Improving oil recovery for Arctic offshore oilfields using efficient multifunctional systems

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Abstract. This work presents the main properties of multifunctional systems designed for improving oil production for Arctic offshore fields. The processes were developed using a system approach to the optimal organization of complex technological objects. This approach employs the principles of general systems theory, which are based on information theory developed by C. Shannon and W. Weaver and can be used to formulate the organization criteria of a technological system with hierarchical structure. This can be applied in technology for creating multifunctional processes with synergistic properties. Technological solutions were designed in order to address a number of important issues associated with the development of offshore oil fields in the Artic region, namely: improving oil recovery, energy saving, environmental problems (problems associated with the conservation of a unique ecosystem) and ensuring the operation of the production platforms. These solutions will allow to solve these problems simultaneously in multifunctional systems that combine power generation modules based on the Brayton and Rankine cycles and modules for carbon dioxide capture. The efficiency of the proposed solution exceeds that of analogous solutions overseas.

1. Introduction
The development of Arctic resources requires a comprehensive and conservation-based approach because they are located at a considerable distance from energy sources, as well as due to the harsh climatic conditions, a unique ecosystem and the presence of large hydrocarbon reserves.

According to the United States Geological Survey (USGS), the Arctic region contains more than 22% of the world's hydrocarbon reserves, including 30% of natural gas reserves, 20% of gas condensate reserves and 13% of the reserves of crude oil. At the same time, up to 70% of the projected hydrocarbon reserves are concentrated in the Russian sector.

This paper proposes a system based on the principle of multifunctionality that solves a number of problems in oil production for Arctic offshore fields. The implementation of this principle will allow to simultaneously achieve multiple effects: energy saving, intensification of the oil production process, carbon dioxide capture, as well supplying the platforms themselves with both energy and heat. However, if the complexity of such systems increases, their efficiency may decrease, and offshore oil production may become unprofitable.

A modern example of such a multifunctional system is a power system developed by the Mayfair Energy Group (MEG) – VENZ 4 (European patent N2009003318, dated February 2010), a diagram for which is given in Fig. 1 [1].

The system is complicated and expensive, and carbon dioxide is captured and produced as a liquid.
Such systems are characterized by minimal mass and energy exchange with the environment, a high degree of process integration and the generation of multiple useful products (effects). For the engine, the VENZ-4 system uses a gas piston engine produced by Wärtsilä (Finland).

![Multifunctional power plant VENZ-4](image)

Figure 1. Multifunctional power plant VENZ-4.

According to literary sources, the exergy efficiency of the VENZ-4 system is 42%. This value was later recalculated in this work.

2. Methods

When developing new technical solutions with improved energy efficiency emphasis was placed on the use of widely manufactured equipment with a long service life, in order to implement the import substitution strategy. To increase the efficiency of complex technological systems, it is advisable to use system approaches that allow to achieve synergistic effects in process integration.

The work uses information theory and the fundamental laws of the development of living matter to employ the “organism-based approach” defined in general systems theory [2–4].

The main idea of the organism-based approach is that the analysis of individual processes and the development of their mathematical models in order to formulate a model for the entire chemical engineering system (CES) does not view the system as a whole and as a single organism with emergent properties. This is why a separate discipline is devoted to studying complex systems in chemical engineering. According to general systems theory, the tendencies in optimal organization for such complex objects in technology are similar to biological or social systems, because they all possess a hierarchical structure.

The criteria used is the organization of a technological object, which in this case a non-uniform chemical engineering system [5].

The organization of a system in chemical technology is defined as a property of system structure, when the elements of a system operate in coordination with each other due to the optimal distribution of system functions between elements and subsystems [6].

Moreover, the optimal organization of a system in chemical engineering is viewed as minimum-maximum optimization problem, in which entropy is maximized at the macrolevel and minimized at the microlevel. As opposed to existing scientific approaches, for the first time the optimal organization of a system in chemical engineering is determined by three laws of thermodynamics: first, second and zeroth. The zeroth law of thermodynamics is used for optimal process coordination at the macrolevel, which is achieved by maximizing the macroentropy.
The macroentropy that defines process coordination is determined by the weight coefficients of system elements which have the meaning of the probability of fluctuation of process mean energy levels (the overall energy or the internal energy).

\[ H_M = -\sum_{i=1}^{I} \ln n_i, \]

where \( n_i \) is the weight coefficient of the \( i \)-th element, and \( I \) is the overall number of elements in the system.

This system approach, instead of formulating and solving local optimization problems, allows us to consider the solution of a general problem, which is the creation of a technological object with a high degree of organization. For such objects energy conservation, system stability and controllability are simply consequences of formulating the general design problem.

The proposed system approach was used to develop a number of innovative technological solutions that utilize the principle of multifunctional systems to improve the energy efficiency of associated petroleum gas use at Russian Arctic offshore oil fields. The proposed solutions were developed for a pilot plant with capacity values similar to those of the analogous plant overseas and can be scaled to a larger power production capacity. They are based on optimally organized systems consisting of: a power module that uses the Brayton cycle combined with a Rankine cycle operating on various working fluids (including low-boiling working fluids); a module for carbon dioxide capture from flue gases; and a module for producing carbon dioxide in a liquid or supercritical state for improving oil recovery, increasing the production capacity of oil wells and carbon sequestration.

In recent years, the application of the Rankine cycle in various economic sectors has seen renewed interest. By 2017, 1754 power modules using the Organic Rankine cycle operating on a low-boiling working fluid were in operation with a total capacity of 2700 MW [7]. The overall market dynamics for Rankine cycle systems for various applications shows a positive trend with some temporary fluctuations, both for the overall numbers and for different areas of application, as shown in Fig. 2.

An example of the application of the Organic Rankine Cycle for waste heat recovery is given in [8].

![Figure 2. Market dynamics for Rankine cycle power systems, according to [7].](image)

The working fluid for the Rankine cycle is selected based on process stream parameters and the possibility of combining the technological functions of different processes [9,10].

In [11], an example of Rankine cycle application for waste heat recovery from gas streams exiting the gas turbine or gas piston type heat engines is presented.

According to [12] the use of the Rankine cycle on a bigger scale is limited by the fact that the industrial sector is unaware of the efficiency of waste heat recovery plants based on the Rankine cycle that can significantly increase the energy efficiency of technological processes and help minimize thermal pollution of the environment.

Seawater or air are used for cooling in Rankine cycle with low-boiling working fluids.

The steam Rankine cycle is combined in the power module with a system for heating and hot water supply for on-site use at oil platforms.
3. Results and discussion
The developed technological solutions and the analogous existing technology were calculated using the CHEMCAD software. A specifically developed module “Exergy Unit” compatible with CHEMCAD [13] was used to compare the efficiency of the systems. The software allows to perform the following computational experiments:
- Simulations of the technological systems in CHEMCAD;
- Calculating the exergy balance, exergy loss and exergyefficience using the “Exergy Unit” module;
- Graphical representation of the results of exergy analysis in the “Exergy Unit” module.

The “Exergy unit” module was developed for calculating the full thermal exergy using the methodology detailed in [14].

Given the parameters of the pilot plant, the flowrate of associated petroleum gas is assumed to be 3500 Nm3/hr. Exhaust flue gas temperature for the Brayton cycle, based on operation data of existing gas turbine systems, was assumed to be 490 °C.

![Figure 3. Schematic diagram of the technological solution with Rankine cycle.](image)

The process scheme of multifunctional system that integrates the Brayton and Rankine cycles (operating on a low-boiling working fluid) and a module for carbon dioxide capture and subsequent CO2 compression to supercritical parameters (20.0 MPa, 200 °C) is presented in Fig. 3.
The proposed technological solution is characterized by process integration, which allows to combine process functions in order to reduce the number of system elements for solving a number of technological issues.

Work [15] presents a comparison of the multifunctional power system with a Rankine cycle using a low-boiling working fluid (Fig. 3) and the existing solution (Table 1).

### Table 1. Power system comparison.

|                       | VENZ-4 technology Mayfair Energy Group | Multifunctional power system (ORC) |
|-----------------------|----------------------------------------|------------------------------------|
| **Associated petroleum gas** | 1 875 Nm³/hr                           | 3500 Nm³/hr                        |
| **CO₂ production**     | 98.5 – 127.8 tonnes/day                | 202.9 tonnes/day                   |
| **CO₂ state**          | liquid                                 | Supercritical (20.0 MPa, 200 °C)   |
| **Power**              | 8 085 – 9 490 kW                       | 13 685 kW                          |
| **Water**              | Condensate                             | Seawater                           |
| (condensate)           | (71.5 – 83.8 tonnes/day)               | (500 m³/hr)                        |
| **Exergy efficiency**  | 49.8 %                                 | 52.2 %                             |

According to the data in table 1, the exergy efficiency of the multifunctional energy system that uses the Rankine cycle with a low-boiling working fluid is higher than that of the analogous technology, while the energy required for carbon dioxide compression to supercritical parameters required to implement gas methods of enhanced oil recovery [15] do not exceed 10% of the energy produced in the power module.

The main operating parameters of the multifunctional power system that uses a steam Rankine cycle are given in Table 2. The power consumption for the process of carbon dioxide compression to supercritical parameters (20 MPa, 200 °C) is taken into account.

It was shown that the calculated value for the exergy efficiency of the multifunctional power system that uses a steam Rankine cycle (Table 2) and is combined with a heating and DHW supply system for the oil platform is higher and was estimated at 67.3 %.

### Table 2. Power system parameters (working fluid: steam).

|                       | 3500                                      |
|-----------------------|-------------------------------------------|
| Associated petroleum gas flowrate, Nm³/hr |                           |
| Supercritical CO₂ production, kg/hr        | 8451.1                                    |

**Power production and consumption, kW**

|                         |                                           |
|-------------------------|-------------------------------------------|
| Air compressor          | 14575.6                                   |
| APG compressor          | 612.1                                     |
| Pumps                   | 7.2                                       |
| Gas turbine             | 26322                                     |
| Rankine cycle steam turbine | 1464.4                                 |
| Total energy production without power consumption for compression | 12592.5                                 |
| CO₂ compression (20 MPa) | 1147.9                                   |
| Total energy production including power consumption for compression | 11401.4                                 |

The developed multifunctional power systems are low-maintenance installations that use only associated petroleum gas and seawater as external resources (for the Rankine cycle with a low-boiling working fluid), and produce electricity, heat and supercritical carbon dioxide while providing the
energy required for process operation, which fully corresponds to the “organism-based” system approach.

4. References

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