**Determination of Economic Feasibility of Heat Supply from NPP for Oilfield**

**V.V. 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. **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. **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-
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 “Uknafta”, 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 m³ hot water per 1 m³ 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]:

\[ EAC = ROI \cdot CAPEX + OC, \] (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:

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

where \( OC_{fuel} \) – annual costs for fuel:

\[ OC_{fuel} = AC_{fuel} \cdot C_{fuel}, \] (3)

\( C_{fuel} \) – fuel costs (700 thou. USD);
\( AC_{fuel} \) – annual fuel consumption (41 cassettes);
\( OC_{ee} \) – annual costs for electric energy:

\[ OC_{ee} = AC_{ee} \cdot C_{ee}, \] (4)

\( C_{ee} \) – cost of electricity, \( C_{ee} = 0.04 \text{ USD/kWh} \);
$AC_{ee}$ – annual electricity consumption, kWh;
$OC_{tw}$ – cost of raw water treating ($OC_{tw} = 0.3$ USD/m³);
$OC_{inv}$ – annual depreciation costs of capital investment and maintenance:

$$OC_{inv} = D_r \cdot CAPEX + OC_{rep} = D_r \cdot CAPEX + 0.1 \cdot D_r \cdot CAPEX = 1.1 \cdot D_r \cdot CAPEX,$$  \hspace{1cm} (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:

$$OC_{op} = 1.2 \cdot OC_{pers} + 0.22 \cdot D_r \cdot CAPEX,$$  \hspace{1cm} (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:

$$EAC = 0.1992 \cdot CAPEX + OC_{fuel} + OC_{ee} + OC_{tw}.$$  \hspace{1cm} (7)

Fig. 1. Location of wells at Okhtyrka oilfield (distance between the injection wells in km)
The key points of cogeneration include 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

| 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/year | Reduced costs, USD/year |
|-----------------|--------------------------|----------------------------------|-----------------------------------------------|----------------------------------------------|------------------------|----------------|-----------------------------|-----------------------------------------------|------------------------|
| Northern        | 22295                    | 10326                            | 236                                           | 221.5                                        | 71313                  | 15474          | 17177                       | 39588                                         |                       |
| Central         | 238                      | 5319                             | 242.8                                         | 227.4                                        | 18702                  | 4767           | 8451                        | 5003                                          | 11361                  |
| Southern        | 238                      | 7269                             | 238                                           | 223.9                                        | 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

| 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    | 4.401            | 188.8                    | 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                       |

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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

\[
C_{\text{TH}}^{\text{SUM}} = C_{\text{TH}} n \cdot \mu + C_{\text{TH}} m \cdot z \cdot \mu,
\]

where

- \( C_{\text{TH}} \) – 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

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

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

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**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
\[ \text{SUM}_c = 1.5 \cdot C_{ni}^{\text{SUM}} = 2.6 \cdot 10^6 \text{ USD}. \]

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

\[ \text{SUM}_{\text{FIN}} = 1.5 \cdot \text{SUM}_c = 3.9 \cdot 10^6 \text{ USD}. \]

The volume of additional oil will be

\[ V_{\text{add}} = V_n (\varepsilon - 1), \]

where \( V_n \) – the annual output of Okhtyrka oilfield;
\( \varepsilon \) – 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:

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

When the technological coolant temperature at the entrance to layer is 223.9 °C, the coefficient \( \varepsilon \) is 10.87. Accordingly, the amount of additional oil will be 9.503 \cdot 10^6 m^3/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

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

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.

| \( \varepsilon \) | 80 | 90 | 100 | 110 | 120 | 130 | 140 | 150 |
|-----------------|----|----|-----|-----|-----|-----|-----|-----|
| 80              | 1.206 | 2.031 | 2.425 | 2.862 | 3.342 | 3.866 | 4.433 | 5.044 |
| 90              | 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.
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:

\[ P_I = \frac{AP}{(C_{NPP} + SUM _{FIN} + C_{TH}^{SUM})} \]

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

Profitability is \( P_I = 22.15 \% \)

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 contrast 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 \( t = 223.9^\circ C \), 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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