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ANALYSIS OF THE EFFICIENCY OF APPLICATION HEAT-USED COOLING SYSTEMS OF GAS TURBINE DRIVE AIR CYCLE

Introduction

Engine performance directly depends on the temperature of supplied air. It has been established that the efficiency decreases with increasing temperature of air entering the compressor. During operation, the air temperature can vary over a wide range not only during the year, but also during the day. As the ambient temperature increases, the density of the air taken into the compressor decreases and this causes an decrease in the air mass flow rate of air through the compressor and thereby the power of the gas turbine. Therefore, the operation of gas turbine plant is carried out for the most part in non-design modes. Due to global warming (Fig. 1) [1], it is necessary to modernize existing gas turbine plants.

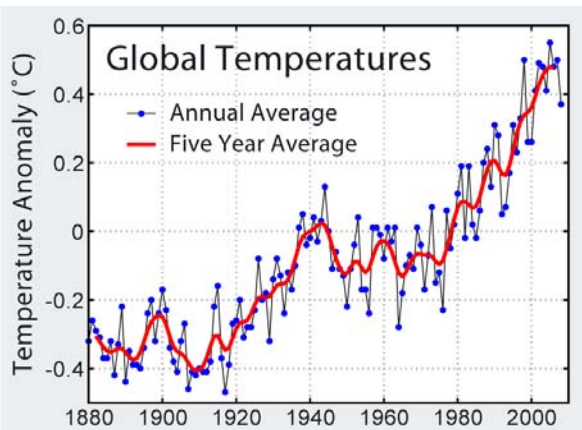

Fig. 1. Global temperature index change

The operation of a gas turbine drive at ambient air temperature above 15 °C is accompanied by a deviation of its operating parameters from the nominal.

This is due to changes in the thermal parameters of the atmosphere air (pressure, temperature, relative humidity) at the compressor inlet.

According to [2], an increase in ambient air temperature by 10 ºC causes a decrease in power of industrial gas turbine drives type FR-7 by 5...9 %.

Power of converted aircraft gas turbine drives with an increase in temperature from 15 to 35 ºC decreases by 20 % compared to its values at temperature $t = 15$ ºC.

The degree of ambient temperature influence on the power of a gas turbine engine depends on the type of an engine.

The author of [3] points that the decrease in power with increasing ambient air temperature, depending on the type of GTD, 0.5...1.2 % of nominal per degree of temperature increase, what negatively affects the energy and economic indicators of GTD.

In this regard, it seems appropriate during periods of peak temperatures, cool the air before entering the compressor, which would allow ensure the normal performance of the compressor and exclude a decrease in the power of the plant.

For this purpose, the calculation of air cooling was performed with a decrease in air temperature before the compressor by 10 °C, the effect of cooling was analyzed in the temperature range of 10–45 °C.

In this article, it is studied influence of climatic conditions on the efficiency of the gas turbine drive AI-336-1/2-10 (Fig. 2).

Fig. 2. Gas turbine drive AI-336-1/2-10

One of the important conditions for the implementation of a cooling system for many gas turbines, including the AI-336 family, is the absence of any structural changes in their flow path. Therefore, in this work, we investigate the pre-cooling system of cyclic air.

Crux of problem

The aim of the work is to evaluate the efficiency of air cooling at the gas turbine inlet.

Analysis of recent research and publications

To maintain the rated power of a gas turbine at high air temperature, it is necessary to cool the air before the compressor. Different methods to cool supplied air are exist.

The influence of the ambient air temperature on the maximum power and energy efficiency of the gas turbine plant is considered in [4]. The authors carried out verification calculations for gas turbines with known design characteristics at different ambient temperatures. In works [5; 6], the issues of outdoor air cooling at the inlet to the gas turbine compressor were considered. Cooling systems based on surface coolers with cold water [7; 8; 9], water injection into air, absorption and vapor compression refrigeration machines were studied. Obtained data indicate an increase in power of the gas turbine by 10.6 % with a decrease in the outside air temperature by 20 °C. Article [10] compares evaporative cooling, vapor compression refrigeration and absorption refrigeration. In these types of cooling electricity is used, so the article provides an estimate of the electricity consumption for these three types of cooling. The author describes the effect of relative humidity on the efficiency of evaporative cooling. An increase in the productivity of gas turbine power plants depending on the air temperature at the compressor inlet is presented in [11; 12].

The work [13] investigated the technical and economic feasibility of air cooling at the inlet to the gas turbine compressor.

Three cooling options were investigated: chillers, air cooling by injection of water droplets, and the use of evaporative cooling systems. The results showed that chillers provide the best cooling. In [14], the authors investigated a gas turbine power plant, showing that its power can be increased by 11.3 % cooling the air at the compressor inlet.

The analysis of publications shows that the currently existing options for air cooling at the inlet to the gas turbine compressor do not fully solve the problems of operation. Each method has its own advantages and disadvantages. A large number of methods proposed for cooling the air at the engine inlet makes the task of forming criteria and approaches for their selection. When choosing a cooling method, it is necessary to take into account the cost of equipment, climatic and technical operating conditions. For the best air cooling and, as a consequence, maximizing the capacity of the gas turbine unit, it is preferable to use refrigeration units. Cooling of air with the help of refrigeration machines that use the heat of exhaust gases seems to be very expedient. GTD of any circuit design has a large waste energy potential, what can be utilized for the production of cold using heat-using refrigerating machines: absorption or steam jet. To cool the air at the inlet of the compressor of the gas turbine drive AI-336-1/2-10, we analyzed the possibility of using a heat-using ejector refrigeration machine. To cool the air at the gas turbine inlet, the exhaust gases of the gas turbine are used to ensure the operation of the steam generator of the steam jet refrigeration machine.

In this paper, the use of a steam ejector refrigerator is considered.

Gas Turbine Drive AI-336-2-10

Industrial gas turbine drive designed to drive gas pumping units and other industrial installations with a capacity of 10 MW. The AI-336-2-10 industrial drive is based on the modules of the highly efficient and reliable aircraft engines D-136, D-36, D-436T1 and the D-336 ground drive. Good performance indicators of AI-336-2-10 are obtained due to the high parameters of the cycle and the efficiency of its units, as well as due to the environmental friendliness, reliability and long service life of the constituent modules.

Basic data of the D-336-2-10 gas turbine engine (Fig. 3):

– drive type — turboshaft, three-shaft Rated power — 10000 kW;

– fuel consumption — 2116 kg /h (Fuel: gaseous (natural or oil gas));

– working fluid consumption through the engine — 41.7 kg /s;

– effective efficiency — 34 %;
– low pressure rotors speed — 10,095 rpm;
– rotation frequency of high pressure rotors - 13,900 1/min;

The rotational speed of the power turbine rotors is 6500 rpm.

These characteristics are used by power plant developers when choosing a gas turbine drive.

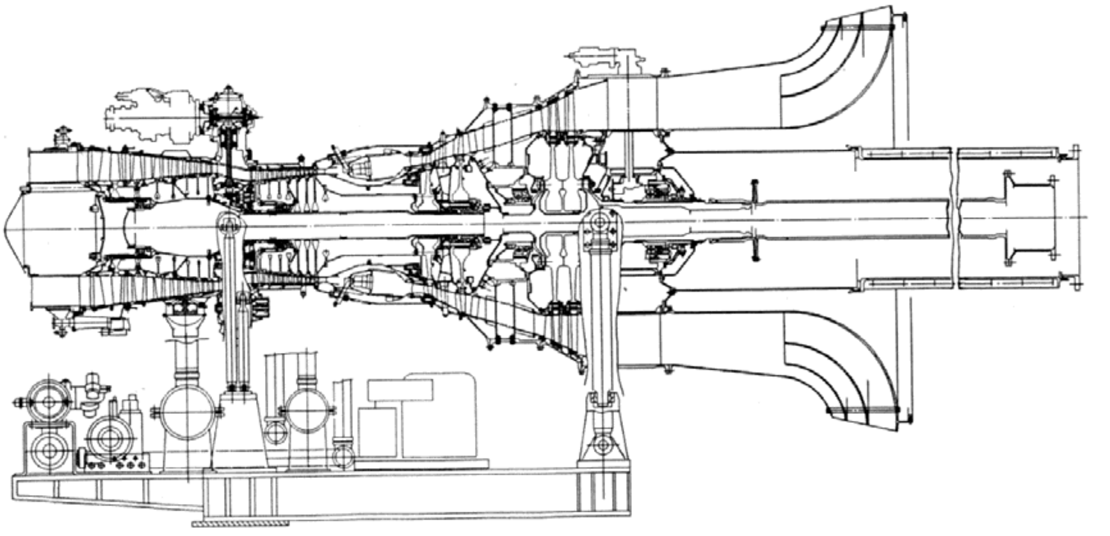

Fig. 3. Schematic layout of the equipment of AI-336-2-10

However, these characteristics represent a generalization of the results of GTU testing under specific conditions and do not make it possible to assess the parameters of the GTU working process in the entire possible range of operating modes, the magnitude and nature of their change under the influence of factors arising during operation.

Steam ejector refrigerator model

The advantages of the steam ejection cooling system are its simplicity, small volume, and the absence of movable wear parts, reliable operation and the possibility of using water vapor as a refrigerant. In ejector chillers, there are no devices operating under excessive pressure, and toxic, explosive and fire hazardous working substances are not used, which increases the safety of the machine and make them ecologically clean.

At the same time, the use of steam ejector refrigerator makes it possible to recycle heat of exhaust gas, which leads to improve the economic performance of the plant.

As it is shown in Fig. 4 this system includes several components: a vapor generator (boiler), an ejector, a condenser, an evaporator, a liquid pump and an expansion valve (throttling device).

The refrigerant vapor (steam) with high parameters is generated by the heat of exhaust gases of a gas turbine drive. The steam leaves the generator at state 1, motive enters the ejector and expands through a nozzle inside the ejector.

High speed flow at low pressure is at the nozzle exit and it causes the suction of the steam with lower pressure (aspirated).

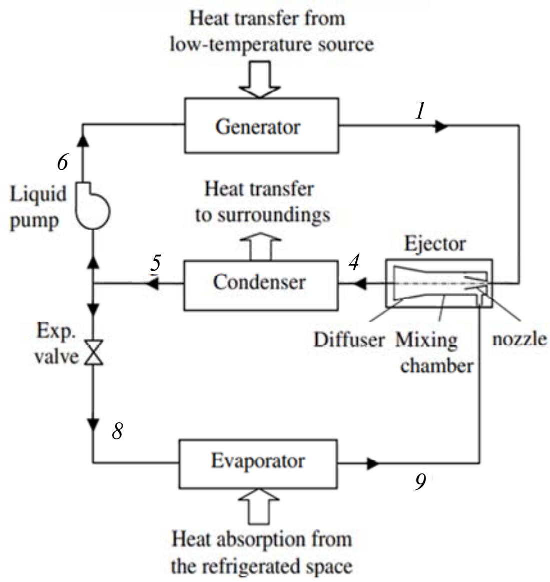

Fig. 4. A schematic diagram of an ejector refrigeration cycle

Then two streams mix with each other in the mixing chamber of the ejector. This mixed steam at state 4 comes to the condenser.

The condensate at point *5* is divided into two parts: one part enters the evaporator through an expansion valve (point *8*) and the other part returns to the steam generator through a liquid pump *6*. The water entering the steam generator is vaporised. The low temperature steam in the evaporator produces a cooling effect by absorbing heat from the ambient air before its entering the compressor.

The changes occurring in the steam flow of the ejector are shown in the *T-s* diagram of Fig. 5.

The operating of an ejector refrigeration system is specified by the evaporator pressure p_e; generator pressure p_g; the condenser pressure p_c; the expansion ratio p_g/p_e and compression ratio p_c/p_e. The thermodynamic properties at states for steam are calculated from the saturation property.

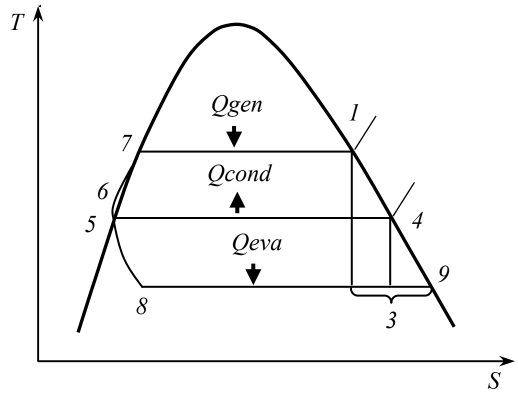

Fig. 5. *T-s* diagram of a refrigeration cycle

The performance of an ejector is measured by its entrainment ratio *w*, the ratio of secondary stream mass flow rate m_e to the primary fluid mass flow rate m_g:

$$w = \frac{m_e}{m_g},$$

where m_e — the mass flow rate of the evaporator; m_g — the mass flow rate of the boiler.

The arm of this study is to analyze condenser pressure given the temperatures of the boiler and evaporator.

The rate of heat transfer to the evaporator is:

$$Q_e = m_9(h_9 - h_8).$$

The rate of heat transfer from the condenser is:

$$Q_c = m_4\left(h_4 - h_5\right).$$

The heat transfer rate of the exhaust gas boiler (steam generator) is:

$$Q_{exh} = Q_e = m_9\left(h_9 - h_8\right).$$

The mass flow rate of the steam is:

$$m_g = Q_g/\left(h_1 - h_5\right).$$

In order to determine the magnitude of the decrease in the air temperature at the compressor inlet and, accordingly, the increase in the engine efficiency, calculations were performed. It was taken into account that the cooling capacity of an ejector refrigeration machine, like any refrigeration machine, depends on the amount of heat removed from the exhaust gases.

Cooling the air at the compressor inlet leads to a decrease in the temperature of the exhaust gases and, accordingly, a reduction in the enthalpy change in the ejector refrigeration machine, and then when calculating the decrease in air temperature, it is necessary to take into account the mutual dependence of temperatures. In this work, the calculation was carried out for a constant temperature of the exhaust gases.

It was studied dependence of given the temperatures of the boiler and evaporator on the condenser pressure, back pressure. Effect of condenser pressure and evaporator temperature on an entrainment ratio is given in Fig. 6.

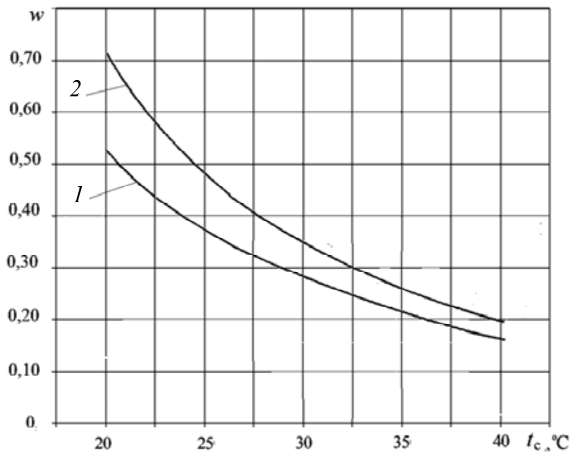

Fig. 6. Dependence of an entrainment ratio with temperature increasing

Line *1* represents change of an entrainment ratio depending on the condenser temperature T_c for evaporator temperature T_e = 10 °C and the saturation temperature in generator T_g = 120 °C.

Line *2* represents change of an entrainment ratio depending on the condenser temperature T_c for evaporator temperature T_e = 5 °C and the saturation temperature in generator T_g = 120 °C.

Changing the parameters of high and low pressures of the steam-ejector refrigerator allows to adjust the degree of cooling for different loads.

For investigation, the following parameters were taken: the vaporator pressure p_e = 871,8 Pa (the corresponding saturation temperature T_e = 5 °C, generator pressure p_g = 198540 Pa, the corresponding saturation temperature T_g = 120 °C.

The method of analysis

The analysis of air cooling at the inlet to the compressor of the AI-336-1 / 2-10 GTU due to the use of a heat-using ejector refrigeration machine was carried out for the structural diagram of the complex shown in Fig. 7.

Calculation was done according the method discribed in [15].

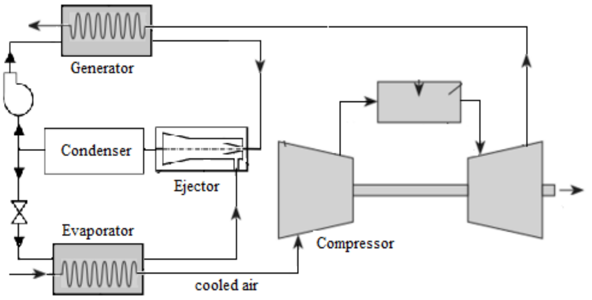

Fig. 7. Schematic diagram of air cooling

Compressor

The air temperature after compression in the compressor is T_2

$$T_2 = T_1\left\{1+\frac{1}{\eta_c}\left[\left(\frac{p_2}{p_1}\right)^{\frac{k_a-1}{k_a}}-1\right]\right\},$$

while the pressure and temperature at the compressor inlet are equal

$$p_1 = p_н;\ T_1 = T_н;$$

where $T_н$, $p_н$ are the temperature and pressure of the environment, ($T_н$ = 298,15K; $p_н$ = 1,013 bar), k_a is the adiabatic index of the air compression process in the compressor.

Compressor drive power is defined as

$$W_c = m_a c_{pa}(T_2 - T_1),$$

where m_a is the mass air flow in the compressor; c_{pa} — specific heat capacity of air, (c_{pa} = 1.004 kJ/kg K).

The combustion chamber

The flue gas flow rate is calculated as

$$m_g = m_a + m_f,$$

where m_f is the mass fuel consumption.

The heat balance equation of the combustion chamber is

$$m_a h_2 + m_f Q_f = m_g h_3 + Q_{cc},$$

where h is the enthalpy of the working substance.

Heat capacity is defined as

$$Q_{cc} = m_f Q_L(1-\eta_{cc})),$$

and the pressure at the outlet of the combustion chamber is

$$p_4 = p_3(1-\Delta p_{cc}),$$

where Q_L is the net calorific value of natural gas; η_{cc} — combustion chamber efficiency; Δp_{cc} — pressure loss in the combustion chamber.

Turbine

The temperature of the working substance at the outlet of the turbine is

$$T_4 = T_3\left\{1-\eta_t\left[1-\left(\frac{p_3}{p_4}\right)^{\frac{k_g-1}{k_g}}\right]\right\},$$

where k_g is the adiabatic index of the expansion process in the turbine.

The turbine power is determined by the equation:

$$W_t = m_g c_{pg}(T_3 - T_4)$$

and the useful output power of the turbine is

$$W_{net} = W_t - W_c.$$

Conclusion

For analyzing of the efficiency of application of heat-using cooling systems calculations of power and efficiency of GTE were carried out.

Calculation was done for gas turbine plant operating at normal conditions, at elevated air temperature with and without air cooling at the inlet, graphs characterizing the change in the characteristics of the gas turbine unit depending on the atmospheric temperature were plotted.

Fig. 7 shows the amplitude of the monthly maximum temperature variation during the year in the climatic region of Kherson.

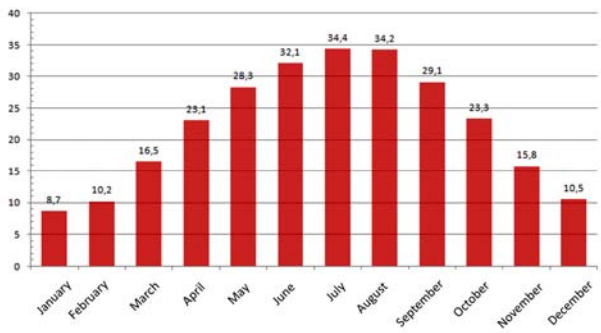

Fig. 7. Maximum temperature of the month, °C (Kherson climate)

The degree of influence of ambient air temperature on the efficiency of the gas turbine plant is shown in Fig. 8.

The efficiency of GTD AI-336-2-10 decreases with increasing temperature, and under standard conditions is about 31 %.

To account for friction losses when the working medium compressed in the compressor adiabatic efficiency of the compressor adopted η_c = 0.8; gas turbine — η_t = 0.88.

Analysis of climatic characteristics showed that the use of air cooling is advisable from April to October, when the average monthly maximum temperature exceeds + 15 °C.

The decrease in the specific work of the GTD with an increase in the outside air temperature is shown in Fig. 9.

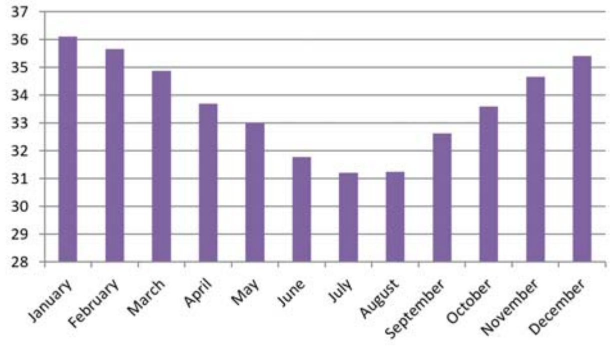

Fig. 8. Monthly average thermal efficiency

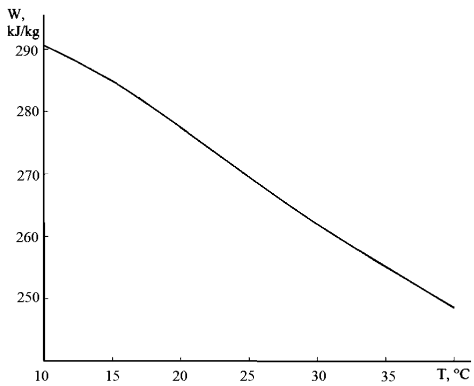

Fig. 9. Dependence of power drop with temperature increasing

The effect of cooling technology on the net power capacity enhancement for the plant is shown in Fig. 10, where the air is cooled through the steam ejector refrigerator by 10 °C.

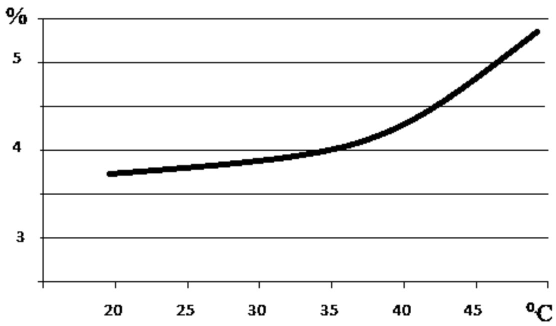

Fig. 10. Change of GTD cycle work depending on the ambient temperature

As the ambient temperature rises, the cooling effect increases.

In connection with the above, a detailed development of a technical solution based on the use of a steam ejector refrigerator, which reduces the negative impact of high outdoor temperatures on the energy and economic efficiency of the GTD is promising.

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АНАЛІЗ ЕФЕКТИВНОСТІ ЗАСТОСУВАННЯ ТЕПЛОВИКОРИСТОВУЮЧИХ СИСТЕМ ОХОЛОДЖЕННЯ ЦИКЛОВОГО ПОВІТРЯ ГТД

Встановлено, що при підвищенні температури на вході в компресор газотурбінного двигуна, ефективність установки знижується. У статті наведено дослідження впливу кліматичних умов на ефективність газотурбінного приводу АІ-336-1/2-10, призначеного для приводу газоперекачувальних агрегатів та інших промислових установок потужністю 10 МВт. Запропоновано метод підвищення ККД установки, заснований на охолодженні повітря на вході компресора.

Проведено порівняння різних існуючих методів охолодження повітря на вході в компресор. Така попередня підготовка повітря дозволяє уникнути зниження потужності в спекотні періоди. Показано, що для найкращого охолодження повітря і, як наслідок, максимізації продуктивності газотурбінної установки слід переважно використовувати холодильні установки. Доцільним представляється охолодження повітря за допомогою холодильних машин, що утилізують теплоту відпрацьованих газів. ГТУ будь-якої схемотехніки має великий потенціал енергії, що може бути використано для виробництва холоду з використанням теплових холодильних машин: абсорбційних або пароструминних. Для охолодження повітря на вході в компресор газотурбінного приводу АІ-336-1/2-10 була проаналізована можливість використання тепловикористовуючої ежекторної холодильної машини, яка має такі переваги як простота, малий обсяг і відсутність рухомих зношувальних деталей і можливістю використання водяної пари в якості холодоагенту. З метою визначення величини зниження температури повітря на вході компресора і відповідно збільшення ККД двигуна, були виконані розрахунки. Виконано аналіз ефективності ГТУ залежно від температури навколишнього повітря і ступеня охолодження повітря перед компресором. Обґрунтовано ефективність застосування пароежекторного холодильної установки для зниження температури повітря на вході в компресор. Показано, що охолодження повітря на вході запобігає зниженню потужності ГТУ і забезпечує утилізацію тепла відпрацьованих газів, призводить до підвищення економічних і екологічних показників установки, забезпечує скорочення витрати палива. У зв'язку з викладеним перспективне детальне опрацювання технічного рішення на основі використання пароежекторної холодильної машини, що знижує негативний вплив високих температур зовнішнього повітря на енергетичну та економічну ефективність ГТУ.

Ключові слова: газова турбіна; підвищення ефективності; утилізація тепла; ежектор; охолодження повітря.

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ANALYSIS OF THE EFFICIENCY OF APPLICATION HEAT-USED COOLING SYSTEMS OF GAS TURBINE DRIVE AIR CYCLE

It was found that with an increase in temperature at the inlet of the compressor of a gas turbine engine, the efficiency of the installation decreases. The article presents a study of the influence of climatic conditions on the efficiency of theAI-336-1/2-10 gas turbine drive intended for the drive of gas pumping units and other industrial installations with a capacity of 10 MW. A method for increasing the efficiency of the installation based on air cooling at the compressor inlet is proposed.

Comparison of various existing methods of air cooling at the compressor inlet is carried out. This air preconditioning avoids power loss during hot periods. It is shown that for the best air cooling and, as a consequence, maximizing the performance of a gas turbine unit, it is preferable to use refrigeration units. It seems expedient to cool the air with the help of refrigerating machines that utilize the heat of the exhaust gases. GTU of any circuit design has a high energy potential, what can be used for the production of cold using thermal refrigeration machines: absorption or steam jet. To cool the air at the inlet to the compressor of the AI-336-1/2-10 gas turbine drive, the possibility of using a heat-using ejector refrigeration machine was analyzed, which has such advantages as simplicity, small volume and the absence of movable wear parts and the possibility of using water vapor as a refrigerant. In order to determine the magnitude of the decrease in air temperature at the compressor inlet and, accordingly, the increase in the engine efficiency, calculations were performed. The analysis of the efficiency of the gas turbine unit depending on the ambient air temperature and the degree of air cooling in front of the compressor is carried out. The efficiency of the use of a *steam jet refrigeration unit for reducing the air temperature at the compressor inlet has been substantiated. It is shown that air cooling at the inlet prevents a decrease in the power of the GTU and ensures the utilization of waste gas heat, leads to an increase in the economic and environmental performance of the installation, and ensures a reduction in fuel consumption. In connection with the foregoing, a detailed study of a technical solution based on the use of a steam-jet refrigeration machine is promising, what reduces the negative effect of high outside air temperatures on the energy and economic efficiency of the gas turbine plant.*

Keywords: gas turbine; efficiency increase; heat utilization; ejector; cooling of air.

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АНАЛИЗ ЭФФЕКТИВНОСТИ ПРИМЕНЕНИЯ ТЕПЛОИСПОЛЬЗУЮЩИХ СИСТЕМ ОХЛАЖДЕНИЯ ЦИКЛОВОГО ВОЗДУХА ГТД

Установлено, что при повышении температуры на входе в компрессор газотурбинного двигателя, эффективность установки снижается. В статье приведено исследование влияния климатических условий на эффективность газотурбинного привода АИ-336-1/2-10 , предназначенного для привода газоперекачивающих агрегатов и других промышленных установок мощностью 10 МВт. Предложен метод повышения КПД установки, основанный на охлаждении воздуха на входе компрессора.

Проведено сравнение различных существующих методов охлаждения воздуха на входе в компрессор. Такая предварительная подготовка воздуха позволяет избежать снижения мощности в жаркие периоды. Показано, что для наилучшего охлаждения воздуха и, как следствие, максимизации производительности газотурбинной установки предпочтительно использовать холодильные установки. Целесообразным представляется охлаждение воздуха с помощью холодильных машин, утилизирующих теплоту отработанных газов. ГТУ любой схемотехники имеет большой потенциал энергии, что может быть использовано для производства холода с использованием тепловых холодильных машин: абсорбционных или пароструйных. Для охлаждения воздуха на входе в компрессор газотурбинного привода АИ-336-1/2-10 была проанализирована возможность использования теплоиспользующей эжекторной холодильной машины, обладающей такими преимуществами как простота, малый объем и отсутствие подвижных изнашиваемых деталей и возможностью использования водяного пара в качестве хладагента. С целью определения величины снижения температуры воздуха на входе компрессора и соответственно приращения КПД двигателя, были выполнены расчеты. Выполнен анализ эффективности ГТУ в зависимости от температуры окружающего воздуха и степени охлаждения воздуха перед компрессором. Обоснована эффективность применения пароэжекторной холодильной установки для снижения температуры воздуха на входе в компрессор. Показано, что охлаждение воздуха на входе предотвращает снижение мощности ГТУ и обеспечивает утилизацию тепла отработанных газов, приводит к повышению экономических и экологических показателей установки, обеспечивает сокращение расхода топлива. В связи с изложенным перспективна детальная проработка технического решения на основе использования пароэжекторной холодильной машины, снижающей негативное влияние высоких температур наружного воздуха на энергетическую и экономическую эффективность ГТУ.

Ключевые слова: газовая турбина; повышение эффективности; утилизация тепла; эжектор; охлаждение воздуха.

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