ENERGETICS. HEAT ENGINEERING.

ELECTRICAL ENGINEERING

ЕНЕРГЕТИКА. ТЕПЛОТЕХНІКА.

ЕЛЕКТРОТЕХНІКА

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DETERMINATION OF ECONOMIC FEASIBILITY

OF HEAT SUPPLY FROM NPP FOR OILFIELD

В.П. Кравченко, О.М. Сорокін. **Визначення економічної доцільності забезпечення теплопостачання нафтового родовища від ядерної енергетичної установки.** Видобуток нафти в Україні постійно знижується. У цих умовах є доцільним використовувати третинні методи інтенсифікації нафтовидобування, що збільшують рухливість нафти. До них відноситься метод, заснований на закачуванні в пласт гарячого теплоносія для підвищення температури нафти, що призведе до зниження її в'язкості і збільшення рухливості. *Мета:* Метою роботи є техніко-економічне обґрунтування доцільності побудови і використання ядерного нафтовидобувного комплексу з метою підвищення нафтовидобування на родовищах, що знаходяться в пізній стадії розробки, на прикладі Охтирського родовища (Україна). *Матеріали і методи:* Охтирське родовище вважається найперспективнішим в Україні. Виявлений сировинний потенціал може забезпечити стабільний видобуток нафти близько 2 млн. т щорічно протягом 50…60 років. За результатом аналізу схеми розташування видобувних свердловин, проведеного на підставі аерокосмічних знімків, виділено три групи свердловин. З урахуванням рози вітрів було визначено оптимальне розташування атомної електростанції відносно р. Охтирка. Запропоновано для забезпечення потреб нафтогазовидобувного підприємства використовувати серійний блок атомної електростанції з реактором ВВЕР-1000. *Результати:* Було розроблено і розраховано схему теплофікаційної установки для турбіни К-1000-5,8/50, що забезпечує підготовку технологічного теплоносія, який закачують в нагнітальні свердловини. Розроблено схему і визначено основні конструктивні характеристики теплової мережі для доставки технологічного теплоносія від АЕС до свердловин. Визначено, що при витраті теплоносія зі швидкістю 675 т/год. електрична потужність блоку дорівнює 935,6 МВт. В результаті розрахунку прибутку від продажу електроенергії і додаткової нафти за рік з урахуванням річних експлуатаційних витрат було визначено прибуток в розмірі 1063,37 млн. USD.
Ключові слова: ядерний нафтовидобувний комплекс, теплова мережа, приведені витрати.

V.P. Kravchenko, O.M. Sorokin. **Determination of economic feasibility of heat supply from NPP for oilfield.** The oil production in Ukraine is constantly decreasing. In these conditions it is appropriate to use tertiary methods of intensifying in oil production which increase the mobility of oil. These include a method based on injection into the layer a hot water to raise the temperature of oil that lead to a decrease its viscosity and increase mobility. *Aim:* The aim of this research is a technical economic feasibility study of constructing and using the nuclear power complex for oil production in order to increase the oil extraction from oilfields in their late stages of production by the example of Okhtyrka oilfield (Ukraine). *Materials and Methods:* Okhtyrka oilfield is considered the most promising in Ukraine. The explored raw material potential can provide the stable oil production about 2 millions tones annually during 50...60 years. On the basis of aerospace photos the oilfield can be divided into three areas which are called North, Central and South. The possible nuclear power plant location selected on the basis of wind rose relative Okhtyrka city and heating networks scheme from NPP to the injection wells. *Results:* It was developed and designed the key diagram of turbine plant K-1000-5,8/50 with a cogeneration plant which provide the technological coolant for injection into the wells. In rated mode the turbine with cogeneration plant provides 675 t/h of technological coolant at temperature of 250 °C and has electrical power 935.6 MW. As a result of calculating the profit from the sale of electricity and additional oil per year with account of annual operating costs, we determine that the profit equal to 1063.37 millions USD.
Keywords: nuclear power complex for oil production, heating network, reduced costs.

Introduction. The average ultimate oil fields output in different countries and regions ranges from 25% to 40% [1]. Therefore to improve the efficiency of oilfields is an actual task today. The studies, which were conducted in Ukraine, shown that using the thermal methods increases oil produc-

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tion more than three times, but other sources provide more modest estimate. So, in [2] indicated that using of thermal methods will increase oil output by 11...33%. For this purpose today the steam generators are installing directly at the wells (US [3]) or, for example, nuclear power plants (NPP) are building to ensure production of viscous oil by coolant (Canada [4]).

After 1972 oil production in Ukraine is constantly decreasing. This is primarily due to the large output of reserves in major oilfields, and their entry in the late stages of development, which is accompanied by a high percentage of water in wells and reduce their production.

In these conditions it is appropriate to use tertiary methods of intensifying in oil production [4], which increase the mobility of oil. These techniques can increase the rate of production of oil up to 60...70%. These include a method based on injection into the layer a hot water to raise the temperature of oil that lead to a decrease its viscosity and increase mobility. In turn, *J. Burger et al.* [5], and *N.K. Baibakov* [6] stated that for the preparation of hot water for further injection into a layer, it is advisable to use nuclear power plants.

The aim of this research is a technical economic feasibility study of constructing and using the nuclear power complex for oil production in order to increase the oil extraction from oilfields in their late stages of production by the example of Okhtyrka oilfield (Ukraine).

The nuclear power complex for oil production consists of NPP, heating networks, which deliver technology coolant (TC), that is hot water, to the injection wells.

Materials and Methods.

Development of heating networks scheme for Okhtyrka oilfield. Okhtyrka oilfield is considered the most promising in Ukraine, but the existing resource base can not guarantee significant growth of oil and gas. Today has been a steady drop in oil production in most of the oilfields in Ukraine on 5...15 % annually. In this sharp decline in funding for geological research and the rising cost of operations in recent years have led to the reduction of deep prospect drilling. Hence the need to use of modern technologies of production. According to specialists of JSC "Ukrnafta", the explored raw material potential can provide the stable oil production about 2 mln. tones annually during 50...60 years [7].

Capacity of the Okhtyrka oilfield currently is 135 tonnes per hour. Based on the accepted value of 5 m^3 hot water per 1 m^3 of oil, i.e. the technology coolant consumption is 675 tonnes per hour.

On the basis of aerospace photos the oilfield can be divided into three areas (Fig. 1), which are called Northern, Central and South. Fig. 1 shows a possible nuclear power plant location selected on the basis of wind rose relative Okhtyrka city and heating networks scheme from NPP to the injection wells. Table 1 shows the main characteristics of the area. Capacity of each area is defined by the number of wells, and average capacity of 18.75 tons per day.

Methods of the technical economic comparison. The reduced costs adopted as a comparison criterion [8]:

$$EAC=ROI \cdot CAPEX+OC, \qquad (1)$$

where ROI – return on investment index, $ROI=0.12$;

  $CAPEX$ – capital expenditure;

  OC – annual operating costs [8, 9].

Annual operating costs calculated by the following formula:

$$OC=OC_{fuel}+OC_{ee}+OC_{tw}+OC_{inv}+OC_{op}, \qquad (2)$$

where OC_{fuel} – annual costs for fuel:

$$OC_{fuel}=AC_{fuel} \cdot C_{fuel}, \qquad (3)$$

C_{fuel} – fuel costs (700 thou. USD);

AC_{fuel} – annual fuel consumption (41 cassettes);

OC_{ee} – annual costs for electric energy:

$$OC_{ee}=AC_{ee} \cdot C_{ee}, \qquad (4)$$

C_{ee} – cost of electricity, $C_{ee} = 0.04$ USD/kWh;

AC_{ee} – annual electricity consumption, kWh;

OC_{tw} – cost of raw water treating (OC_{tw}=0.3 USD/m^3);

OC_{inv} – annual depreciation costs of capital investment and maintenance:

$$OC_{inv}=D_r \cdot CAPEX+OC_{rep}=D_r \cdot CAPEX+0.1 \cdot D_r \cdot CAPEX=1.1 \cdot D_r \cdot CAPEX, \qquad (5)$$

$D_r \cdot CAPEX$ – depreciation costs (depreciation rate D_r is 0.06);

OC_{rep} – cost of current repairs (10…20 % of depreciation costs [9]);

OC_{op} – annual costs for personnel and other general expenses:

$$OC_{op}=1.2 \cdot OC_{pers}+0.22 \cdot D_r \cdot CAPEX, \qquad (6)$$

where OC_{pers} – annual personnel costs.

Considering that personnel costs at facilities which compare are equal, however, these costs in variable part of the resulted expenses can be ignored. Then the final formula for the variable part of these expenses is as follows:

$$EAC=0.1992 \cdot CAPEX+OC_{fuel}+OC_{ee}+OC_{tw}. \qquad (7)$$
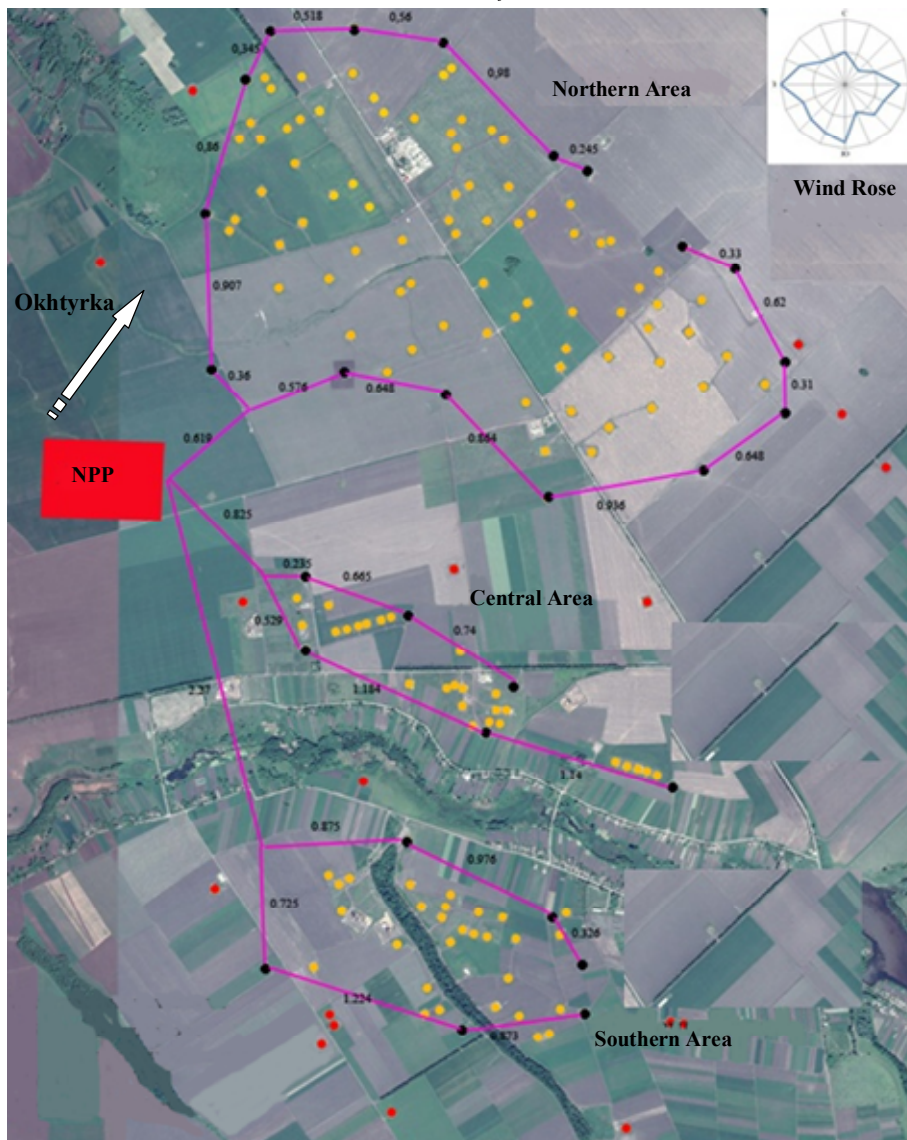

Fig. 1. Location of wells at Okhtyrka oilfield (distance between the injection wells in km)

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Table 1

Characteristics of the oilfield areas

Area	Number of producing wells	Production of oil, m³/h	Estimated TC consumption, m³/h
Northern	99	74.25	371.25
Central	35	26.25	131.25
Southern	46	34.5	172.5

The calculation of the heating networks "NPP – injection wells". According to the scheme of heating networks shown in Fig. 1, we prepared algorithm and conducted the calculation of the resulted expenses in thermal network that consists of three sections. Each section consists of two branches – southern and northern.

We calculated the heating networks considering the following characteristics:
– diameters and cost of pipelines;
– number, power and cost of pumps;
– cost of thermal insulation;
– energy costs for pumping of coolant.

Algorithm of hydraulic calculation and determination of the costs of pipelines, pumps and thermal insulation are given in [10]. When calculating the network the diameters of pipelines at each site were selected in terms of the minimum reduced costs.

The results of calculating the costs of pipes, pumps and insulation, as well as the required pumps power with optimum diameters of pipelines are shown in Table 2.

Table 2

The results of calculation of the main characteristics of heating networks

Oilfield area	Coolant consumption, t/h	The length of the TC pipelines, m	TC temperature at the entrance to the well, °C	TC temperature at the exit from the well, °C	TC pipelines costs, USD	Pump costs, USD	Thermal insulation costs, USD	The cost of electricity for pumping, USD/h	Reduced costs, USD/year
Northern	371.25	10326	236	221.5	71313	25715	15474	17177	39588
Central	131.25	5319	242.85	227.4	18702	4767	8451	5003	11361
Southern	172.5	7269	238.4	226.65	36901	7373	15255	10969	22827
Total	**675**	**22295**	**238**	**223.9**	**126916**	**37855**	**39180**	**33149**	**73776**

The calculation of cogeneration plant for TC preparation. The key diagram of turbine plant K-1000-5,8/50 with a cogeneration plant is shown in Fig. 2. The results of calculation of parameters in key points of cogeneration plant are shown in Table 3.

Table 3

The main parameters of cogeneration plant

| Heater	G of steam, kg/s	Temperature of steam, °C	Pressure of steam, MPa	TC temperature at entrance, °C	TC temperature at exit, °C	TC enthalpy at entrance, kJ/kg	TC enthalpy at exit, kJ/kg
PSV1	4.982	66.5	0.024	30	50	157.1	268.8
TH1	3.687	88.9	0.061	50	86.4	268.8	345.9
TH2	3.933	130.9	0.121	86.4	126.4	345.9	423.7
TH3	4.601	188.81	0.249	126.4	182.7	423.7	516.7
TH4	12.649	158.8	0.564	182.7	156.4	516.7	642.8
TH5	5.185	177.2	0.893	156.4	175	642.8	687.7
TH6	9.213	198.3	1.44	175	196.4	687.7	806
TH7	12.269	222.9	2.377	196.4	221.3	806	935.1
TH8	15.46	272	5.8	221.3	250	935.1	1085
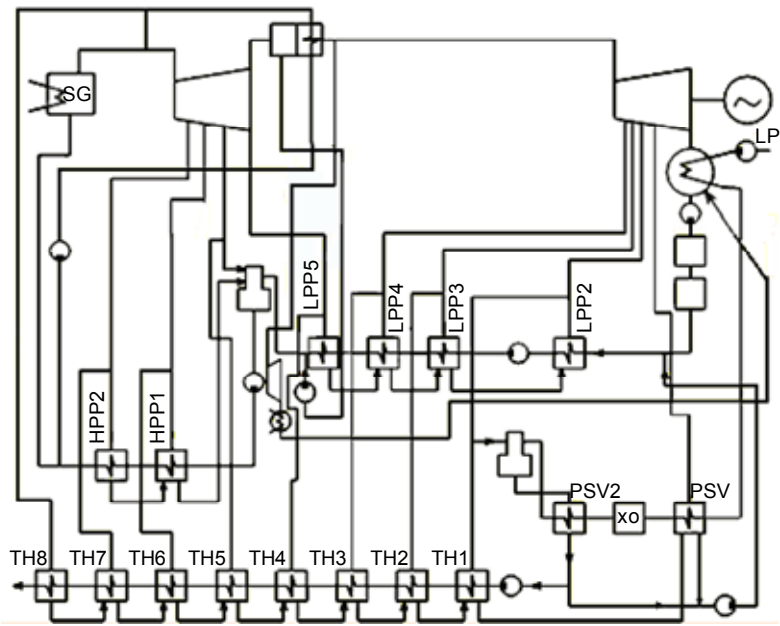
Fig. 2. The key diagram of turbine plant K-1000-5,8/50 with a cogeneration plant:
LPP – low-pressure preheater, HPP – high-pressure preheater, SG – steam generator, LP – line pump

As a result of the calculations of the design circuit of turbine plant K-1000-5,8/50 without cogeneration plant [11], we found that if steam feed rate is 5189 t/h then turbine plant capacity is 1022 MW. Cogeneration plant performs the following functions: heating water in the primarily condenser and in the raw water heater up to 50 °C, chemical water treatment, feed-water preheating, deaeration and heating in eight technological heaters. In rated mode the turbine with cogeneration plant provides 675 t/h of technological coolant at temperature of 250 °C and has electrical power 935.6 MW.

Results. The cost of the nuclear power complex for oil production consists of the costs of cogeneration plant, NPP, and heating network. The cost of cogeneration plant can be defined as the sum of the costs of technologic heaters and costs of strapping and installation (strapping and installation costs approximately 50% of the technologic heaters costs). The first three cascades of technologic heaters are made of steel mark 20. The other five – made of stainless steel (stainless steel in pipes in 7.36 times more expensive than carbon steel). Given that the cost of heat exchangers are not directly proportional to cost of pipe still, we decided that the cost of heat exchangers that made of stainless steel in 7 times greater than made of steel mark 20.

The cost of raw water heater PSV-200-7-15 is 53900 USD. Water flow consumption through the heater is 800 t/h. Thus, each step of heating conventionally "contains" $\mu = 675/800 = 0.84$ of heater.

The integrated value of technologic heaters is

$$C_{TH}^{SUM} = C_{TH} \cdot n \cdot \mu + C_{TH} \cdot m \cdot z \cdot \mu,$$

where C_{TH} – the cost of raw water heater PSV-200-7-15;

n – number of cascades of technologic heater that made of steel mark 20 (n=3);

m – number of cascades of technologic heater that made of stainless steel (m=5);

z – coefficient considering differences in the cost of raw water heater making from various types of steel (z=7).

After substituting all known values, we got that

$$C_{TH}^{SUM} = 1.721 \cdot 10^6 \text{ USD}.$$

The cost of the cogeneration plant, including installation costs, will be calculated as

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$$SUM_C=1.5 \cdot C_{TH}^{SUM}=2.6 \cdot 10^6 \text{ USD}.$$

Finally, including the costs of deaerator, raw water heater and chemical water treatment, the total cost of cogeneration plant will be calculated as

$$SUM_{FIN}=1.5 \cdot SUM_C=3.9 \cdot 10^6 \text{ USD}.$$

The volume of additional oil will be

$$V_{add}=V_a \cdot (\varepsilon-1),$$

where V_a – the annual output of Okhtyrka oilfield;

ε – increasing coefficient of oil production with hot water pumping.

This coefficient was determined according to Table 4 [12]. Dependence can be described by polynomial of degree 6:

$$\varepsilon = -7.26 \cdot 10^{-13} t^6 + 8.77 \cdot 10^{-10} t^5 - 4.3 \cdot 10^{-7} t^4 + 1.1 \cdot 10^{-4} t^3 - 1.5 \cdot 10^{-2} t^2 + 1.1t - 30.9.$$

When the technological coolant temperature at the entrance to layer is 223.9 °C, the coefficient ε is 10.87. Accordingly, the amount of additional oil will be $9.503 \cdot 10^6$ m³/year. With oil price is at level of 31 USD/bbl, the total profit from the sale of additional oil will be 1.853 billion USD.

Annual electricity supply can be determined by the formula

$$E=N_n \cdot (1-b) \cdot T \cdot K,$$

where N_n – nominal capacity of nuclear power unit;

b – part of electricity that goes to its own needs, b=9 %;

T – number of hours in a year;

K – capacity factor, K=0.82.

With cost of electricity is at level of 0.026 USD/kWh, the profit from electricity sales will be 155.5 million USD.

Total annual profits will be 2.008 billion USD.

Table 4

Dependence of increasing coefficient of oil production with hot water pumping (ε) on temperature of oil

t, °C	80	90	100	110	120	130	140	150
ε	1.206	2.031	2.425	2.862	3.342	3.866	4.433	5.044
t, °C	160	170	180	190	200	210	220	230
ε	5.697	6.394	7.134	7.915	8.738	9.601	10.504	11.447

Results of calculation of components of annual costs are summarized in Table 5.

Table 5

Components of annual costs

Item	Value, million USD	Percentage, %
Fuel	28.7	3.037
Personnel costs	2.4	0.254
General plant expenses	68.96	7.297
Heating network	0.423	0.0447
Water treatment	2.155	0.228
Additional oil production	304.1	32.18
Current investment	528.047	55.9
Heating network maintenance costs	10.292	1.089
Total	**945.077**	**100**

Thus, the annual profit (AP) from this manufacturing enterprise is expected to be about 1063.37 million USD.

Profitability of the nuclear power complex for oil production can be determined by the formula:

$$PI=AP/(C_{NPP}+SUM_{FIN}+C_{TH}^{SUM}),$$

where C_{NPP} – cost of nuclear power unit (4.8 billion USD per unit) [15].

Profitability is PI = 22.15 %

Pay-back period is 4.5 years.

Conclusions. We developed and designed the key diagram of turbine plant K-1000-5,8/50 with a cogeneration plant which provide the technological coolant for injection into the wells.

We developed the scheme of the heating networks for delivering the technological coolant to the injection wells. Location of injection wells taken as contour thus thermal network consists of the six lines, which include pipelines between wells and injection pumps.

Heating of technological coolant is carried out (sequentially) in primarily condenser, in raw water heater – up to 50 °C, in feed-water preheater, in deaerator, and finally – in eight technological heaters. In rated mode the turbine with cogeneration plant provides 675 t/h of technological coolant at temperature of 250 °C and has electrical power 935.6 MW.

As a result of calculating the profit from the sale of electricity and additional oil per year with account of annual operating costs, we determine that the profit equal to 1063.37 million USD.

According to the conducted analysis, we found that when the temperature of pumping coolant into a layer is $t = 223.9$ °C, the productivity of the nuclear power complex for oil production increases in 10.87 times.

Pay-back period of the nuclear power complex for oil production is 4.5 years.

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