ALTERNATIVE TECHNOLOGIES AND ENERGY PERFORMANCE

Exhaust gases heat recovery of GPU gas turbine compressor of gas-main pipelines

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The choice of the rational heating scheme of gas turbine exhaust-gas heat utilization of main gas pipeline gas-compressor units is one of the actual problems of increasing energy efficiency of gas transportations. A number of well-known publications state that problem solution can not be considered to be completed, some results of investigation being conflicting and requiring more precise definition, taking into consideration that the processes of converting low potential heat into electric power are considerably complex. The thermodynamic efficiency and various parameter influences are also analyzed. The choice of the plant working-medium at the temperature of exhaust gases of 350-380C is explained in detail.

Improvement of energy performance of gas main pipelines is ensured by energy saving during the transportation of natural gas. The power resources growing prices tendency impetuses to conduct energy-saving measures in the transportation of gas in the following areas: energy saving processes gas transportation, gas pumping energy saving appliances, use of waste energy [1–4].

At the compressor stations (CS) of gas mains pipelines is used centrifugal supercharger with turbine drive. Efficiency of gas turbine plant, is 23-28%. In modern gas turbine plant under operation the efficiency is higher. However, over 70% of heat is lost with exhaust gases. The temperature of the exhaust gas reaches 450-500°C, the gas losses is 60–120 kg/s.

Number of recovered heat for various types of gas turbine is based on the temperature: 20–32 MWtt for gas turbine complex is 10-4, 25–30 MWtt for GTC -16 and 28–46 MWtt for GTC -25 [5–9].

At the gas compressor stations are installed several gas turbines units. It depends on the performance and mode of operation of the pipeline, which determines the annual amount of recovered heat of the multi-workshops CS. Thus the indexes of CS gas efficiency (the ratio of the GTU CS gas-flow rate to the transport work) inferior to foreign at 7.12 m^3/(mil m^3• km) [3 , 4]. The use of combined cycle gas turbine (CCGT) with high-pressure steam generator and efficiency near to 40-44% will require significant capital expenditures, and the high-pressure mode of operation of pipeline reduces the effectiveness of their application. More effective is use of recycling steam turbine unit GTU with low temperature steam-generator unit organic working agent. Use of water vapor does not provide effective power generation due to low steam parameters : temperature 520–685K, pressure 2–3 Mpa.

Secondary energy sources (SES) of driving gas main pipelines can be used for heating, ventilation and warming of various objects, power production and additional quantity of mechanical energy, refrigeration [5-9]. Theretofore, these methods are not widely known. Share of SES usage for thermal needs of the CS is about 1-3% per year from the current amount of heat.

Due to common usage and development of geothermal energy abroad are generalized power plants that implement Rankine cycle with organic working medium (i.e Organic Rankine Cycle – ORC) [10–16]. Known recycling power plants at CS of gas main pipelines GTU Rolls-Royce RB211 with waste-heat steam utilization plant firm Ormat-Energy Converter. Power circuits of plant operates on Rankine cycle with an organic coolant n-pentane (н-C_5H_{12}) [13].

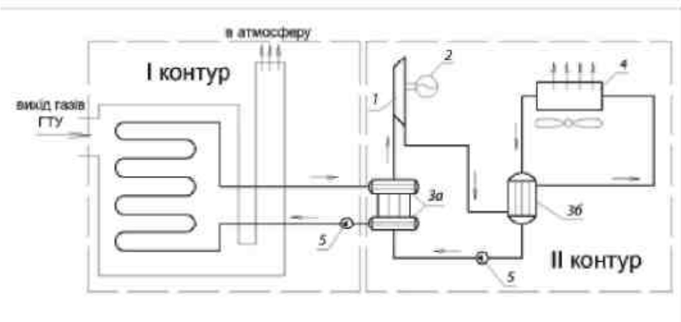

Fig. 1. Flowsheet of energy disposal power plant: *1* - turbine; *2* - generator; *3а* and *3б* - evaporators, regenerative heat exchanger; *4* - condenser; *5* – pump

GTU Rolls-Royce RB211 with a capacity of 28MW generation provides an additional generation of 6.5 MW electrical power. For personal use of unit (pumps, fans, etc.) the necessary capacity is 0.8 MW, remaining 5.7 kW can be transferred to an external network or consumed for compressor station. Similar studies are conducted in Ukraine [12–16].

For today, the OJSC "Gazprom" produce a water-steam turbine type K-6-1, 6 with capacity of 4–12 MW.

In the JSC "Sumy NPO n.a. MV Frunze" created gas turbine unit with capacity of 4 MW of close circuit and working fluid n-pentane [14].

However, efficiency data of cycles in professional literature either are not given or are contradictory [12–16].

Its known about the study, limited by working organic agent - n-pentane [10-16], some - n-hexane [13, 15] and benzene. Other substances are in the concrete unexplored. Payments are limited to water temperature (less than 200°C) plants cycle at higher temperatures are also more or less unexplored. Calculated data in professional literature is very scattered, its difficult to comparable them due to the lack of complete information.

In this regard, it is necessary to extend the theoretical and experimental researches on search and reasoning of rational thermal utilization schemes for waste treatment plants, selection of effective working agent and the optimal parameters of the power unit cycle.

Analysis of thermodynamic cycle parameters of energy disposal power plant and a choice of efficient working fluid is the purpose of this work.

Research results reported in this article relate to subcritical and supercritical cycle of power units. As working fluids were studied working agents R600, R600a, R601a, R602, R13в, R134a, R142в, R143a, R404a, R407a, R410a, R503в, R600a/R161, R600a/R141, R600a/R601, C_7H_{16}, C_8H_{18}, $C_{10}H_{22}$, NH_3/R170, other organic substances and their mixtures.

Thermodynamic efficiency of the cycle can be determined by the conversion factor (COF) and the coefficient of heat recovery. The thermal cycle efficiency (or COF) varies in the narrow range of 0,13-0,16 that is not adequately characterize the efficiency of cycles, and therefore more important selecting criterion of the working agent is a work that is carried out during steam expansion in the turbine.

In Fig.1 is shown the flowsheet of waste-heat utilization of the power unit. First circuit (I) includes a heat exchanger, pump 5, working agent circulation system, connected to the evaporator and the regenerative heat exchanger 3, 3 a, the second circuit - turbine with generator, evaporator, pump, air condenser and regenerative heat exchanger. In the first and second circuits is circulating one and the same working agent.

Cycles of the power unit is shown in Figure. 2.

In Table 1 are shown characteristics of working agents.

Table 1 Physicochemical properties of working agents

Substance	$t_{кр}$, °C	МПа	$t_{н.к.}$, °C	$t_{всп}$, °C	Flash limits	
					bottom	upper
Propane (C_3H_8)	96,67	4,25	-42,07	466	2,1	9,5
n-butane (C_4H_{10})	152,93	3,60	-0,5	431	1,5	8,5
i- butane (C_4H_{10})	134,0	3,70	-12,55	431	1,8	8,4
n-pentane (C_5H_{12})	196,65	3,37	36,0	284	1,47	7,8
n-hexane (C_6H_{14})	234,15	3,05	69,0	261	1,24	7, 5
n-heptane (C_7H_{16})	267,15	2,68	98,43	240	1,07	6,7
n- octane (C_8H_{18})	296,0	2,49	126,0	210	0,94	3,2
n-decane ($C_{10}H_{22}$)	344,65	2,096	174,1	208	0,60	5,5
ethane (C_2H_6)	32,68	4,88	-89,63	472	3,07	15,0
ammonia (R717)	132,25	11,15	-33,35	650	15,0	28,0
water vapor (H_2O)	374,15	21,77	100	–	–	–

Calculations are performed under the same hypotheses: the temperature difference between the combustion products and the working agent, 10°C, the efficiency of the turbine - 0.7-0.8; pump efficiency - 0,75-0,80; steam expansion process in the turbine ends in the single-phase area, condensation of steam after the turbine takes place in the air-cooled condenser, the temperature of the air 15°C (288,15 K).

As a part of the study and optimization cycles with many working agents in both subcritical and supercritical cycles in the single stage power plant, it was found that the maximum power production is provided in the supercritical cycle [17]. It should be noted that the use of a mixture of working substances is more effectively than pure substances.

In the Table 2 are shown large body of results.

Table 2 Thermal parameters energy disposal power unit *

Working agent	t_T, °C	P_T, кПа	$P_к$, кПа	m, кг/с	N, кВт/(кг/с	$\eta_ц$, %
i- pentane (i-C_5H_{12})	347	3200	80	0,3	60,8	14,4
n-butane (C_4H_{10})	347	3500	220	0,38	58,9	13,1
n-heptane (C_7H_{16})	347	4000	5,35	0,53	106,5	18,4
n- octane (C_8H_{18})	347	4000	1,6	0,54	109,6	18,9
n-decane ($C_{10}H_{22}$)	347	4000	1,5	0,59	114,7	19,4
water vapor (H_2O)	347	4000	550	0,057	17,8	10,4
C_7H_{16}(80 %) / H_2O(20 %)	347	4000	6,25	0,38	138,9	24,3
i- pentane (i-C_5H_{12})	347	6000	80	0,53	96,0	16,2
i- pentane (i-C_5H_{12})	297	6000	92	0,56	83,8	20,2
i- pentane (i-C_5H_{12})	247	6000	220	0,62	56,1	15,2

* P_T – steam pressure at the turbine; t_T – steam temperature at the turbine; N –available spec. gravity; generated by turbines $\eta_ц$ – thermal efficiency of the cycle; m – working agent consumption.

It will be seen from results of calculations, the specific capacitance produced in supercritical cycles with organic agents several times higher than in the cycles with water vapor.

The electric power generated increases with increasing of temperature steam at the turbine. The dependence of the specific operation of steam expansion in the turbine(Δi), and generated specific capacitance *(N)* on pressure is more complicated: at subcritical temperatures, pressure increasing (up to critical) leads to increase of Δi (and *N);* at the steam parameters close to critical

- to decrease of Δi *(N)*; at overcritical temperature increase of pressure leads to increase of Δi *(N)*. In addition to these parameters, to produced power level affects the vapor pressure in the condenser. With pressure increasing in the condenser a capacity of turbine is reduced by 8-12 %.

Superheat working agent temperature limitation of relative critical temperature [15] is not needed because the main limitation is the temperature of the thermal decomposition of organic compounds - hydrocarbons, rather than ignition temperature, whose influence can be reduced by introducing into the working agents various phlegmatizing agents (nitrogen dioxide carbon, fluorine- and bromine-containing additives, water vapor, etc..) to prevent ignition of gas mixture.

Changes in vapor temperature of i -pentane (R601a) at the turbine from 350 to 250 ° C leads to decrease of specific capacity, which is generated from 96.0 to 56.1 kW / (kg/s), i.e. 32.2%.

The minimum temperature difference between the coolant and the working agent, which determines the efficiency of heat transfer in the power unit elements Atmin. is materially affected by generated power level. Thus, the increase of Atmin from 3 to 10 K leads to a power decrease produced by 15-20%. Also effected by the efficiency value of the turbine and the pump. Power increase produced by 12-20% is obvious with decrease of air temperature (seasonal effect) from 25 to 0°C and below by changing the coolant temperature in air condenser.

The results are compared with minor figures on n-pentane cycle, combined with the professional literature.

In Fig. 3 are shown calculated data of the specific enthalpy steam drop in turbine according to the temperature and steam pressure at the turbine.

In accordance with results of various researchers, the use of n-pentane and i-pentane as the working agent in vapor pressure of 6.5 MPa and temperatures up to 350°C provides the expansion in the turbine of about 170-180 kJ/kg. In case of heptane usage (C_7H_{12})Δi = 208,6 kJ/kg; while the mixture is especially effective a noconstant boiling mixture (C_7H_{17} + H_2O) (80 % / 20 %), specific enthalpy vapor drop is Δi = 375,7 kJ/kg at steam pressure of 4,0 MPa. A mixture of carbohydrate with water steam reduces their flammability.

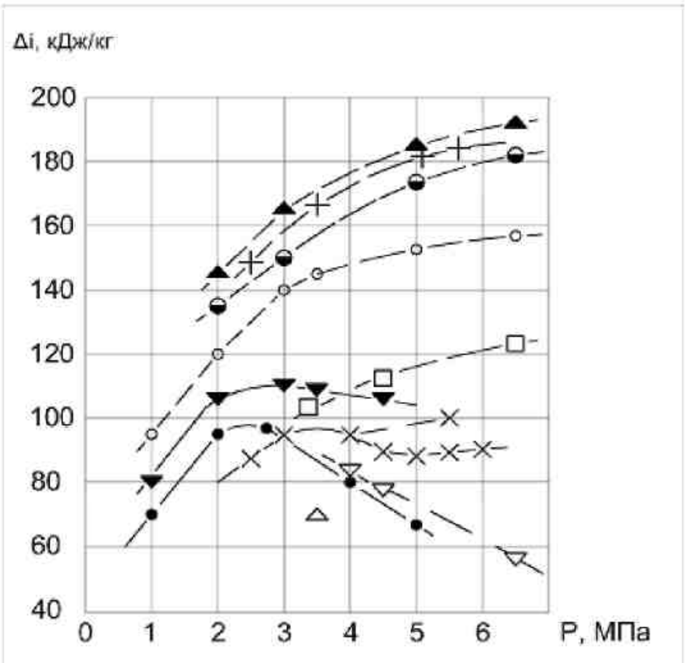

Fig. 3. Dependence of working steam expansion in the turbine on pressure and temperature: ● - n- pentane, *t* = 200 °C [12]; ○ - n- pentane, *t* = 300 °C [12]; △ - n- pentane, *t* = 200 °C [15]; ▽ - n- pentane, *t* = 220 °C [15]; ▼ - n- pentane, *t* = 220 °C [14]; □ - n- pentane, *t* = 300 °C [15]; × - mixture of i-butane + R141в(60/40, *t* = 200 °C (authors); +- n- butane, *t* = 350 °C (authors); ▲ - i- pentane, *t* = 350 °C (authors); ◒ - mixture of i- butane +i- pentane (40/60), *t* = 350 °C (authors)

Thus, comparing various organic agents, we see that the generation of electric power in the turbine with decane reaches to 114.7 kW/ (kg/s). Herewith the mixture C_7H_{16}(80 %) + H_2O(20 %) gives a possibility to increase a specific capacity up to 138,9 кW/(kg/s), i.e. in 17,2 %. Comparison results of specific steam drop enthalpy in turbines with different working agents at $t_п$ = 347 °C show for the heptane turbine specific steam drop enthalpy is 208.6 kJ/kg, and for a mixture of n-heptane (80%) + H_2O(20% – 375,7 kJ/kg. Cycle on a mixture of n-heptane (C_7H_{16})+water steam (H_2) is characterized by low compression work (7,3 kJ/kg and 2,74 кW) due to small cost of working substance (m = 0,38 kg/s), pressure in the condenser – 6,25 kPa, cycle efficiency – 24,7%. The results of numerical studies show the possibility energy production in the amount of 6882-16670 kW in the case of heat recycling from exhaust gas mass flow rate of 60-120 kg/s gas turbine type ГТН-16, ГТН-25, ГТН-32. As the working agent of power unit can be used organic substances - heptane (C_7H_{16}), octane (C_8H_{18}) or decane ($C_{10}H_{22}$) and noconstant boiling mixture with water vapor. Electricity generated can be used for personal needs of CS, drive АПОГ та and additional electric drive GPU that reduces power consumption of gas transportation.

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