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Study of the Efficiency of Operation of a Fuel-Free Energy Generating Installation Based on an Expander-Generating Unit and a Heat Pump

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ABSTRACT: The development of resource-saving technologies for existing energy sources is one of the priority tasks of the energy strategy of the Republic of Uzbekistan, which provides for the reduction of losses and cost reduction at all stages of the technological process during the extraction, preparation and transportation of natural gas. Today, it is very promising to utilize the energy of excess pressure of natural gas at gas distribution stations using expander units. A solution to the problem of lack of gas heating in the expander-generator unit can be a heated installation scheme through the use of a gas heating system of a heat pump station.

KEY WORDS: gas distribution station, natural gas, expander-generator unit, heat pump, fuel-free installation, energy saving.

I.INTRODUCTION

Energy saving is an essential reserve for increasing production efficiency not only in consumption, but also in the generation of various types of energy. These include, first of all, electricity, heat, as well as cold. In the global energy sector, the overwhelming amount of electricity and heat is produced at installations that use the energy released by burning organic fuels for operation. In recent years, in most industrialized countries, sufficiently advanced installations have been created and implemented to convert the energy of organic fuels into electrical energy and heat. Further improvement of the technical and economic indicators of such installations requires the search for new, non-traditional methods, the use of which would significantly improve the technical and economic performance of power equipment and at the same time improve its environmental performance.

One of the energy-saving technologies for generating electricity is expander-generator technology, based on the use of expander-generator units (EGU) at stations for technological reduction of gas pressure in gas supply systems, at enterprises using natural gas as fuel, the high energy efficiency of which has been practically confirmed [1,2].

The disadvantage of using turbo expander units is a significant decrease in temperature during the gas expander process due to the Joule-Thomson effect. Therefore, in order to prevent the formation of condensate and hydrates in gas pipelines and fittings, as well as to provide gas consumers with fuel at the required temperature (3-7°C), the gas is heated before entering the expander.

One of the main systems that determine the volume and technical and economic indicators of EGU is the gas heating system. Its thermal capacity is equivalent to approximately the capacity of the EGU, and its cost, according to various estimates, can be up to 40% of the total cost of the EGU [3,4].

The issue of choosing a gas heating source is one of the main ones when deciding whether to use these units. In addition, the performance of the gas heating system significantly affects the operating costs of the EGU and, as a result, the cost of electricity produced by the EGU. Therefore, the selection and optimization of the gas heating scheme in the EGU is one of the priority tasks to be solved when designing the EGU.

If we take into account the continuous increase in gas consumption in the world, as well as increased environmental requirements for existing and new energy facilities, we can conclude that it is necessary to further introduce such installations in various industries [5-7].

The most common options for including EGU in GDS have a heat exchanger located in front of the EGU, which preheats the gas before it is fed to the expander generator set [8,9].

II. METHODOLOGY

The scheme being developed for switching on the EGU at the GDS of an automobile gas-filling compressor station (AGFC) “Navoi Concrete Complex” in the Republic of Uzbekistan, which refuels motor vehicles with compressed natural gas, where the EGU was introduced, is shown in Fig.1.

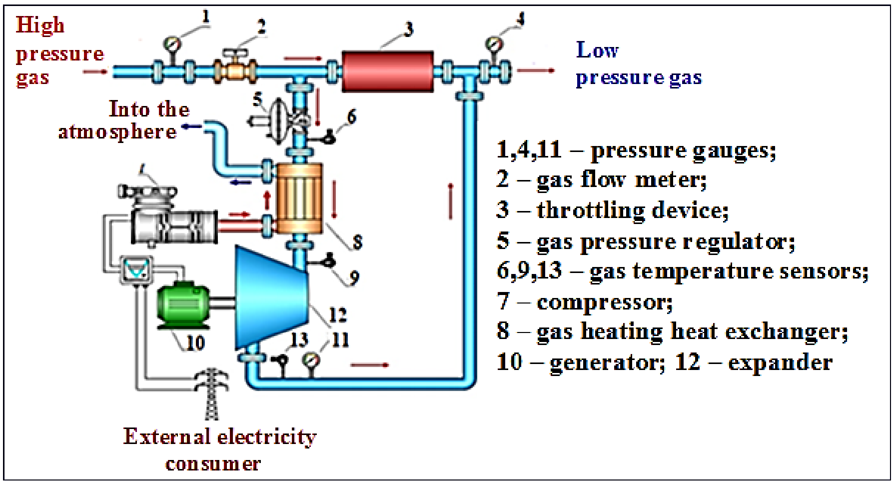

Fig. 1. Installation diagram with EGU and AHPU

The experimental setup had the following main components:
BROTJE Heizung model BSW 6A air heat pump, which was used as an air HPU when heating gas before entering the expander. The coolant was air. High-precision ultrasonic flow meter FLEXIM model FLUXUS ADM 6725, which was used to measure gas flow at the inlet and outlet of the expander. Two ALMEMO 2590-9 V5 measuring complexes with Ni-CrNi thermocouples, which were used to measure the gas temperature at the inlet and outlet of the expander. An electric power measuring device that was used to measure the electric energy consumed by the compressor drive [8,9,10].

III.RESEARCH RESULTS AND DISCUSSION

Initially, the gas flow through the gas pipeline was determined at the available capacity of the units and the initial design parameters: the operating pressure in the gas pipeline; ambient air temperature; gas cooling temperature.
The initial data are presented in tables 1 and 2.

Table 1. Technical parameters of GDS AGFC

AGFC	**Gas pressure at the entrance to the GDP, P_{ent}, kgs/sm^2**	**Gas pressure at the outlet to the GDP, P_{out}, kgs/sm^2**	**Gas consumption at the GDP, Q, m^3/month**
"Navoi Logistics"	6,0	1,5-2,0	723000
"Navoi Concrete Complex"	6,0	1,5-2,0	810000
"Navoi Fayz Oil"	6,0	1,5-2,0	625000

Table 2. Main parameters of gas components at GDP

Components	**Volume concentration, in fractions of unt**	**Molecular weight kg/kmol**	**T_{cr}, K**	**P_{cr}, MPa**	**Dynamic viscosity, kgs/m^3 10^{-7}**
Methane	0,98	16,04	190,5	4,49	10,3
Ethan	0,01	30,07	306	4,77	7,5
Propane	0,0003	44,09	369	4,26	6,9
Bhutan	0,0007	58,12	425	3,5	6,9
Pentane	0,00023	72,15	470,2	3,24	6,2
Carbon dioxide	0,0007	44,01	305	7,28	13,8
Nitrogen	0,008	28,02	126	3,39	16,6
Oxygen	0,00007	32,00	154,9	5,01	1,94

To determine the efficiency of the circuit shown in Fig.1, experiments were carried out on the installation, fragments of which are shown in Fig.2.

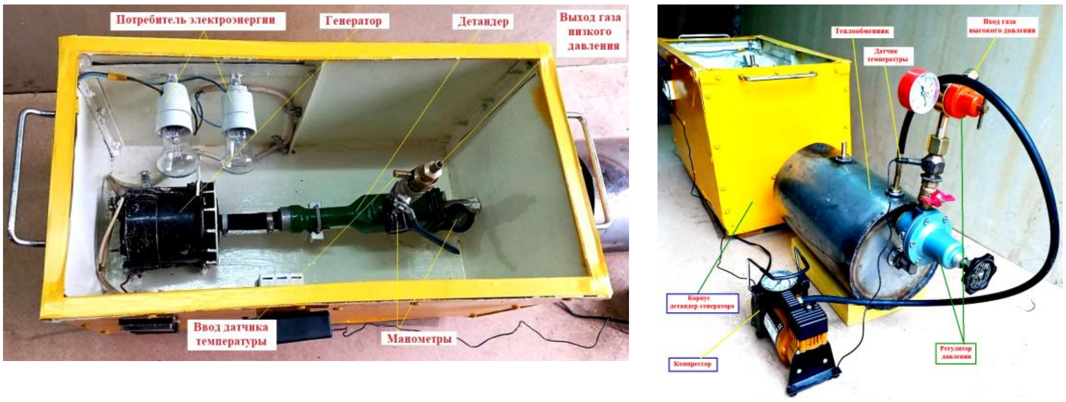

Fig. 2. Fragments of the expander generator set

The following initial data were accepted for the calculation:
Density of the gas mixture ρ_{mxt} =0,709 kg/m^3; Gas temperature t=40^{0}C;
Pressure at the entrance to the installation P_{ent} = 0,6 MPa;
Pressure at the outlet to the installation P_{out} = 0,15 MPa;

Gas consumption Q =810000 m^3/month
Gas constant R, kJ/kg·K, for natural gas mixture:

$$R=\frac{R_0}{M_{mxt}}=\frac{8,314}{15,97}=0,523\ \text{kJ/kg}\cdot\text{K},$$

where M_{mxt} - molecular weight of the gas mixture, kg/kmol;
R_0 - universal gas constant, J/(mol·K);
R_0 = 8,314 J/(mol·K).

Molecular weight of natural gas, M_{mxt}, kg/kmol:

$$M_{mxt}=\rho_{mxt}\cdot 22,4 \text{ (if the density of the mixture is given } \rho_{mxt}\text{) or } M_{mxt}=\frac{\Sigma V_i\cdot m_i}{100}.$$

$$M_{mxt}=\rho_{mxt}\cdot 22,4 = 0,709\cdot 22,4 = 15,97\ \text{kg/kmol},$$

where V_i – volume concentrations of gas components, %: V_1 – (90-97.9%) volume concentration of methane; V_2 – (0.75-4.75%) volume concentration of ethane; V_3 – (0.30-1.2%) volume concentration of propane; V_4 – (0.01-0.5%) volume concentration of i-butane; V_5 – (0-0.4%) volume concentration of n-butane; V_6 – (0-0.2%) volume concentration of i-pentane; V_7 – (0-0.15%) volume concentration of n-pentane; V_8 – (0-0.3%) volume concentration of hexane; V_9 – (0.1-2.5%) volume concentration of carbon dioxide; V_{10} – (0.2-1.3%) volume concentration of nitrogen; V_{11} – (0-0.3%) volume concentration of oxygen.

m_i–molar mass of components, kg/mol: m_1=16.04 - molar mass of methane; m_2=30.07 - molar mass of ethane; m_3=44.09 - molar mass of propane; m_4=58.12 - molar mass of i-butane; m_5=58.12 - molar mass of n-butane; m_6=72-molar mass; mass m_7=72.15-molar mass of n - pentane; m_8=86.18 - molar mass of hexane; m_9=44.01 - molar mass of non-acid gas; m_{10}=28.01 - molar mass of; m_{11}=31.99-molar mass of acid.
Enthalpy drop in the process of pressure drop in gas:

$$H=\frac{k}{k-1}\cdot z\cdot R\cdot T\cdot\left(1-\left(\frac{P_{out}}{P_{ent}}\right)^{\frac{k-1}{k}}\right)=\frac{1,3}{1,3-1}\cdot 0,9933\cdot 0,523\cdot 313\cdot\left(1-\left(\frac{0,15}{0,6}\right)^{\frac{1,8-1}{1,8}}\right)=193,1\ \text{kJ/kg}$$

where k is the volume index of the adiabatic;
R – individual gas constant, J/kg·K;
z – compressibility coefficient of the natural gas mixture;
z = 0,9933;
T – temperature of the gas before the expander, K;
where $T = t + 273$; t – ^{0}C;
$T = t + 273=40+273=313\ ^0$C.
P_{ent} – gas pressure in front of the expander, MPa;
P_{ent} – gas pressure after the expander, MPa.
Volumetric adiabatic index:

$$k_\upsilon=\frac{\sum k_{\upsilon i}\cdot V_i}{100},$$

where V_i – volume concentrations of gas components, %.
$k_{\upsilon i}$ – volume index of adiabate: $k_{\upsilon 1}$ = 1,3144 – volume index of methane adiabate;
$k_{\upsilon 2}$= 1,1405 – volume index of ethane adiabate;
$k_{\upsilon 3}$= 1,2181 – volume index of propane adiabate;
$k_{\upsilon 4}$= 1,4192 – volume index of nitrogen adiabate;
$k_{\upsilon 5}$= 1,2232 – volume index of carbon dioxide adiabate;
$k_{\upsilon 6}$= 1.4085 is the volume index of oxygen adiabatic.
Mass flow rate of natural gas mixture through GDP, kg/s:

$$G=\frac{Q_k\cdot\rho_{mxt}}{3600}=\frac{1125\cdot 0,709}{3600}=0,222\ \text{kg/s}$$

where Q_k is the volume flow rate of gas, m^3/h;

ρ_{mxt} is the density of the gas mixture, kg/m^3.

$$Q_{\text{k}}=\frac{Q}{30\cdot 24}=\frac{810000}{30\cdot 24}=1125\ \text{m}^3/\text{h}$$

The nominal available power that can be obtained in the EGU:

$$N_{\text{EGU}}=G\cdot H\cdot \eta=0,222\cdot 193,3\cdot 0,7802=33,45\ \text{kWt},$$

where H is the enthalpy difference, kJ/kg;
η – the total efficiency of the EGU:

$$\eta=\eta_{\text{gen}}\cdot\eta_{\text{mech}}\cdot\eta_0=0,94\cdot 1\cdot 0,83=0,7802,$$

where η_{gen}=0,94; η_{mech}=1; η_0=0,83.

Annual electricity generation EGU:

$$W_{\text{EGU}}=N_{\text{EGU}}\cdot 24\cdot\tau=33,45\cdot 24\cdot 350=280980\ \text{kWt}\cdot\text{h/year},$$

where τ is the duration of the EGU operation in a year; τ=350 days.
Average annual tariff for purchased electricity C= 0,036 \$/k·Wt.
Cost reduction: $\Delta S=W_{\text{EGU}}\cdot C$=280980·0,036=10115,28 \$/year.
The results of theoretical and experimental calculation of the share of generated electricity supplied to the AHPU power grid for heating gas at the inlet and outlet of the GDP are shown in Table 3.

Table 3. Verification results of calculation of theoretical and experimental data for the share of electricity supplied to the grid at a pressure ratio of 0.6/0.15 MPa

PARAMETERS	Calculated data	Experimental data	% discrepancy of results
Air heat pump installation			
The heat that is received by the gas in the heat exchanger before the EGU: $Q_3=Q_{\text{g}}\cdot(h_4-h_3)$, kJ/s	13,1	12,9	-1,53
Air consumption in the air HPU: $Q_{\text{air}}=\frac{Q_3}{(h_7-h_6)\cdot\eta_{\text{he}}}$, kg/s	0,127	0,125	-1,57
Power consumed by the compressor drive: $N_5=\frac{G_{\text{air}}\cdot(h_7-h_6)}{\eta_{\text{he}}}$, kWt	15,72	16,21	+0,49
Expander-generator unit			
Power generated by EGU, kWt: $N_2=G_{\text{air}}\cdot\frac{k}{k-1}\cdot z_4\cdot R_{\text{g}}\cdot T_4\cdot\left(1-\left(\frac{P_5}{P_4}\right)^{\frac{k-1}{k}}\right)\cdot\eta_{\text{oi}}\cdot\eta_{\text{em}}$	23,77	23,43	-1,43
Gas temperature per EGU: $T_5=T_4\cdot\frac{z_4}{z_5}\cdot\left[\eta_{\text{oi}}\left(\left(\frac{P_5}{P_4}\right)^{\frac{k}{k-1}}-1\right)+1\right]$, K	50,3	51,21	+1,81
The share of electricity generated in the network: $\alpha=\frac{N_2-N_6}{N_2}$	0,375	0,368	-1,86

Graphs representing the dependences of experimental calculations of the share of electricity produced, on the heating temperature of the gas mixture before the EGU and the amount of gas transported are shown in Fig. 3-8.

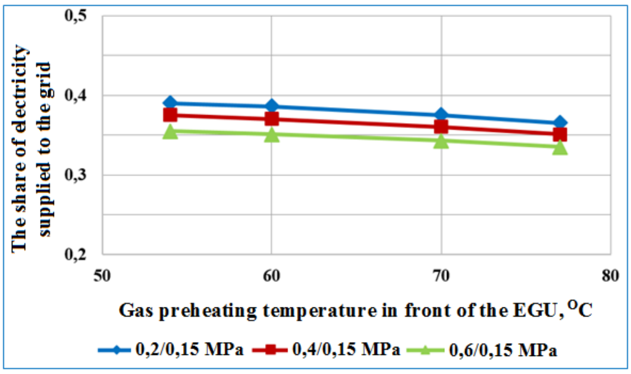

Fig. 3. The relationship between the gas heating temperature before the EGU and the share of electricity supplied to the grid

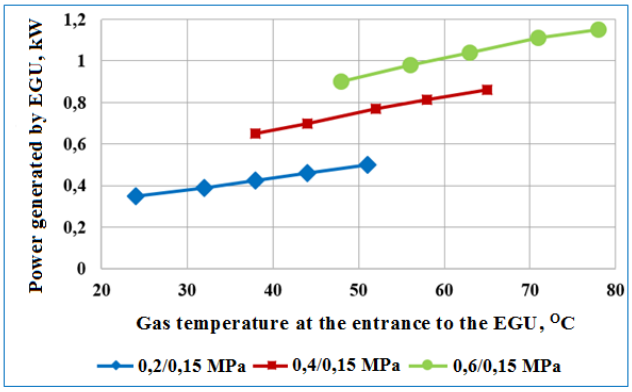

Fig. 4. The relationship between the gas heating temperature and the generated EGU power

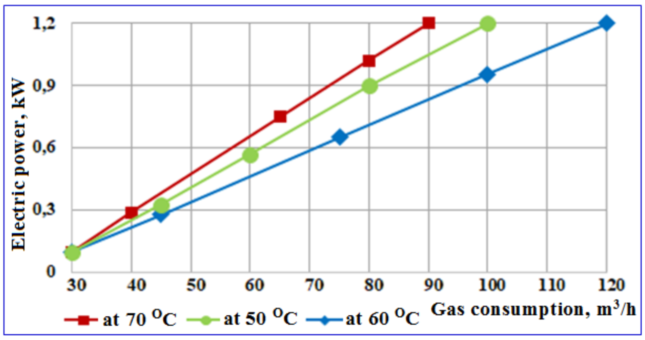

Fig. 5. Dependence of the produced power of the installation on the gas consumption at different gas heating temperatures at the EGU inlet

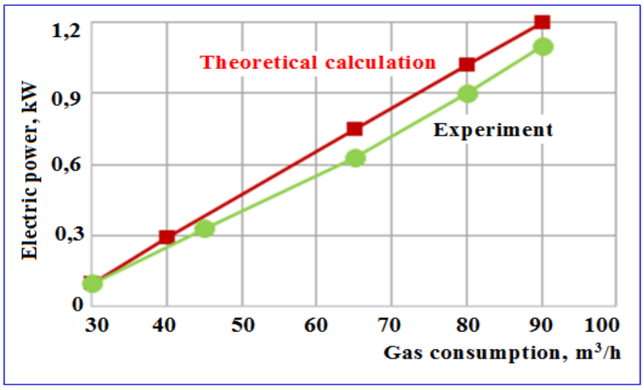

Fig. 6. The effect of gas flow at a heating temperature of 70 ° C in front of the expander (theor./exp.) on the generated power of the EGU

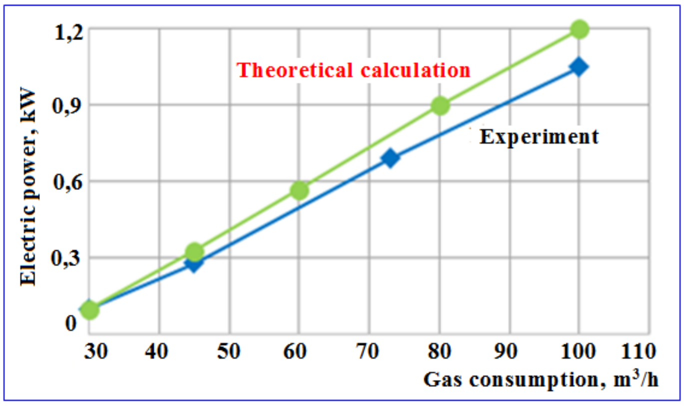

Fig. 7. The effect of gas flow at a heating temperature of 60 °C in front of the expander (theor./exp.) on the generated power of the EGU

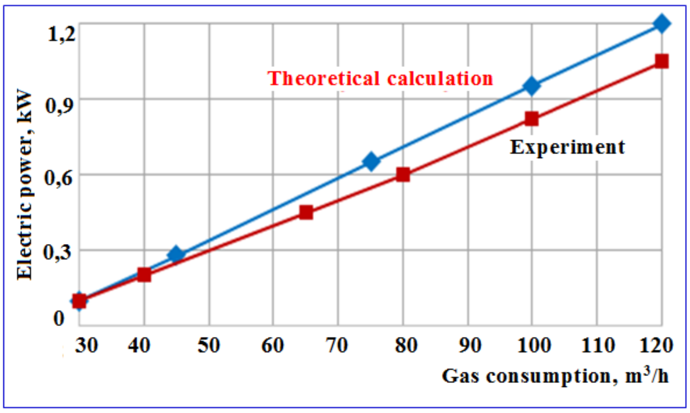

Fig. 8. The effect of gas flow at a heating temperature of 50 °C in front of the expander (theor./exp.) on the generated power of the EGU

IV. CONCLUSION

1. Heating the gas in front of the expander-generator unit due to low-grade heat using a heat pump unit makes it possible to obtain electricity with high efficiency.
2. An assessment of the technical and economic efficiency of a fuel-free installation based on EGU was carried out, which allows reducing the consumption of electricity for own needs from the external network at the GDP of the “Navoi Concrete Complex” automobile gas filling compressor station by up to 70% with a production of 280 980 kWh /year and a payback period of 4 years.

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