Method for calculation and control of parameters of the cluster pumping station with autonomous power supply and thermal water-gas impact on the reservoir

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Abstract. An increase in the oil recovery rate is a crucial problem for the national energy industry. This paper discusses improvement of energy production and management of technical systems through the use of exhaust gases of internal combustion engines. To implement this method, a cluster pumping station (CPS) with an autonomous power supply, thermal and water-gas impact on the formation was used. The article considers water saturation with carbon dioxide and its heating to increase oil recovery and prevent harmful combustion products from being released into the atmosphere. All the associated gases enter the heat engine turning mechanical energy into electrical one. Exhaust gases released from the heat engine are not emitted into the atmosphere. Using a smoke exhauster, they enter the mixing heat exchanger. In the mixing heat exchanger, water is heated and saturated with carbon dioxide. Then it enters the well which increases oil recovery, prevents air pollution and reduces greenhouse gas emissions.

1. Introduction
To improve the structure of oil reserves, it is necessary to apply various technologies that will increase the degree of extraction of hydrocarbons. In addition, the remoteness of new fields, as well as relatively small amounts of oil reserves require development of special technologies. One of the ways to solve these problems is to use a cluster pumping station with a water-gas effect on the formation, which allows for increasing the coefficient of oil recovery of the formation.

Most oil companies aim to increase the oil recovery rate and maintain the economic level of oil. This is due to the fact that it is more and more difficult to develop new deposits. Currently, most oilfield enterprises buy electricity [1]. The energy sector is of paramount importance for the global economy, but the current energy balance creates problems that need to be overcome due to excessive dependence on fossil fuels.

In recent years, generation has been carried out in the field [2]. Energy balance is an important issue when installing any type of energy project. It is important to implement a variety of combinations. This method was suggested by Kirshenbaum in his article “On the expediency of building power stations in oil fields”.

This is due to significant energy costs, because the task was to electrify all the technological processes. Kirshenbaum considers the task to use oil or natural gas to the maximum extent possible, to
ensure economic needs of the field (to generate electricity and heat). This method of gas utilization under the existing sale conditions and environmental requirements can be quite effective.

But technical and economic calculations for the use of autonomous power plants showed the feasibility of studying such factors as: capital investment in modernization, production costs, selling prices of excess electricity in the power system, etc. [3]. This paper discusses improvement of energy production in the field by using engine exhaust gases. The focus is on reviewing the latest developments and technologies for the disposal of exhaust gases.

In addition, potential saving of energy and efficiency of application of these technologies are analyzed [4]. The current global trend of increasing energy demand in the transport sector is one of many segments that are responsible for the growing share of fossil fuel use and indirectly contribute to the emission of harmful greenhouse gas. Accounting for recent exhaust recovery results will reduce the global energy demand. Therefore, e effects of global warming effects caused by greenhouse gas emissions will disappear [5].

Emission control is important because existing methods for limiting nitrogen oxides and particulate emissions imply additional energy consumption. Unconventional fossil fuels produce a larger amount of greenhouse gases than conventional fuels, while the vehicle used by non-renewable hydrogen fuel cells does not necessarily provide improved emissions over the best hybrid internal combustion engines [6].

In the field, energy is produced by pumping gas using horizontal wells with several transverse cracks. Gas injection is the most commonly used approach to enhanced oil production. [7] The oil recovery ratio is only a few percent. Mixed flooding is a generic term for injection processes that inject mixed gases into a reservoir. The mixing displacement process maintains reservoir pressure and improves oil displacement as interfacial tension between gas and water decreases.

It increases displacement efficiency. Carbon dioxide, natural gas or nitrogen is injected into the well. The fluid used for mixing, i.e. carbonated water, reduces viscosity of oil and is less expensive than liquefied petroleum gas [8, 9]. Oil displacement by pumping a mixture of water and carbon monoxide depends on the phase behavior of mixtures of this mixture and crude oil which depend on the formation temperature, pressure and composition of crude oil. A mixture of water with carbon dioxide is particularly effective in the reservoirs which are deeper than 600 m, where this mixture is in a supercritical state.

At high pressure, water saturated with carbon dioxide is mixed with oil followed by swelling of oil and a decrease in viscosity and surface tension with the rock. At low pressure, the mixture is partially mixed with oil. Consequently, it is necessary to increase pressure [10]. Oil can be swelled and its viscosity can be significantly reduced.

Carbon dioxide returns with the oil produced and is usually re-injected into the reservoir to minimize operating costs. The remaining part of the mixture is in the oil reservoir. Carbon dioxide as a solvent is more economical than propane and butane.

The method “Increase in the oil recovery rate by injecting water-carbon dioxide mixture into the well” increases the cost of oil production from $ 1 to $ 8 per barrel. Application of this method is economically beneficial depending on oil prices. Since gas prices are low and oil prices are high, maximization of liquid oil production from gas condensate reservoirs is crucial for shale producers [11].

Prevailing prices depend on many factors. They can determine economic suitability of any procedure. It is believed that using a mixture of water and carbon dioxide derived from oil reserves to stimulate electricity generation and support large oil companies is economically and environmentally beneficial.

To mix CO\textsubscript{2} and petroleum hydrocarbons at high temperatures, pressure should be increased. The main obstacle to the further use of carbon dioxide in oil and gas wells is an insufficient supply of CO\textsubscript{2}. Currently, there is a gap between the costs an oil field can pay for CO\textsubscript{2} in normal market conditions, and the cost of CO\textsubscript{2} transportation from power plants and industrial sources. Therefore, CO\textsubscript{2} comes from natural sources. However, the use of carbon dioxide from power plants or industrial sources can reduce the volume of carbon (if CO\textsubscript{2} is stored underground). For some industrial sources (processing of natural
gas or production of fertilizers and ethanol, the gap in cost is small (potentially $10–20 per tonne \( CO_2 \)) [12].

Let us consider implementation of the cluster pumping station with an autonomous power supply and thermal, water-gas impact on the reservoir. Associated gas flows through the device for its supply to the heat engine which turns mechanical energy into electrical one. Exhaust gases released from the heat engine are not emitted into the atmosphere. They enter the mixing heat exchanger with the help of an exhauster [13]. In the mixing heat exchanger, water is heated and saturated with carbon dioxide. Then it enters the well which increases the oil recovery rate.

2. Materials and methods

The article aims to improve efficiency of oil production using a developed rational technology of water-gas impact on the reservoir, as well as to develop programs for mathematical calculations which include the following steps:

• Calculation of the combustion product.
• Determination of the heat exchanger parameters.
• Carbon Dioxide Saturation:
  • calculation of solubility of carbon dioxide in water at constant pressure and different temperatures;
  • calculation of solubility of carbon dioxide in water at increasing pressure.
• Calculation of water heating.

To implement these tasks, a cluster pumping station with a heat engine was used (Figure 1) and an effective mixing heat exchanger was selected for heating water using engine combustion products. Calculation of combustion products and water heating aims at assessing energy efficiency of the pumping station. Rational and efficient use of energy is essential for sustainable development. In Russia and in many other countries, electrical energy is the main source of energy in many areas, including the oil and gas industry [14, 15].

![Figure 1. The cluster pumping station (CPS) with an autonomous power supply and thermal water-gas impact on the formation: 1 - a device for supplying gas to a heat engine; 2 - heat engine; 3 - high-pressure pump; 4 - electric generator; 5 - exhaust fan; 6 - mixing heat exchanger; 7 - sprinkler; 8 - nozzle; 9 - pump.](image)

The purpose of the study is to develop a model for theoretical analysis of energy efficiency at pumping stations which would help increases pressure of process water to the level that ensures water injection into the wells of the reservoir pressure maintenance system.

Associated petroleum gas is a mixture of gas and vaporous hydrocarbon and non-hydrocarbon components released from oil wells and reservoir oil during its degassing. Associated petroleum gas released from a well is energy that can be used for electrical and thermal operations [16]. The method allows us to inject associated gas into deep-saline aquifers or oil and gas reservoirs in a supercritical state \( (P > 7.4 \text{ MPa} \text{ and } T > 304.2 \text{ K}) \) to achieve a higher density rate and [17]. Experimental and numerical simulations showed that massive injection of associated gas into oil and salt reservoirs causes a serious imbalance in the physical and geochemical characteristics of the aquifer [18].

Effective use of associated gas helps derive useful energy from it and reduce air pollution and greenhouse gas emissions.
To eliminate carbon dioxide emissions, a mixing heat exchanger was used. The mixing heat exchanger (contact heat exchanger) is a heat exchanger designed for heat and mass transfer processes by direct mixing of media (as opposed to surface heat exchangers).

To determine the size of the heat exchanger at a gas flow rate $V = 1188 \, \text{m}^3/\text{h}$ we use the data [4], where the main parameters of the heat exchanger are presented at $V = 225 \, \text{m}^3/\text{h}$. This consumption is five times less than the consumption under consideration. Since the heat exchanger is a cylinder whose area is proportional to the square of the diameter, the diameter of the heat exchanger is proportional to $\sqrt{5}$ in comparison with [20].

The main dimensions of the heat exchanger are specified in Table 1 shown in Figure 2. The designations in Figure 2 correspond to Table 1.

### Table 1. Parameters of the heat exchanger [4].

| Size   | Values, mm | Size   | Values, mm |
|--------|------------|--------|------------|
| $D_1$  | 1265.6     | $d_6$  | 448        |
| $D_2$  | 1400       | $H_1$  | 2755.2     |
| $D_3$  | 1500.8     | $H_2$  | 2502       |
| $d_1$  | 356.2×4.5  | $H_3$  | 2278       |
| $d_2$  | 242×4      | $h_1$  | 318        |
| $d_3$  | 298×3.5    | $h_2$  | 168        |
| $d_4$  | 170×4      | $L$    | 224        |
| $d_5$  | 298×4      | $n$    | 27         |

**Figure 2.** General view of the mixing heat exchanger NIIST: 1 - nozzle for gas-air mixture discharge; 2 - support frame; 3 - water inlet; 4 - two-tier water dispenser; 5 - ring nozzle, 6 - wall of the cylindrical body; 7 - supporting grid; 8 - pipe for combustion products.
To saturate water with carbon dioxide, it is necessary to know solubility of this gas at \( M_p(\text{CO}_2) = 268 \, \text{kg CO}_2/\text{h} \).

Solubility of carbon dioxide in water at constant pressure and different temperatures is presented in Table 2 [21].

To begin with, let us present a graph (Figure 3) from the reference book [21] for specific values of \( \text{CO}_2 \) absorption (depending on solubility (gram of gas per kg of water) and temperature).

![Figure 3. Water solubility of CO\(_2\) \( g_{\text{CO}_2}/k\text{g} \_\text{H}_2\text{O} \) at \( P = 1 \, \text{kg cm}^2 \).](image)

Then we recalculate parameters for the CNS-180 pump (\( Q = 180 \, \text{m}^3/\text{h} \)) and enter the data in Table 2.

**Table 2.** Temperature dependent solubility of carbon dioxide

| Temperature (T), °C | Pressure (P), atm | Solubility, kg CO\(_2\)/h |
|---------------------|-------------------|--------------------------|
| 24                  | 1                 | 270                      |
| 30                  | 1                 | 225                      |
| 50                  | 1                 | 135                      |

Table 2 shows that solubility of carbon dioxide in water depends on the temperature (the lower the temperature, the more soluble it is). It can be seen that at \( t = 24 \, \text{°C} \), solubility of \( \text{CO}_2 \) in water is 1.5 g/kg. Hence, solubility of \( \text{CO}_2 \) is 270 kg CO\(_2\)/h with water consumption of 180 m\(^3\)/h which allows us to dissolve 268 kg CO\(_2\)/h.

Let us consider an increase in solubility by increasing pressure (Figure 4).

Figure 3 shows that at a pressure of 10 atm. and at \( t = 25 \, \text{°C} \), the solubility of \( \text{CO}_2 \) in water is 7.8 m\(^3\)/m\(^3\). Hence, solubility of \( \text{CO}_2 \) will be 1404 m\(^3\) at water consumption of 180 m\(^3\)/h.

For a 350 kW engine, \( \text{CO}_2 \) combustion product mass is 268 kg. Using the Mendeleev-Clapeyron equations for high pressure, bulk density can be determined. It is 150 m\(^3\). Thus, for a given water flow rate, 9 engines can be used.
Let us analyze the second variant of calculation, given that outlet pressure of the combustion product is 5 atm. Figure 4 shows that at \( t = 25 ^\circ C \), solubility of \( \text{CO}_2 \) in water is 6 m\(^3\)/m\(^3\). With water consumption of 180 m\(^3\)/h, solubility of \( \text{CO}_2 \) is 1080 m. At a given flow rate, you can use 7 engines.

**Figure 4.** Solubility of \( \text{CO}_2 \) in water at increase pressure values: 1 - at 0 \( ^\circ \)C; 2 - at 12.5 \( ^\circ \)C; 3 - at 25 \( ^\circ \)C; 4 - at 50 \( ^\circ \)C; 5 - at 75 \( ^\circ \)C; 6 - at 100 \( ^\circ \)C.

Let us calculate the temperature of water heating for nine and seven engines with a total power of 3150 kW from the formula for calculating heat.

Let us calculate maximum pressure on the tube walls of the mixing heat exchanger with a thickness of 4 mm using the Burlow formula:

\[
P = \frac{2b}{D} \sigma
\]

where \( b \) is wall thickness, \( b = 0.004 \text{ m} \); \( D \) is the external diameter of the tube of the mixing heat exchanger, \( D = 1 \text{ m} \); \( \sigma \) is allowable stress (yield strength), \( \sigma = 245 \text{ MPa} \);

\[
P = \frac{2 \times 0.004}{1} \times 245 \times 10^6 = 1.96 \text{ MPa} = 19 \text{ atm}.
\]

3. Conclusion

According to the results of the calculation, we see that the pipe wall withstands pressure. Analysis of the method for improving energy production of technical systems through the use of exhaust gases of an internal combustion engine will allow for heating and saturating water which will eliminate air pollution and reduce greenhouse gas emissions.

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