Power plant on the basis of internal combustion engine with gas dropping in the technological furnace of oil refining plant

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Abstract. The main results of the evaluation of the technical and economic indicators of power plants based on internal combustion engines (ICE) that are integrated into the refinery process cycle are considered. The statistical processing of commercial offers has been carried out, which allow to evaluate capital investments in the main power equipment. The results of the calculation for the operating conditions of the power plant on its own gas of refining showed a good investment attractiveness of the project. The calculations found that the influencing factors can be ranked in descending order of importance: the cost of electricity, the rate of discount, capital investments in the object, the fee for the power supported for the reserve from the power system. Since the generator voltage of the internal combustion engine is 0.4 kV, the economic efficiency of the proposed power plant will be higher than the considered base case and it is advisable to produce electricity supply in the factory network on the low voltage side.

Keywords: fan, technological furnace, waste-heat boiler, pump, smoke exhauster, electric generator, coefficient of efficiency, specific fuel consumption, cost price

1. Introduction

Refining of oil feedstock at refineries is characterized by high costs of heat and electricity. Thus, according to the data of the energy audit of Saratov Refinery Company the process of primary separation in ELOU-AVT-6 is characterized by the consumption of 11.65 kW·h of electricity; 54.4 MJ of thermal energy and 38.34 kg of fuel equivalent per ton of original petroleum. At the same time, during the operation of the process equipment, combustible gases are formed and sent to the fuel ring of the plant, emergency emissions of combustible components and hydrocarbon slurry, which, after appropriate processing can be involved in the fuel and energy balance of the enterprise in the form of combustible secondary energy resources (SER).

In the article [1] it is proposed to organize energy technological schemes based on gas turbine plants with the dropping gases into utilization apparatuses or tube furnaces. However, it is necessary to understand that gaseous fuel, including low-calorie, can be used in both diesel and spark internal combustion engines [2]. Moreover, a number of studies have shown that when using a dual fuel supply system in a diesel engine, namely, supplying diesel liquid fuel as a portion of ignition fuel to an air-fuel mixture consisting of air and gas fuel (waste gas in oil refining technology), a decrease in performance values is only 20-30%, while saving diesel fuel reaches 70-90% compared with the work on the commonly used fuel [3].

2. Statement of the problem

As already noted, in recent times, projects to create a mini thermal power plant and, for the most part, based on the internal combustion engine, become relevant. In [4] the features of the thermal mode of the internal combustion engine and the design schemes of the heat utilization unit are considered, and a schematic diagram of the automation system is proposed, which provides the standard temperatures of coolants (coolant and oil, combustion products, network water) when the electrical and thermal loads of the consumer change. At the same time alternative fuels that are alternative to natural gas are considered, for example, such as associated petroleum gas. The economic feasibility of building power plants on this type of fuel is presented in the publication [5].
Considering the above it seems highly relevant to assess the technical and economic indicators of a combined installation based on an internal combustion engine with the dropping of gases into a technological tubular refinery furnace. As an energy-power plant we propose to consider the medium-speed four-stroke engine 9L32. The main advantages of this series of engines are reduced overall dimensions and weight, high performance of the working process, high fuel efficiency (185 g/(kW·h) at 100% load and 191 g/(kW·h) at 25%; engine weight 51 tone; maximum combustion pressure 19 MPa) and a wide range of load control (up to 25% of rated power), as well as the possibility of deep unloading. In work [6] it is noted that ICE operating with low and medium crankshaft rotation speed (up to 900 rpm) are the most efficient and economical. And initially, these engines were designed and operated on natural or associated gas. An important circumstance in favor of energy sources on the basis of a gas turbine or an internal combustion engine is the possibility of their block delivery to the construction site, quick commissioning and warranty service by equipment manufacturers.
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In Fig. 1 shows the basic thermal scheme of the proposed installation. It works as follows: the fuel is supplied to the internal combustion engine (1) with which an alternating current electric generator (2) is connected, the combustion products are sent to the process furnace (3). Additional fuel and air with the fan (5) are supplied to the furnace to maintain the capacity. The use of the potential of the exhaust gases behind the furnace block is performed in a steam recovery boiler (4), into which feed water is pumped (6). The cooled products of combustion after the recovery boiler by the smoke exhauster (8) are sent to the chimney (7).

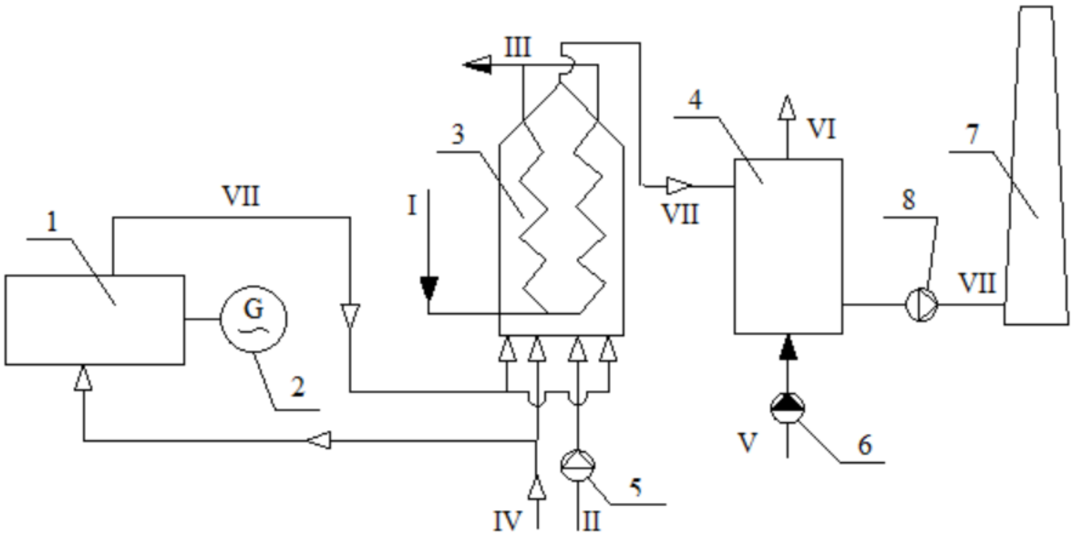

Figure 1. The scheme of the combined heating of the target product with heat utilization of the combustion gases of the tubular furnace: 1 – internal combustion engine; 2 – electric generator; 3 – oven unit; 4 – waste heat boiler; 5 – fan; 6 – pump; 7 – chimney; 8 – smoke exhauster; I – raw materials; II – air; III – heated mixture; IV – fuel; V – feed water; VI – saturated steam; VII – combustion gases.

The preliminary estimates [7] shown that from 1 kW of electric power of a power plant based on internal combustion engines it is possible to obtain up to 1.5 kW of thermal energy in special utilization circuits: cooling of flue gases – 25-45 %; oil cooling – 8-20 %; cooling of the case and casing – 30-50 %.

3. Theory

The calculation of the basic parameters of the thermodynamic cycle of the engine, necessary for further calculations of the heat recovery boiler or process furnace is based on the well-known technique of V.I. Grinevetsky and E.K. Masinga [8]. In this case the engine cycle is represented by a set of sequentially occurring processes: cylinders filling, compression, fuel combustion, burnout of residual components, expansion and release. The main calculated dependences are obtained by jointly solving the equation of state of an ideal gas, the equations of balance of energy and matter. The process of dropping exhaust gases and its impact on the process of filling in the framework of these approaches is excluded from consideration, which does not reduce the practical accuracy of the engineering calculation.

According to [8], the effective efficiency of the engine is determined by the ratio, rel. units:

$$\eta_e = \eta_i \cdot \eta_m \,, \tag{1}$$

where $\eta_i = \dfrac{R \cdot L \cdot p_i \cdot T_s}{Q_l^w \cdot p_s \cdot \eta_F}$ – is the indicator coefficient efficiency of cycle, rel. units; $R = 8.314$ kJ/(kmol·K) - is the universal gas constant; L – is the actual number of moles of air involved in the combustion of 1 kg of fuel, kmol/kg; p_i – is the average indicator pressure related to the full stroke of the piston, MPa; T_S – is the temperature in the purge air receiver, K; Q_l^w – is the net calorific value of fuel, kJ/kg; p_s – is the boost pressure, MPa; η_F – is the filling ratio, referred to the full stroke of the piston, rel. units; η_m – is the mechanical coefficient efficiency, rel. units.

Specific effective fuel consumption is determined by the expression, kg/(kW·h):

$$b_e = 3600 / (\eta_i \cdot \eta_m \cdot Q_l^w) \,. \tag{2}$$

An important indicator in the calibration calculation of the internal combustion engine is the effective power that can be determined by the ratio, kW:

$$N_e = V_s \cdot p_e \cdot n \cdot z \cdot i / 60 \,, \tag{3}$$

where V_s – is the working volume of the cylinder, m^3; p_e – is the average effective pressure, MPa; n – is the crankshaft rotation speed, rpm; z – is the number of working strokes per one revolution of the crankshaft; i – is the number of cylinders, pcs.

To calculate the fuel economy during the integration of the internal combustion engine in the refinery process, you can use the modified ratio proposed in the work [9]. Fuel economy in the absence of outside consumers of thermal and electrical energy is determined by the following expression, kg/year:

$$\Delta B = b_{ge} \cdot Э_{eng}^{y} + b_{tb} \cdot Q_{tb} - B_{eng} \,, \tag{4}$$

where b_{ge} – is the specific fuel consumption in a replaceable installation for the generation of electricity, kg/(kW·h); b_{tb} – is the specific fuel consumption per unit thermal output of the tube furnace, kg/GJ; $Э_{eng}^{y}$ – is the annual generation of electric energy by the engine, kWh/year; Q_{tb} – is the heat used is useful in a tube furnace, GJ; B_{eng} – is the annual fuel consumption of the engine, kg/year.

To assess the economic efficiency of creating such installations, it is necessary to obtain correlations between the electric motor power and its cost. In the Fig. 2 using data [10-12] such data processing was performed, which allows to predict the cost of the main and auxiliary equipment of power plants equipped with internal combustion engines.

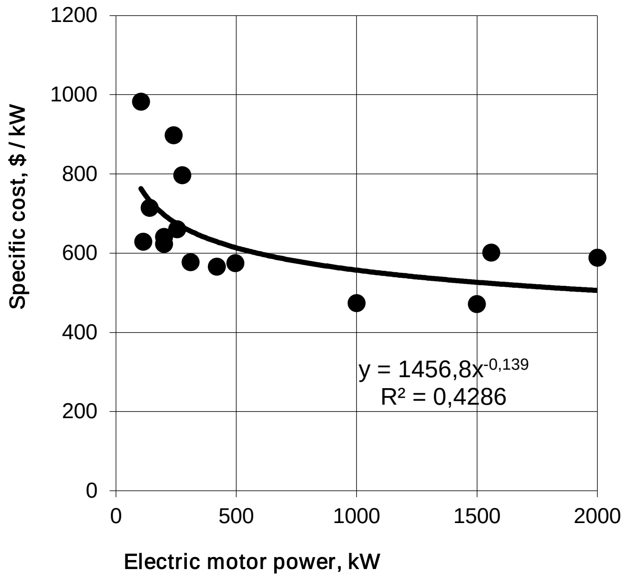

Figure 2. Statistical data processing at the specific cost of power stations based on the internal combustion engine.

The analysis of the market and proposals for the creation of energy sources based on diesel and gas piston units showed a very significant cost spread. For European and North American manufacturers a regression ratio was obtained, but the statistical characteristic of the approximation accuracy is only R^2=0.4286, which can be explained by the pricing policy. The cost of manufacturing of gas waste heat boiler was estimated 8-12 $/kW, water and oil waste heat boiler- 14-22 $/kW at the end of 2000 [7].

The magnitude of the integral effect for the variant of the internal combustion engine with the dropping of combustion gases in the refinery process furnaces is determined by the formula, $:

$$E_{\text{int}} = \sum_{t=0}^{T_{sl}} (R_t - \sum Z_t) \cdot \frac{1}{(1+E)^t} \cdot (1-n) - K \ , \tag{5}$$

where R_t – is the result achieved in the calculated year t, $/year; $\sum Z_t$ – are the operating costs associated with the operation of the energy source in year t, $/year; E – is the discount rate, 1/year; t – is the number of the calculated step (0, 1, 2 ... T_{sl}); T_{sl} – is the estimated service life of the object, years; n – is the coefficient taking into account income tax; $K = \sum_{t=0}^{T_{sl}} K_t \frac{1}{(1+E)^t}$ – is the cited investment in the implementation of the investment project, $; K_t – is the capital investment in the construction project in the year t, $.

The peculiarities of the refinery's operation consisting in fuel self-sufficiency make it possible to exclude from the economic result in expression (5) the monetary equivalent of the fuel which saved and consumed during the operation of the engine together with the process furnace and to allocate only the component of electricity.

An important point in assessing the technical and economic indicators of energy projects is to bring them to comparable working conditions, since two options are possible. The first option to create a power plant provides for an increase in the productivity of the process furnace and the recovery boiler with a simultaneous increase in electricity consumption, i.e. this option provides for an increase in the installed capacity of the enterprise's electrical receivers. The second option (considered in this work) assumes the unchanged installed electric capacity of the enterprise and the fixed performance of the heating furnace for raw materials and the waste heat boiler for the generated steam due to compensation for the missing part of thermal energy released in the process furnace by burning the main fuel. In this case, there will be fuel savings due to the organization of energy technology combination of the processes of heating the raw materials and the generation of electric energy in the internal combustion engine.

4. The experimental results

Results of calculations for scheme (Fig. 1) using ratios (1-4) for 9L32 engine with a boost pressure of 0.35 MPa, residual gas temperature of 800 K, actual compression ratio 16, excess air coefficient 2.2, mechanical efficiency 0.91, cylinder diameter 320 mm, piston stroke 400 mm and crankshaft rotation speed of 750 rpm are presented in Table 1. Primary gas of petroleum refining is accepted as a fuel [13].

Table 1. Results of calculation of the engine on characteristic modes

Indicator	Unit of measurement	Ambient temperature, ^oC				
		-30	-15	0	+15	+30
Gas temperature at the end of the expansion process (exhaust)	^oC	672	687	703	721	739
Specific effective consumption of natural fuel	kg/(kW·h)	0.1544	0.1536	0.1531	0.1528	0.1527
Effective efficiency	%	45.74	45.97	46.12	46.21	46.26
Effective engine power	kW	5611.4	5133.2	4726.5	4376.2	4071.0
Engine thermal power	MJ/s					
- used in the furnace (flue gas temperature 400 °C)		2.818	2.706	2.622	2.567	2.520
- used by the waste heat boiler (flue gas temperature 220 °C)		1.766	1.607	1.475	1.363	1.267

From the Table 1 we can see that a decrease of the ambient temperature (air) is leads to an increase in power, while the effective coefficient of efficiency decreases, which can be explained by a decrease in the maximum cycle temperature. The annual electricity production for the conditions of the Middle Volga region will be 38.936 million kWh, this will require up to 5.955 million kg of fuel, which is 43% of the gas currently discharged to the flare Saratov refinery. The calculations to determine the composition of the products of combustion showed that they will consist of 4.54 vol. % CO_2; 10.53 vol. % H_2O; 0.01 vol. % SO_2; 9.95 vol. % O_2 and 74.97 vol. % N_2.

In the Table 2 the annual indicators of the proposed scheme of the energy complex with the dropping of gases into the refinery process furnace are presented. The additional initial data on economic indicators are: the coefficient of contributions to the social insurance fund A_{cc}=0.39; the staff for the newly introduced installation is 20 people; p_{rep}=0.02; the base rate of discount E=0.1; construction period T_{build}=1 year; lifetime T_{expl}=30 years; the depreciation ratio p_{depr}=0.12; coefficient taking into account the tax on profit n=0.2 and the specific fuel consumption at the replaced power plant for the base case b_{es}=0.25 kg/(kW·h). The base cost of electricity is 4.6 ¢/(kW·h) and the charge for installed capacity is 21.63 $/kW. The specific fuel consumption per unit of useful heat output of the tubular furnace for the considered variant of the installation of an internal combustion engine is b_{tf}=28.7 kg/GJ.

Table 2. Results of calculation of technical and economic indicators of installation

Indicator	Unit of measurement	Value
1. Capital investment in equipment	million $	2.460
2. The cost of design work, installation and commissioning of equipment	million $	1.230
3. The annual power generation	million kW·h	38.936
4. The annual volume of useful thermal energy of combustion products	GJ	125044.593
5. Annual fuel consumption of the engine	million kg	5.955
6. Fuel economy	million kg	6.097
7. The cost of repair and maintenance of equipment	thousands $/year	73.800
8. Depreciation charges	thousands $/year	442.846
9. Salary with charges	thousands $/year	10.692
10. The cost of compensation for negative environmental impact	$/year	144.954
11. Other types of expenses	thousands of $/year	9.600
12. The cost of ensuring the reliability of power supply	thousands $/year	121.369

13. Net present value (NPV) for the life of 30 years	million $	6.804 / 7.636
14. Discounted payback period	year	4.9 / 4.5
15. Yield index	$/$	2.84 / 3.07

Note. In the numerator the indicators of economic efficiency of the proposed installation, taking into account fees for maintaining electrical power are shown, in the denominator - without such fees.

When considering the received technical and economic indicators, it can be seen that the charge for the reservation of electrical capacity primarily effects on the value of net present value (increases by 12.2%) and the profitability index (increases by 8.1%), while the payback period decreases by 8.8%.

Taking into account the uncertainty in the external economic conditions, we evaluated the degree of influence of the main factors on the relative effectiveness of the installation proposed for implementation (Fig. 3). The factors subjected to variation in the process of analysis can be divided into two components:

1) affecting on the amount of cash inflows (tariff for electric energy, discount rate);

2) affecting on the amount of costs (capital investment, payment for electrical power).

An important element of the economic analysis is the determination sensitivity index of NPV, which is the ratio of the deviation to its base value, reduced to a 1% change in the variable external parameter. At the same time, depending on the degree of influence of factors on the criterion value, they can be divided into three sensitivity groups: high, medium and low.

On the Fig. 4 the results of alternative fuel economy calculations using expression are shown (5).

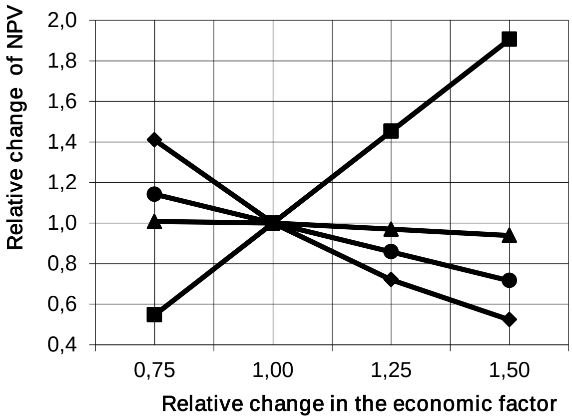

Figure 3. The effect of the relative change in economic factors on the relative value of NPV: ● - capital investment; ■ - the cost of electricity; ♦ - discount rate; ▲ - fee for ensuring the reliability of power supply.

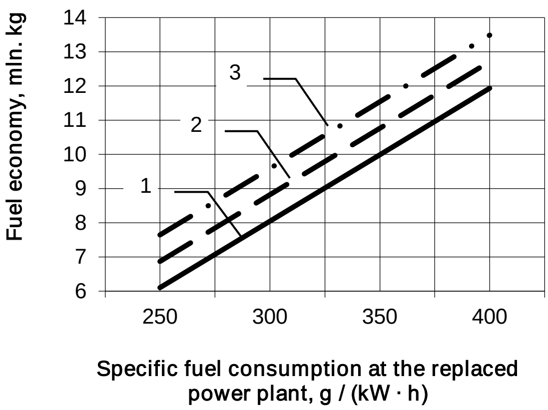

Figure 4. Fuel economy depending on the specific fuel consumption at the power plant being replaced and with different fuel consumption by the process furnace: 1 – b_{tf}=28.5 kg/GJ; 2 – b_{tf}=38.0 kg/GJ; 3 – b_{tf}=47.5 kg/GJ.

As can be seen from Fig. 3 and taking into account the definition of sensitivity index of NPV, the influencing factors can be ranked in descending order of importance: the cost of electricity, the rate of discount, investment in the facility, payment for the power supported for the reserve from the power system. Since the generator voltage of the internal combustion engine is 0.4 kV, the economic efficiency of the proposed power plant will be higher than that considered at an electricity cost of 4.6 ¢/(kW·h) and it is advisable to produce electricity to the network on the low voltage side.

5. Discussion of results

It also can be noted that the fuel efficiency of the proposed energy complex increases as the specific fuel consumption in the replacement power plant increases. So while reducing the electric efficiency of the power plant from 50 to 31%, the specific fuel consumption increases by 61%, which leads to an increase in fuel

economy by 1.96 times. With the increase in fuel consumption in the refinery process furnace 1.33 times, an increase in fuel economy by 12-13% is also observed.
Thus, based on the results of the preliminary studies, we can conclude that the use of internal combustion engines as an own source of power supply allows solving a number of important production problems at a refinery with high economic efficiency. The main advantages of creating power plants in the structure of the refinery are:
- increase energy security and security of the enterprise;
- improving the reliability and quality of energy supply;
- reducing the cost of purchasing electricity from the power system;
- release of financial resources by reducing the volume of purchased electricity, which the company can use for its own development.
- reducing the cost of thermal energy for internal consumption or fuel consumption in a process furnace.

6. Conclusion
The use of internal combustion engines at oil refineries when organizing their own generation sources based on 9L32 engine is characterized by high rates of thermal efficiency: energy efficiency - 46.17%; specific effective fuel consumption - 152.9 g/(kW·h). With the implementation of the proposed technical solutions, the annual electricity generation will be 38.936 million kW·h and heat energy 125044.603 GJ. At the same time the fuel economy of the process furnace is estimated at 6.097 million kg. The economic efficiency of the project amounted to 7.636 million $ over 30 years of operation with a payback period of 4.5 years and a profitability index of $ 3.07 $/$. As a result of the calculations, it was established that the most significant factor influencing the economic efficiency indicators is the cost of electricity (the cost of electricity based on internal combustion engines is estimated at 1.9 ¢/(kW·h)). This circumstance will facilitate the implementation of such projects in the context of constantly growing tariffs.
Thus, the results obtained in the assessment of the possibility of creating a power plant based on the 9L32 brand internal combustion engine in terms of determining operational parameters for its operation on refinery gas and potential fuel economy when integrated into the thermal circuit of a refinery have a scientific novelty.

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