. In the process of cooling down the circulation-pressurization system or supply of cryogenic fuel to the combustion chamber of the engine, part of the previously spent energy can be returned. Energy return can be carried out in several ways, one of which is the use of power plants operating according to Rankine or Brighton cycles [2, 3]. The electricity generated during the operation of these auxiliary cycles can be used for the operation of onboard systems, and can also be accumulated in special storage devices for further operation.

This article discusses the possibility of using the installation of generating additional energy as part of the fuel complex of the Tu-330. It is proposed to use a heat engine operating on the Rankine cycle.
or on the Brayton cycle as such a plant. The installation can operate on various cryogenic substances: nitrogen, krypton, argon, air, ethane, R12 freon, R22 freon, R134a freon and others [4, 5].

The scheme of the fuel system, with the installation for generating additional energy included in it, is presented in Figures 1 and 2.

![Fig. 1. The scheme of the fuel system with the installation of generating additional energy according to the Rankine cycle](image1)

![Fig. 2. The scheme of the fuel system with the installation of generating additional energy according to the Brayton cycle.](image2)

**Nomenclature**

| BP   | booster pump;                              | HEEv | heat exchanger-evaporator; |
|------|-------------------------------------------|------|---------------------------|
| DisV | distribution valve;                       | K    | compressor;               |
| DrV  | drain valve;                               | N    | nozzles.                  |
| FG   | fire hydrant;                              | SOV  | shutoff valve;            |
| FGD  | fuel gas dispenser;                        | T    | turbine;                  |
| GFS  | gas flow sensor;                           | Th   | throttle;                 |
| HEC  | turbopump unit;                            | P    | Pump                      |
| HEE  | heat exchanger-condenser;                  |      |                           |

The installation is as follows. In the process of supplying cryogenic fuel to the combustion chamber of the engine or in the cooling process, when only the circuit of the circulation-pressurization system
is working, the LNG passes through the heat exchanger-condenser of the additional energy generation unit. As a result, condensation of the working fluid used in the installation cycle occurs. Then there is an increase in the pressure of the working fluid (compressor or condensate pump). After increasing the pressure, the working fluid enters the heat exchanger-evaporator, and then into the turbine, where the energy of the working fluid is converted into mechanical work on the turbine shaft. The conversion of turbine energy into electricity is carried out by an electric generator.

2. CALCULATION OF THERMODYNAMIC CHARACTERISTICS
Based on well-known calculation methods [6,7], the prospects of such a solution were evaluated for various cryogenic substances suitable for operation at a temperature of 100-120 K in a liquid phase. The heat of the environment \( (T_H = 288 \text{ K}) \) was used as the heat supplied to the working fluid.

For the calculation, the following initial data were used:
- at cruising flight mode, fuel consumption in the engine PS-90A \( G_{\text{LNG}} = 0.548 \text{ kg/s} \);
- at cruising flight mode, fuel consumption in the engine NK-93 \( G_{\text{LNG}} = 0.345 \text{ kg/s} \);
- fuel temperature at the inlet to the fuel assembly \( T_{\text{in,LNG}} = 110 \text{ K} \).
- the temperature of the fuel at the outlet of the fuel system of the \( T_{\text{out,LNG}} = 115 \text{ K} \).

In the Brayton cycle, the working fluid warms up to ambient temperature \( T_3 = 288 \text{ K} \).

The general expression for the thermal efficiency of the cycle is:

\[
\eta_t = \frac{q_1 - q_2}{q_1} = 1 - \frac{q_2}{q_1}
\]

(1)

where \( l_c \) – specific work of the cycle, \( q_1 \) - amount of heat supplied to the working substance, \( q_2 \) - amount of heat removed from the working substance.

The power generated by the turbine can be defined as:

\[
N = l_c \cdot G
\]

(2)

where \( G \) – flow rate of the working substance.

An estimate of the amount of additional electrical energy received is given in tables 1 and 2.

| Cryoproduct  | \( q_1, \text{kJ/kg} \) | \( q_2, \text{kJ/kg} \) | \( l_c, \text{kJ/kg} \) | \( G, \text{kg/s} \) | \( N, \text{kW} \) | \( \eta_t, \% \) | \( G, \text{kg/s} \) | \( N, \text{kW} \) | \( \eta_t, \% \) |
|--------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Nitrogen     | 90              | 89              | 1               | 2.6             | 2.6             | 1.1             | 1.6             | 1.6             | 1.1             |
| Nitrogen     | 92              | 89              | 3               | 2.6             | 7.8             | 3.3             | 1.6             | 4.9             | 3.3             |
| Krypton      | 113             | 109             | 3.5             | 2.0             | 7               | 3.1             | 1.3             | 4.4             | 3.1             |
| Krypton      | 119             | 109             | 10              | 2.0             | 20              | 8.4             | 1.3             | 12.6            | 8.4             |
| Krypton      | 123             | 109             | 14              | 2.0             | 28              | 11.4            | 1.3             | 17.6            | 11.4            |
| Argon        | 130             | 123             | 7               | 1.8             | 12.4            | 5.4             | 1.1             | 7.8             | 5.4             |
| Argon        | 133             | 123             | 10              | 1.8             | 17.7            | 7.5             | 1.1             | 11.2            | 7.5             |
| Argon        | 140             | 123             | 17              | 1.8             | 30.1            | 12.1            | 1.1             | 19              | 12.1            |
| Air          | 123             | 122             | 1               | 1.8             | 1.8             | 0.8             | 1.1             | 1.1             | 0.8             |
| Air          | 125             | 122             | 3               | 1.8             | 5.4             | 2.4             | 1.1             | 3.4             | 2.4             |
| Ethane       | 610             | 568             | 42              | 0.4             | 16.1            | 6.9             | 0.2             | 10.2            | 6.9             |
| Ethane       | 618             | 568             | 50              | 0.4             | 19.2            | 8.1             | 0.2             | 12.1            | 11.3            |
| Ethane       | 640             | 568             | 72              | 0.4             | 27.6            | 11.3            | 0.2             | 17.4            | 11.3            |

TABLE I. ESTIMATION OF THE AMOUNT OF ADDITIONAL ELECTRIC ENERGY RECEIVED IN A UNIT OPERATING ACCORDING TO THE RANKINE CYCLE

TABLE II. ESTIMATION OF THE AMOUNT OF ADDITIONAL ELECTRIC ENERGY
RECEIVED IN A UNIT OPERATING ACCORDING TO THE BRAYTON CYCLE

| Cryoproduct | \( q_1, \text{kJ/kg} \) | \( q_2, \text{kJ/kg} \) | \( l, \text{kJ/kg} \) | \( G, \text{kg/s} \) | \( N, \text{kW} \) | \( \eta, \% \) | \( G, \text{kg/s} \) | \( N, \text{kW} \) | \( \eta, \% \) |
|-------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Nitrogen    | 115            | 78             | 37             | 0.09           | 3.2            | 32.3           | 0.06           | 2.1            | 32.3           |
| Krypton     | 20             | 12             | 8              | 0.6            | 4.2            | 41.2           | 0.4            | 2.6            | 41.2           |
| Argon       | 40             | 24             | 17             | 0.3            | 5.4            | 41.3           | 0.2            | 3.4            | 41.3           |
| Air         | 110            | 74             | 36             | 0.09           | 3.3            | 32.9           | 0.06           | 2.1            | 32.9           |
| Ethane      | 96             | 72             | 24             | 0.08           | 1.8            | 24.7           | 0.05           | 1.2            | 24.7           |
| Freon R12   | 18             | 15             | 3              | 0.2            | 0.6            | 16.4           | 0.1            | 0.4            | 16.4           |
| Freon R22   | 14             | 10             | 3              | 0.4            | 1.4            | 26.7           | 0.2            | 0.9            | 26.7           |
| Freon R134a | 37             | 35             | 2              | 0.2            | 0.6            | 6.5            | 0.2            | 0.3            | 6.5            |
| Nitrogen    | 93             | 56             | 37             | 0.1            | 4.7            | 39.5           | 0.08           | 3              | 39.5           |
| Krypton     | 11             | 6              | 5              | 0.9            | 4.9            | 47.6           | 0.6            | 3              | 47.6           |
| Argon       | 21             | 11             | 10             | 0.7            | 6.4            | 47.0           | 0.4            | 4              | 47.0           |
| Air         | 53             | 88             | 35             | 0.3            | 5.3            | 39.9           | 0.1            | 3              | 39.9           |
| Ethane      | 70             | 48             | 23             | 0.05           | 1.2            | 32.0           | 0.04           | 0.7            | 32.0           |
| Freon R12   | 11             | 9              | 2              | 0.4            | 0.9            | 21.3           | 0.3            | 0.6            | 21.3           |
| Freon R22   | 3              | 1              | 2              | 0.6            | 1.4            | 69.7           | 0.4            | 0.9            | 69.7           |
| Freon R134a | 30             | 29             | 2              | 0.2            | 0.2            | 5.1            | 0.1            | 0.2            | 5.1            |

3. PROCESSING RESULTS
Based on the results obtained, the dependences of the amount of heat, cycle operation, plant power, thermal efficiency, substance flow rate on the degree of expansion of the gas in the turbine are obtained (Figures 3-7).

Fig. 3. Color designations of the investigated substances.
Fig. 4. The dependence of the cycle on the degree of expansion of the gas in the turbine of the unit. left) according to the Rankine cycle; right) according to the Brayton cycle.

According to the results of calculations in Figure 4, we see that in the case of using a power plant operating according to the Rankine cycle, the dependence of the cycle mode on the expansion ratio is direct in the case of operating according to the Rankine cycle. The Brayton cycle is reversed, and it should be noted that, under equal conditions, the ethane work values in the Rankine cycle are higher than in the Brayton cycle and increase with increasing expansion (compression in the cycle) in the turbine. However, the work of substances such as argon and krypton in the case of the Brayton cycle is higher than in the Rankine cycle. But as the degree of expansion increases, the value of work decreases. This is due to the fact that with a constant increase in the compression ratio in the compressor, the work losses multiply increase.

Fig. 5. Dependence of plant power on the magnitude of the degree of expansion of gas in a turbine of a plant with a Rankine cycle. left) when operating as part of the fuel circuit PS-90A (LNG); right) when operating as part of the NK-93 (LNG) fuel circuit.

In Figure 5, you can see that in the case of using the power plant of the Rankine cycle for both engines, the power lines for each substance from the expansion ratio behave the same. For example, in both cases, the dependence of power on the expansion ratio is almost linear. However, the numerical values of the generated power in the case of the installation with the PS-90A engine are much higher than in the case of the application with the NK-93 engine.
It can also be said from the graphs that in the case of high values of the expansion ratio, it is more efficient to use argon and ethane.

**Fig. 6.** The dependence of thermal efficiency on the magnitude of the degree of expansion of the gas in the turbine of the installation. left) power plants with a Rankine cycle; right) power plants with a Brayton cycle.

Considering Figure 6, we can conclude that the behavior of substances such as argon and krypton in the Rankine cycle differs from the Brayton cycle. For example, in the Rankine cycle, with an increase in the degree of expansion, the value of the thermal efficiency increases.

The power values in the case of using the working fluid of ethane in both cases change relatively the same.

It is also worth noting as the main difference between the two presented power plants that in the case of the Rankine cycle, the thermal efficiency values are significantly lower than in the application of the Brayton cycle.

**Fig. 7.** Dependence of plant power on the magnitude of the degree of expansion of gas in a turbine of a plant with a Brayton cycle. left) when operating as part of the fuel circuit PS-90A (LNG); right) when operating as part of the NK-93 (LNG) fuel circuit.

Figure 7 shows that by analogy with Figure 5, the behavior of the graphs is relatively the same. And also, similar conclusions can be drawn about the values of the capabilities in the case of using each of the engines.

**4. CONCLUSIONS**

Thus, for the installation of generating additional energy as part of the fuel complex of the Tu-330 aircraft, the most effective is the use of power plants operating according to the Rankine cycle using argon as a working substance and a turbine with a degree of expansion of \( \pi_T=5.56 \). With these
parameters, the power generated by the installation is the largest and amounts to N=30.141 kW and N=18.972 kW for PS-90A and NK-93 engines, respectively.

This article describes and describes the operation of the installation for generating additional energy included in the cryogenic fuel complex. The parameters of the installation based on the Rankine and Brayton cycle were calculated for various cryogenic products: nitrogen, krypton, argon, air, and ethane, R12 freon, R22 freon and R134a freon. Plots are plotted for the amount of heat input, the cycle operation, cryoproduct consumption, thermal efficiency, and the power generated by the installation, depending on the degree of expansion of the turbine. Diagrams of the Rankine and Brighton cycle are constructed for various degrees of expansion of the turbine. Analysis of the calculation results shows that it is most efficient to use power plants of the auxiliary circuit operating according to the Rankine cycle, it is advisable to use argon as the working fluid, and the degree of expansion of the turbine is πT=5.56. Moreover, the power generated by the installation is the largest and is equal to N=30.141 kW and N=18.972 kW, when operating as part of the fuel system with PS-90A and NK-93 engines, respectively.

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REFERENCES
[1] I. Barmin. Liquefied natural gas yesterday, today, tomorrow [Text] / I. V. Barmin, I. D. Kunis; under the editorship of A.M. Arkharov.- M.: MSTU. N.E. Bauman, 2009. -- 256 p.
[2] Song Y, Wang J, Dai Y, Zhou E. Thermodynamic analysis of a transcritical CO2 power cycle driven by solar energy with liquified natural gas as its heat sink. Appl Energy2012; 92: Pp. 194–203.
[3] Zaika A.V., Tereshchenko O.V., Uglanov D.A. et al. Determination of the effectiveness of steam turbine plants utilizing low-grade heat of a cryogenic product // XIV KOROLOVSKIY READINGS. - 2017. - T. 1. - Pp. 381-382
[4] Andreev V.A., Borisov V.D., Klimov V.T., Malyshev V.V., Orlov V.N. Caution: gases. Cryogenic fuel for aviation. - M.: Moscow Worker, 2001. - 224 p.
[5] Vargaftik, N.B. Handbook of thermophysical properties of gases and liquids [Text] / NB. Wargaftik. - Moscow: Nauka, 1972 - 720p.
[6] Grigoryev V.A., Zhdanovsky A.V., Kuznichiev V.S., Osipov I.V., Ponomarev B.A. The choice of parameters and thermogasdynamic calculations of aircraft gas turbine engines: a training manual. - Samara: Publishing house of the Samara State Aerospace University, 2009. - 202 p.
[7] Grigoriev V.A. Design thermogasdynamic calculation of civil aviation aircraft GTE: a training manual. - Samara: Publishing House of the Samara State Aerospace University, 2001. - 170 p.