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ENERGY-ECONOMIC RESULTS OF USING THE METHOD OF REDUCING ENERGY LOSSES OF MOBILE DIESEL COMPRESSOR STATIONS BY ADDITIONAL COOLING OF COMPRESSED GASES

The article conducts experimental studies of the use of additional freon cooling systems instead of water systems, which allows reducing the specific consumption of the coolant per kilogram of cooled gas by 2-3 times. For example, for the compressor unit KPU-16/250 the specific consumption of the heat carrier per kilogram of cooled gas when pumping nitrogen for the operating cooling system will be 1.71 kg/kg, and for the designed freon system - 0.69 kg/kg; the specific consumption of the heat carrier per kilogram of cooled gas when pumping air for the operating cooling system will be 1.76 kg/kg, and for the designed freon system – 0.72 kg/kg;

When using additional freon systems of high-efficiency cooling for cooling compressed air with a decrease in the temperature of the working medium in gas coolers to -10 0C, the specific energy consumed by the compressor is reduced for diesel compressor units of the oil and gas industry, on average, by 14-17%. Thus, for the SD-9/101M compressor unit, when nitrogen is injected, the specific energy consumed by the compressor decreases from 315.21 kJ/kg to 263.34 kJ/kg or by 16.5%; when air is injected, the specific energy consumed by the compressor decreases from 320.74 kJ/kg to 275.46 kJ/kg or by 14.2%.

Keywords: energy efficiency, compressor, cooling system, energy, power.

INTRODUCTION

Currently, manufacturers and researchers are developing promising energy saving directions in compressor units, for example, by reducing leaks, optimizing output pressure, choosing the right control and management systems, etc. But it is obvious that the greatest reserve of energy saving of mobile diesel compressor stations will be the effective recovery of thermal energy, which is carried out with exhaust gases and thermal energy of compressed gases, which is released into the environment. Thermal energy, which is transferred through the cooling system to the environment, is of low potential, the efficiency of its use is relatively low, but further use of thermal energy, which is transferred through the cooling system to the environment, is also advisable.

LITERATURE REVIEW AND PROBLEM STATEMENT

The main directions for reducing the energy consumption of mobile diesel compressor stations are [1]:

- efficient use of heat from the working process;
- improvement of the design of the compressor and its compressed gas preparation and release systems, primarily its compressed gas cooling system;
- reduction of fuel costs for the compressor (switching to cheaper alternative fuels: pyrolysis, biogas, methane, etc.);
- improvement of the compressor drive engine (switching to improved electronic fuel injection systems, multi-valve cylinder heads, increasing turbine pressure, etc.)

Let's take a closer look at the first direction.

In modern diesel engines, approximately 35-40% of the total amount of thermal energy introduced into the engine with fuel goes to perform useful work, approximately 25-30% of the energy is removed with exhaust gases and 30-35% is transferred through the cooling system to the environment [2].

As for the use of thermal energy carried away with exhaust gases and thermal energy of compressed gases released into the environment, the most effective device for heat utilization for mobile technological installations will be a thermoelectric generator [3]. Modern thermoelectric generators are reliable semiconductor devices, and the efficiency of modern thermoelectric generators with a temperature difference of more than 100 0C already reaches 20%. Even when using only 10% of thermal energy, about 3% will be saved on the heat carried away with exhaust gases, and about 2% on the thermal energy of compressed gases from the total amount of thermal energy introduced into the engine with fuel.

In other words, in the overall heat balance, where in modern diesel engines approximately 35-40% of the total amount of thermal energy introduced into the engine with fuel goes to perform useful work, about 5% of the energy of the overall heat balance of the engine can be converted into electrical energy.

A well-known method of reducing energy consumption, in terms of improving the design of the compressor, is to reduce energy losses due to friction in the elements of the compressor station, as well as to reduce total pressure losses during gas movement in the inlet and outlet pipes.

Regulating the gas compression pressure is a fairly effective method of saving energy. It has been found that reducing the output pressure by every 10 kPa reduces the compressor's energy consumption by 1-2% [4].

For the efficient operation of the compressor station, it is also rational to increase the compressor load and organize the operation of the equipment in energy-efficient modes. Such optimization of the compressor operating mode allows reducing energy consumption by 2-3% [4].

Thus, from the point of view of maximum energy saving of mobile diesel compressor stations, the most effective direction will be the use of thermal energy of compressed gases and heat, which is carried out with exhaust gases, with the conversion of this thermal energy into electrical energy.

It has been analyzed that for mobile diesel compressor stations, about 5% of the total heat balance energy can be converted into electrical energy, while in modern diesel engines, about 35-40% of the total amount of thermal energy introduced into the engine with fuel is used to perform useful work. In other words, through the effective use of excess heat, an additional amount of electricity can be obtained within 12-14% of the nominal effective engine power.

But at the same time, another problem arises - the effective use of the received electricity. The capacity of the own systems of electric energy consumption and energy supply for existing engines and technological installations as a whole is much smaller. For example, the capacity of electric generators of existing internal combustion engines is about 1% of the nominal effective power of the engine. Therefore, it will not be rational to use the received electricity only to meet the own electric energy needs of the engine [5]. Therefore, the problem of using excess electricity within 12-14% of the nominal effective power of the engine requires a different solution.

As has already been established, the energy efficiency and cost-effectiveness of compressor stations are significantly related to the removal of heat from gas compression. In addition, the process of gas compression in compressor plants is accompanied by a significant increase in temperature, which, when the pressure increases, can reach more than 200 °C and worsen the operation of compressor units, including the risk of explosion in compressors due to ignition of oil vapors [6].

Therefore, it follows from the above that for energy-efficient operation of the compressor, it is necessary to additionally artificially cool the compressed gas during its operation without increasing the area of the cooling heat exchangers.

The most economical cooling is achieved by increasing the water temperature in the heat exchanger by 15-20 °C. It is not recommended to heat the water above 40 °C, since at higher temperatures salts are released on the heat exchange surfaces [7].

Thus, for energy-efficient operation of the compressor, it is necessary to artificially cool the compressed gas during its operation. The efficiency of cooling the compressed gas in the intermediate and final coolers directly affects the specific compression costs, and therefore the lower the temperature of the compressed gas in the intermediate coolers, the higher the energy efficiency of the compressor unit.

Given the low efficiency of air and water cooling and water injection cooling, the most effective is to cool compressed gases in closed intercooling systems with a coolant other than water.

PURPOSE AND OBJECTIVES OF THE STUDY

The aim of the work is to conduct experimental studies of the energy and economic results of the method of reducing energy losses of mobile diesel compressor stations through additional highly efficient cooling of compressed gases.

The scientific and technical tasks are as follows:

- study of potential directions of energy efficiency of mobile diesel compressor stations;
- analysis of directions of energy saving of mobile diesel compressor stations by improving the compressed gas cooling system and by using the heat of compressed gases;
- assessment of energy efficiency of the proposed methods of increasing energy saving.

RESEARCH RESULTS

As it was established, to achieve minimum energy consumption of mobile diesel compressor stations, it is necessary to ensure the deepest possible cooling of compressed gas in the heat exchangers of the intercooling system.

This is explained by the fact that the decrease in gas temperature before each stage of the compressor increases the gas density. At the same time, in direct proportion to the increase in gas density in the cylinders, the compressor performance increases. Calculations show that a decrease in gas temperature by 1 K leads to an increase in performance by approximately 0.3% [8]. Thus, with a decrease in the temperature of the sucked gas, the specific energy consumption for the compressor drive decreases proportionally, and the most efficient from an energy point of view is the process of isothermal gas compression in the compressor. But the implementation of isothermal gas compression is possible only due to the maximum increase in the areas of cooling heat exchangers. This, in turn, will lead to an increase in pressure and energy losses. At the same time, in existing compressors, on average, from 5 to 10% of the gas compression power is spent on overcoming losses in gas coolers.

Research into a promising system for highly efficient cooling of compressed gas in compressor stations was carried out on a specially designed and manufactured experimental stand with an evaporator, two compressed air circuits, and air cooling and heating units (Fig. 1). Two identical CO-7B compressors were used to pump gas (Fig. 2). The air in the gas cooler circuit was cooled using an Electrolux mobile air conditioner.

1 – air heating unit; 2 – stand frame; 3 – control panel; 4 – gas cooler damper control compressor; 5 – gas cooler-evaporator;

Figure 1 – Installation with a system of highly efficient compressed gas cooling of compressor stations

Figure 2 – Compressor SO-7B

To determine the energy consumption for gas pumping, gas flow and pressure data were used. Pressure measurements were performed using a manometric manifold (Fig. 3), and the flow rate of pumped gases was measured using a gas meter (Fig. 4).

When conducting experimental studies of the proposed scheme for energy saving of compressors due to highly efficient additional cooling of compressed gas, the energy losses of the compressor were determined. For this purpose, two identical compressors CO-7Б were used, which created two air injection circuits. The first compressor pumps air into the gas cooler, the second pumps cooled air. The maximum compression ratio ε of the compressors can be 6 units. When conducting experimental studies, the compression ratio ε of the compressors was limited to 3 units. The air in the gas cooler circuit is cooled using a mobile Electrolux air conditioner. The air conditioner operates in two modes: in the first, it supplies ordinary uncooled air from the environment (simulation of the operation of existing compressor stations in the oil and gas industry), in the second, it supplies cooled air (simulation of the operation of a promising scheme for highly efficient additional cooling of compressed air).

Fig. 3. Manometric manifold for measuring the compressed gas pressure of the installation

Fig. 4. Flowmeter for measuring volumetric flow of compressed gas

The energy consumption per unit time of each circuit was determined by the corresponding transformation of the formula 1.

$$L_г = \frac{k}{k-1} \cdot P_{i1} \cdot V_{i1} \cdot \left(\left(\frac{P_{i2}}{P_{i1}} \right)^{\frac{k-1}{k}} - 1 \right), \text{ MJ/h.} \qquad (1)$$

where P_{i1} – pressure at the inlet of the i-th circuit, Pa;

P_{i2} – pressure at the outlet of the i-th circuit, Pa;

V_{i1} – compressor capacity at the inlet of the i-th circuit, m^3.

The outlet pressure of each stage P_2 was determined from formula 2 through the inlet pressure and gas temperatures at the inlet T_1 and outlet of each circuit T_2.

$$P_2 = P_1 \cdot \sqrt[2]{\left(\frac{T_2}{T_1} \right)^7}. \qquad (2)$$

Initially, experimental studies were conducted and the specific work of compression was determined for existing compressor units for different seasons without cooling and with artificial cooling from ambient air. This is necessary to assess the efficiency of standard compressed air-cooling systems. The results of experiments and calculations are shown in the figure 5.

From the results of the performed experimental studies, the following conclusions can be drawn:

- the lower the ambient temperature, the lower the specific work of compression of the compressor. For example, the specific work of compression of the second circuit at an ambient temperature of -5 0C is 97.1 kJ/kg, +5 0C – 104.2 kJ/kg, +35 0C – 111.6 kJ/kg;

- the higher the ambient temperature, the worse the cooling of the compressor and the higher the specific work of compression of the compressor. For example, the specific work of compression of the second circuit at an ambient temperature of -5 0C and forced cooling is 67.9 kJ/kg (69.9%), and at +35 0C – 87.5 kJ/kg (78.4%);

- with increasing ambient temperature, the useful power consumption of the compressor also increases, for example, from 82.9% at an ambient temperature of -5 0C to 86.7% at an ambient temperature of +35 0C;

- cooling of compressed air, which is used at existing compressor stations, is an effective way to reduce the specific work of compression of the compressor. In this case, the range of reduction in the specific work of compression of the compressor varies within 69-78%.

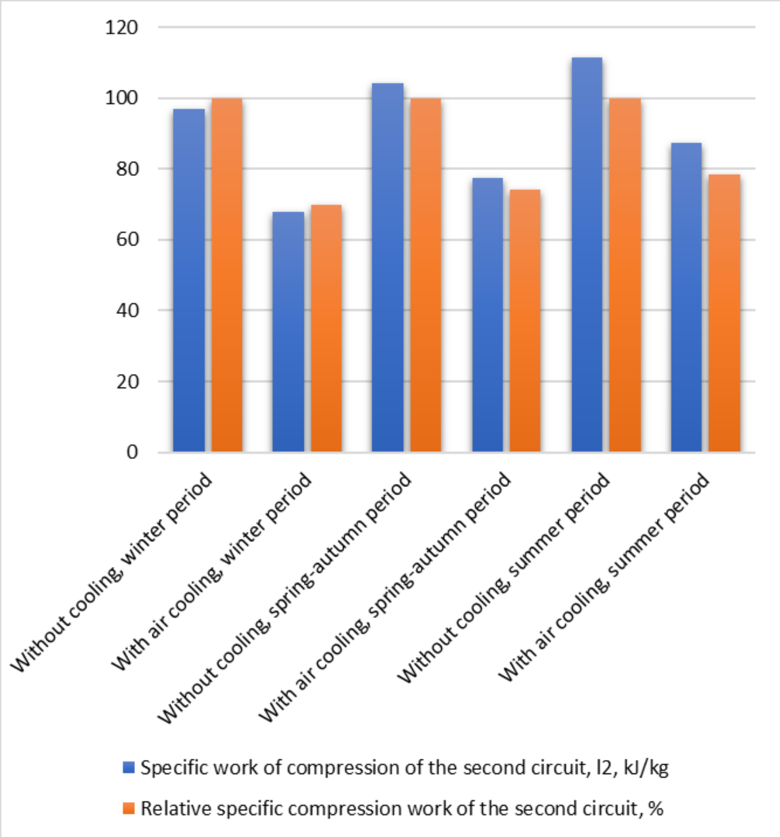


Fig. 5. Results of experimental studies of cooling schemes of existing compressor units

Further, experimental studies of the proposed scheme for energy saving of compressors due to highly efficient additional cooling of compressed gas were carried out and compared with the existing cooling scheme. During the experiments, the power consumed by the freon compressor was limited to a value that was 5% of the power of the main compressor.

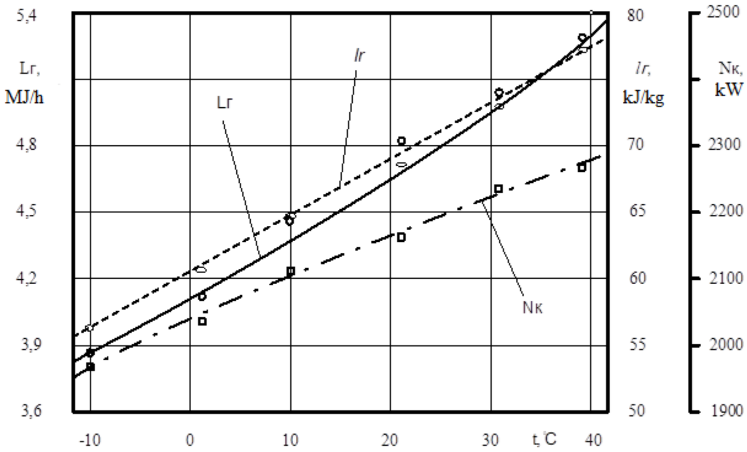
The results of experimental studies of hourly energy consumption, specific compression work and total useful power of compressors depending on the temperatures at the inlet to the gas cooler circuits are shown in Fig. 6.

From the results of the experimental studies of the proposed scheme for energy saving of compressors due to highly efficient additional cooling of compressed gas, the following conclusions can be drawn:

- compressed air cooling due to highly efficient additional cooling of compressed gas of the proposed compressor energy saving scheme is an effective way to reduce the specific work of compression of the compressor. In this case, the maximum value of the reduction in the specific work of compression of the compressor reaches 72.7%;

- the lower the temperature of the gas cooler, the lower the specific work of compression of the compressor. For example, the specific work of compression of the second circuit at a gas cooler temperature of -10 0C is 56.2 kJ/kg, +1 0C – 60.4 kJ/kg, +21 0C – 68.9 kJ/kg;

- compressed air cooling due to highly efficient additional cooling of compressed gas of the proposed compressor energy saving scheme allows to reduce the total useful power of the compressor to 14.5%.



L_2 - hourly energy consumption for the second circuit, MJ/h;;

l_2 - specific work of compression of the second circuit, kJ/kg;

N_{kc} - total useful power of the compressor, kW

Fig. 6. Dependence of hourly energy consumption L_2, specific work of compression l_2 and total useful power of compressors N_{kc} on temperatures t at the inlet to the gas cooler circuits

DISCUSSION OF RESEARCH RESULTS

The results of theoretical and experimental studies have shown that the greatest energy saving reserve for mobile diesel compressor units in the oil and gas industry is realized with the deepest possible cooling of compressed gas in the heat exchangers of the intercooling system due to the recovery of excess heat.

This is explained by the fact that a decrease in gas temperature before each compressor stage increases gas density. At the same time, in direct proportion to the decrease in gas temperature in the cylinders, compressor performance increases and energy consumption decreases. Calculations show that a decrease in gas temperature by 1 K leads to an increase in performance and a decrease in energy consumption by approximately 0.3%.

To assess the energy efficiency of the proposed methods for increasing energy saving based on the results of theoretical and experimental studies, energy efficiency calculations were performed for the most common typical mobile diesel compressor stations in the oil and gas industry for the existing and proposed gas cooling systems when using different types of gases. The design season is autumn-spring, the ambient temperature is 15 ^{0}C, the working fluids are air and nitrogen.

The results of calculations of the main energy efficiency indicators of mobile diesel compressor stations in the oil and gas industry during air injection are shown in Fig. 7,8.

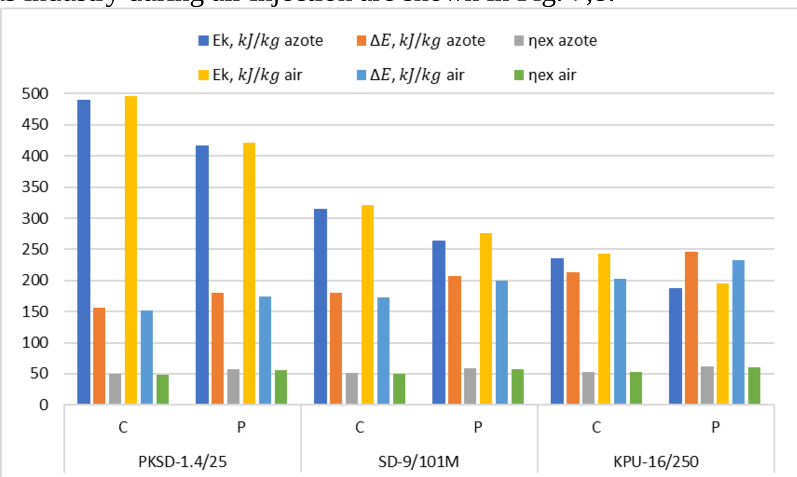
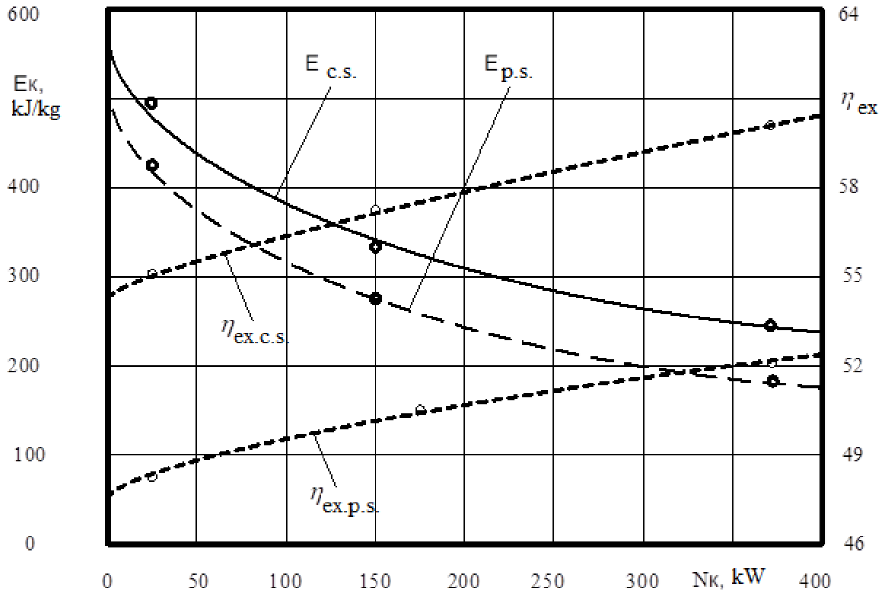


Fig. 7. Energy efficiency calculations for common mobile diesel compressor stations in the oil and gas industry for air injection

In Figure 7, the following notations are used:

C – the current existing cooling system of compressed gases;

P – proposed additional compressed gas cooling system;
E_k – specific energy consumed by the compressor, kJ/kg;
$\Delta E_{ст.г}$ - change in exergy of compressed gas, kJ/kg;
$\eta_{екс}$ - exergy efficiency.



$E_{к.д}$ – specific energy consumed by compressors according to the current scheme, kJ/kg; $E_{к.п}$ – specific energy consumed by compressors according to the proposed scheme, kJ/kg; $\eta_{екс.д.}$ - exergy efficiency according to the current scheme; $\eta_{екс.д.}$ - exergy efficiency according to the proposed scheme

Fig. 8. Results of calculations of the main indicators of energy efficiency of mobile diesel compressor stations in the oil and gas industry when pumping air

CONCLUSIONS

Based on the calculations and results obtained, the following conclusions can be drawn:

The more stages, the more intermediate cooling circuits and the higher the energy savings for compressor stations when using additional high-efficiency freon cooling systems for compressed gas.

At low compressor pressure stages (one to two), it is not advisable to use advanced gas cooling systems with freon, since the energy savings are not very significant.

At high compressor pressure stages (three and more), it is already advisable to use advanced gas cooling systems with freon. In this case, an increase in the number of compression stages leads to an increase in the energy efficiency index.

The highest energy efficiency is achieved when compressing gases with a lower molar mass. Thus, the energy efficiency when compressing nitrogen gases is higher than when compressing air. For example, the specific energy consumed by the compressor for the PKSD-1.4/25 installation when pumping nitrogen is 490.22 kJ/kg for existing cooling systems and 416.55 kJ/kg when using additional freon systems of high-efficiency cooling; when pumping air for existing cooling systems 495.93 kJ/kg and 420.76 kJ/kg when using additional freon systems of high-efficiency cooling;

The exergy efficiency of compressor units tends to increase with increasing absolute power. Thus, for the PKSD-1.4/25 compressor unit with a capacity of 23 kW, the exergy efficiency when pumping air is 48.2%, and for the KPU-16/250 compressor unit with a capacity of 368 kW, the exergy efficiency is 52.1%; When using additional freon systems of high-efficiency cooling for compressed air cooling with a decrease in the temperature of the working medium in gas coolers to -10 0C, the exergy efficiency of the compressors increases by approximately 15%. For example, for the PKSD-1.4/25 compressor unit, the exergy efficiency increases from 48.2 to 55.2%, for the SD-9/101M compressor unit, the exergy efficiency increases from 51.0 to 58.7%, for the KPU-16/250 compressor unit, the exergy efficiency increases from 53.2 to 61.3%;

When using additional freon systems of high-efficiency cooling for compressed gas cooling with a decrease in the temperature of the working medium in gas coolers to -10 0C, the specific heat transfer coefficient of heat exchangers - compressed gas coolers - decreases, on average, by 25%. Thus, for the compressor unit SD-9/101M, when nitrogen is injected, the specific area of heat exchangers decreases from 5.201 m2/kg to 3.894 m2/kg; when air is injected, the specific area of heat exchangers decreases from 4.434 m2/kg to 3.327 m2/kg;

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Гнип М.М. **Енерго-економічні результати використання методу зниження втрат енергії пересувних дизельних компресорних станцій шляхом додаткового охолодження стиснених газів**

У статті проведено експериментальні дослідження використання додаткових фреонових систем охолодження замість водяних систем, що дозволяє в 2-3 рази знизити питому витрату охолоджувача-теплоносія на один кілограм охолодженого газу. Наприклад, для компресорної установки КПУ-16/250 питома витрата теплоносія на один кілограм охолодженого газу при прокачуванні азоту для діючої системи охолодження складе 1,71 кг/кг, а для проектованої фреонової - 0,69 кг/кг; питома витрата теплоносія на один кілограм охолодженого газу при прокачуванні повітря для діючої системи охолодження складе 1,76 кг/кг, а для проектованої фреонової – 0,72 кг/кг;

При використанні для охолодження стисненого повітря додаткових фреонових систем високоефективного охолодження зі зниженням температури робочого тіла в газоохолоджувачах до -10 ^{0}С питома енергія, що споживається компресором, знижується для дизельних компресорних установок нафтогазової галузі, в середньому, на 14-17 %. Так, для компресорної установки СД-9/101М при нагнітанні азоту питома енергія, що споживається компресором, зменшується з 315,21 кДж/кг до 263,34 кДж/кг або на 16,5 %; при нагнітанні повітря питома енергія, що споживається компресором, зменшується з 320,74 кДж/кг до 275,46 кДж/кг або на 14,2 %.

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