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DEVELOPMENT OF THE IMITATION MODEL OF THE TWO-STAGE SEPARATION PROCESS OF OIL

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На основі розробленої математичної моделі двоступеневої сепарації нафти було проведено ідентифікацію параметрів, що дало змогу створити імітаційну модель для першого та другого ступенів сепарації. Досліджена числовим методом в програмі MatLab імітаційна модель може бути використана для синтезу ефективних систем керування процесом двоступеневої сепарації та створення математичних моделей у термінах «вхід-вихід»

Ключові слова: синтез систем, двоступенева сепарація, числовий метод, ідентифікація параметрів, імітаційна модель

На основе разработанной математической модели двухступенчатой сепарации нефти была проведена идентификация ее параметров, что позволило создать имитационную модель для первой и второй ступеней сепарации. Исследованная численным методом в программе MatLab имитационная математическая модель может служить основой для синтеза эффективных систем управления процессом двухступенчатой сепарации и создания математических моделей в терминах «вход-выход»

Ключевые слова: синтез систем, двухступенчатая сепарация, численный метод, идентификация параметров, имитационная модель

1. Introduction

Separation systems carry out operations on collection, preparation and storage of oil. One of the main functions is the transport of well products under the action of reservoir pressure or at the expense of the energy of pumps to the point of oil preparation [1]. In these systems, there is a separation of gas from oil and supply of it to consumers, as well as a free water separation from well products (in the case of flooded oil).

The efficiency of the separation process to a large extent is determined by the methods and algorithms of the automatic control systems. The process of separation of oil proceeds under the influence of numerous obstacles and inherent in it complex internal communications [2]. Therefore, the actual task will be the development of effective systems of automatic control, which will be based on adequate mathematical models, which quantitatively and qualitatively will characterize the process of separation in general.

2. Literature review and problem statement

The production economy shows that oil separation processes should be as efficient as possible, since separated oil can contain partially captured water or gas and vice versa. This means that any gas-oil emulsion must be detached to the commercial state, the water content must not exceed 1 % [1]. The reflection of the scientific problem of separation of oil can be found in the papers [2, 3]. However, the greatest problem of the current state of oil separation processes is the lack of integrated automated control systems, where the parameters of the flow of each component with the enabled function of flow management must be controlled. An integral part of such complexes are two-stage oil separation systems [4]. Typically, single-stage separation systems are used for oil separation at primary oil preparation plants. But the use of such equipment is fair and reasonable for oil with low water and gas content, that is, less than 1/3 of the total mixture. When the total content of water and gas is significantly higher than the oil content or equal, it is expedient to use two-stage separation systems, which will significantly increase the efficiency of the oil separation process [4, 5].

In the first stage of the creation of two-stage separation systems, the issue of mathematical modeling will be put forward [5, 10], which includes such important factors as productivity, gas factor, solubility factor, separation coefficient, geometric dimensions of the separator, etc. The study of oil separation by computer simulation was performed in the paper [6], but the disadvantage was the exclusion of water from the structure of the model, which significantly influences the key parameters: pressure, temperature, level, expense. The development of computer models of the separation process is necessary to provide engineers with valuable tools for obtaining more reliable qualitative and quantitative solutions for the further processing of oil and exploitation of oil fields. In the paper [7], a detailed description of the theory of motion of gas particles in a gravitational field has been made which significantly influences the performance of the separator, but this effect does not investigate the effect on multi-stage separation systems. One of the first mathematical models that describe the process in terms of "input-output" and is suitable for the synthesis of automated control systems was the model suggested in the paper [8]. In the scientific paper [9], the mutual influence of the level of fluid and pressure in the separator was taken into account. But the disadvantage is that the last two papers are not sufficiently substantiated and are intended only for single-stage separation. Two-stage separation systems are considered to be the most effective, since the operation of the first stage significantly affects the efficiency of the second one. In the scientific paper [10], the work of the two-stage separation system is described in details, but according to the authors, it would be expedient to use a system with horizontally placed separators B-1 and B-2, as this can significantly affect the overall separation factor in subsequent calculations [11, 12]. Consequently, the issue of two-stage separation systems will remain inadequate. Therefore, based on the literature review, an imitation model of a two-stage separation system consisting of two horizontally placed separators and a vertical oil storage tank is suggested.

3. The aim and objectives of the study

The aim of the work is to develop a numerical simulation model of the two-stage oil separation model in the MatLab program, taking into account the features of the technological process for the synthesis of efficient systems for automatic control of the separation process and the further development of mathematical models in terms of "input-output". In other words, it is about determining the mutual influence between the technological parameters of each of the separators of the two-stage separation system.

To achieve this aim, it was necessary to fulfill the following objectives:

– the creation of a mathematical model of the material balance of a two-stage separation for the first B-1 and the second B-2 horizontally placed separators;

– the identification of parameters of the mathematical model of two-stage separation for further simulation in MatLab;

– the development of a simulation model of two-stage separation and examine it numerically in the MatLab program to change the key parameters of the level and pressure in each separator.

4. The object and methods of research of the separation unit

The object of research is the technological process of oil separation. The two-stage separation system (Fig. 1), which contains the first and second degree of separation [11], is taken into consideration.

Working pressure at the first stage of separation is created by reservoir pressure at the outlet of the well. Such pressures range from 4.1 to 8.3 MPa [11]. The technological scheme of the simulation model of the two-stage separation unit is shown in Fig. 1.

Production of wells of an oil and gas deposit at a pressure of P_0=4.0 MPa enters the horizontal separator B-1. Oil from the separator B-1 at a pressure of P_1=1.6 MPa enters the second degree of separation into a horizontal separator B-2 through the actuator (executive device) ED_h. Gas from the separator B-1 enters the compressive compressor station "CCS" through the actuator ED_p (Fig. 1).

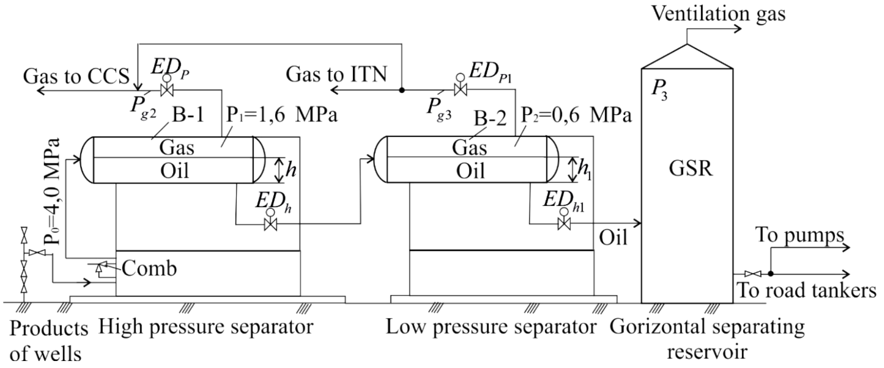

Fig. 1. Technological scheme of the simulation model of the two-stage separation unit

Oil from the separator B-2 at a pressure of P_2=0.6 MPa enters the reservoirs of the GSR. Further oil through the pipeline is provided at the entrance to the oil pumping station and to the oil pipeline, where it is shipped to the tanker. Gas from B-2 at a pressure of P_2=0.6 MPa enters the "CCS" through the actuator ED_{h1}. At the same time, gas from B-2 is supplied also for industrial and technological needs (ITN).

The main technical and technological parameters of the separation unit are given in Table 1.

Table 1

The main technical and technological parameters

No.	Device name	Parameter name	Unit of measurement	Parameters	
				Maximum permissible	Installed technologically
1	Separator B-1	pressure	MPa	1.6	0.6÷1.5
		temperature	°C	–40÷+100	–20÷+40
		volume	m^3	100	30
2	Separator B-2	pressure	MPa	0.6	0.1÷0.6
		temperature	°C	–40÷+100	–20÷+40
		volume	m^3	100	30
3	High-pressure gas line	diameter	mm	–	89
		length	m	–	1,700
		pressure	MPa	16.0	8.0÷15.0
4	Gas line CCS	diameter	mm	–	159
		length	m	–	930
		pressure	MPa	6.4	3.5÷4.5
5	Gas line ITN	diameter	mm	–	219
		length	m	–	5,740
		pressure	MPa	0.6	0.52÷0.57

Some characteristics of oil and gas mixture together with oil and gas parameters after separation are shown in Table 2.

Table 2

Characteristics of oil and gas mixture together with oil and gas parameters after separation

Parameter name	Designation	Value	Unit of measurement
Physical properties of crude oil			
Oil density	ρ_o	843	kg/m^3
Mass fraction of water	x_w	0.5	%
The gas separated from the equipment			
Gas density at t=20 °C	ρ_g	0.819	kg/m^3

The necessary efficiency of the separation process is achieved by stabilizing such mode parameters as the level of fluid and pressure in the separator [12]. Therefore, material flows in a two-stage separation system are described using the equations of the material balance, respectively, for each separator individually.

5. Mathematical model of operation of a two-stage separation unit

The two-stage separation unit has two horizontal separators B-1 and B-2 (Fig. 1).

Since the first stage B-1 separator is horizontal and cylindrical, the degree of its filling will be given by the equations [14]:

$$\nu_p(h)=\frac{1}{\pi}\left(\pi-\operatorname{acos}\left(\frac{h}{r_s}-1\right)+\left(\frac{h}{r_s}-1\right)\sqrt{1-\left(\frac{h}{r_s}-1\right)^2}\right), \quad (1)$$

$$q_p(h)=\frac{2}{\pi r_s}\sqrt{1-\left(\frac{h}{r_s}-1\right)^2}, \quad (2)$$

where h is the oil level in the separator B-1; r_s is the radius of the separator B-1.

Consequently, the mathematical model for the first degree of separation will be as follows [14]:

$$\frac{dP_1}{dt}=\frac{1}{1-\nu_p(h)}\left(\left(\frac{\varepsilon_g}{\theta_g}+\frac{P_1}{M_0}\varepsilon_{f1}\right)\xi_f\sqrt{\rho_f\left(P_0-P_1\right)}-\right.$$
$$-\frac{\alpha_g(U_1)}{\theta_g}\sqrt{\frac{\left(P_1^2-P_{g2}^2\right)}{\tilde{z}T_1}}-$$
$$\left.-\frac{P_1}{M_0}\alpha_o(U_2)\sqrt{\rho_{f1}\left(P_1+\rho_{f1}gh\cdot 10^{-6}-P_2\right)}\right), \quad (3)$$

$$\frac{dh}{dt}=\frac{1}{q_p(h)M_0}\times$$
$$\times\left(\varepsilon_{f1}\xi_f\sqrt{\rho_f\left(P_0-P_1\right)}-\alpha_o(U_2)\sqrt{\rho_{f1}\left(P_1+\rho_{f1}gh\cdot 10^{-6}-P_2\right)}\right), \quad (4)$$

where νp(h) and qp(h) are calculated by formulas (1) and (2).

Other notations in equations (3) and (4) will be as follows: εg stands for the gas separation factor; $\theta=V_0/zR_gT_1$, where V_0 is the total volume of the separator B-1, z is the gas compressibility factor, R_g is the gas constant; T_1 stands for gas temperature in the separator B-1; P_1 is gas pressure in the separator B-1; $M_0=V_0\rho_o$, where ρ_o is the density of oil; ε_o is the oil separation factor;

$$\xi_f=\frac{1}{\sqrt{A_f}},\ A_f=\lambda\frac{l_f}{D_f}\cdot\frac{1}{2F_f^2},$$

where λ is the coefficient of friction resistance, D_f is the diameter of the inlet pipe, l_f is the total length of the section, which includes the equivalent lengths of the local resistances, F_f is the cross-sectional area of the pipeline; ρ_f, ρ_{f1} are the density of oil and gas mixtures entering the separation system and the second stage of separation, ρ_g stands for gas density; P_0 is the pressure at the inlet of the separator B-1; $\alpha_g(U_1)=K_{L1}K_v(U_1)\xi_{nc}$, where K_{L1} is the shutter release ratio, which is proportional to the command signal of the controller U_1, $K_v(U_1)$ is the throughput of the ED_p actuator (Fig. 1);

$$\xi_{cv}=\sqrt{\frac{\rho_{cv}T_{cv}}{P_{cv}}},$$

where ρ_{cv}, T_{cv}, P_{cv} stand for gas density, temperature and pressure under normal conditions (T_{nc}=273 K and P_{nc}= =0.1013 MPa); P_{g2} is pressure after shutting down of the regulating body (RB); $\tilde{z}$ is the gas compressibility factor, which is calculated at temperature T_1 and pressure

$$\tilde{P}_g=\frac{P_1+P_{g2}}{2};$$

$\alpha_o(U_2)=K_{L2}K_v(U_2)$, where K_{L2} is the proportionality factor between the transfer of the stem RB of the executive device ED_h and the command signal U_2, $K_v(U_2)$ is the throughput of the actuator ED_h.

The mathematical model of the material balance for the separator B-2 will be determined by the equations [14]:

$$\frac{dP_2}{dt}=\frac{1}{1-\nu_{p1}(h_1)}\left(\left(\frac{\varepsilon_{g1}}{\theta_{g1}}+\frac{P_2}{M_{01}}\right)\alpha_o(U_2)\times\right.$$
$$\times\sqrt{\rho_{f1}\left(P_1+\rho_{f1}gh\cdot 10^{-6}-P_2\right)}-$$
$$-\frac{P_2}{M_{01}}\alpha_{o1}(U_{s2})\sqrt{\rho_o\left(P_2+\rho_o gh_1\cdot 10^{-6}-P_3\right)}-$$
$$\left.-\frac{1}{\theta_{g1}}\alpha_{g1}(U_{s1})\sqrt{\frac{P_2^2-P_{g3}^2}{T_2}}\right), \quad (5)$$

$$\frac{dh_1}{dt}=\frac{1}{q_{p1}(h_1)M_{01}}\left(\alpha_o(U_2)\sqrt{\rho_{f1}\left(P_1+\rho_{f1}gh\cdot 10^{-6}-P_2\right)}-\right.$$
$$\left.-\alpha_{o1}(U_{s2})\sqrt{\rho_o\left(P_2+\rho_o gh_1\cdot 10^{-6}-P_3\right)}\right), \quad (6)$$

$$\nu_{p1}(h_1)=\frac{1}{\pi}\left(\pi-\operatorname{acos}\left(\frac{h_1}{r_{s1}}-1\right)+\left(\frac{h_1}{r_{s1}}-1\right)\sqrt{1-\left(\frac{h_1}{r_{s1}}-1\right)^2}\right), \quad (7)$$

$$q_{p1}(h_1)=\frac{2}{\pi r_{s1}}\sqrt{1-\left(\frac{h_1}{r_{s1}}-1\right)^2}, \quad (8)$$

where h_1 is the oil level in the separator B-2; r_{s1} is the diameter of the separator B-2.

As the initial conditions for differential equations (3)–(6), we take the fixed values of the corresponding quantities – $P_1(0)=P_1^{(0)}$, $h(0)=h^{(0)}$, $P_2(0)=P_2^{(0)}$ and $h_1(0)=h_1^{(0)}$.

In equations (5) and (6), the following designations are taken: P_2 is gas pressure in the separator B-2; $\varepsilon_{g1}=(1-r_{g1})G_1$ stands for the gas separation factor, where r_{g1} is the efficiency indicator of the second stage of separation, $G1$ is the gas factor of the second stage of separation; $\theta_{g1}=V_{01}/R_gT_2$, where V_{01} is the total volume of the separator B-2, T_2 is the gas temperature in the separator B-2; $M_{01}=V_{01}\rho_o$ is the mass of oil in the separator B-2 at its full filling; $\alpha_{o1}(U_{s2})=K_{sL}K_{sv}(U_{s2})$, where K_{sL} is the proportionality factor between the transfer of the stem RB of the operating device ED_{h1} and the command signal U_{s2}, $K_{sv}(U_{s2})$ is the throughput of the actuator ED_{h1} (Fig. 1); P_3 is an average pressure in reservoirs (Fig. 1); $\theta_{g1}=V_{01}/R_gT_2$, where T_2 is the gas temperature in the separator B-2; $\alpha_{g1}(U_{s1})=K_{s1}K_{g1}(U_{s1})\xi_{cv}$, where K_{s1} is the gate transfer coefficient of the ED_{p1} actuator, which is proportional to the command signal of the controller U_{s1}, $K_{g1}(U_{s1})$ is the throughput of the ED_{p1} actuator (Fig. 1); P_{g3} is the gas pressure after the RB of the ED_{p1} actuator of the second stage of separation.

Thus, the mathematical model of a two-stage separation system, which has two cylindrical horizontal separators B-1 and B-2 in its composition, is given by systems of differential nonlinear equations (3)–(6). The peculiarity of the two-stage separation system is that the output (regulated) quantities P_1 and h of the first degree of separation, as well as the control action U_2, act as a perturbation for the second degree of separation. Such interference with the separation stages worsens the efficiency of the separation unit and requires systemic solutions to eliminate or reduce the effect of the first stage on the efficiency of the second stage. Such solutions can be found by developing structural schemes that will make it possible to compensate or weaken the effect of the first degree of separation on the second stage.

In formulas (3)–(6), it is taken into account that the pressure is measured in MPa, and the hydrostatic pressure ρgh in Pa. The linearization was carried out to solve the problem of mathematical models of the two-stage separation system [15].

6. Identification of the parameters of the mathematical model of the separation system

The initial data for calculating the parameters of the mathematical models of the separation system are given in Table 3.

The calculation of the compressibility factor z of natural gas is carried out according to the modified Benedict-Webba-Rabin equation [8]:

$$z^3-z^2-az-b=0, \tag{9}$$

where

$$\alpha=\pi((0.1237/\tau)-(0.3468/\tau^2)-(0.1188/\tau^4));$$

$$b=\pi^2((0.0291/\tau^2)-(0.0273/\tau^3)+(0.0390/\tau^5));$$

$\pi=(P+1.33\cdot10^{-4}P_a)/P_{kp}$ is the given pressure; $\tau=(t_g+273)/T_{kp}$ is the given temperature; $P_{kp}=4.67-0.1\Lambda$ is the critical pressure measured in MPa; $T_{kp}=99.8+162.8\Lambda$ is the critical temperature measured in K; P_a is atmospheric pressure measured in mm Hg.; P is excess pressure of natural gas measured in MPa; t_g is temperature of natural gas measured in °C.

Table 3

Initial data for calculating the parameters of the mathematical models of the separation system (the established mode of operation of the separation system)

Parameter name	Designation	Value	Unit of measurement
Pressure at the inlet of the separator B-1	P_0	4.0	MPa
Gas pressure in the separator B-1	P_1	1.6	MPa
Gas pressure in the separator B-2	P_2	0.6	MPa
Gas temperature at the entrance to the B-1	T_0	286	K
Oil density	ρ_o	843	kg/m^3
Gas density at standard conditions	ρ_{cv}	0.820	kg/m^3
Gas pressure in GSR tanks	P_3	0.1	MPa
Gas pressure after ED_p	P_{g2}	0.85	MPa
Gas pressure after ED_{p1}	P_{g3}	0.32	MPa
The volume of the separator B-1	V_0	100	m^3
The volume of the separator B-2	V_{01}	100	m^3
Diameter of the separator B-1	r_s	3.0	m
Diameter of the separator B-2	r_{s1}	3.0	m
Oil level in the separator B-1	h	1.51	m
Oil level in the separator B-2	h_1	1.47	m
Diameter of the inlet pipeline	D_f	0.219	m
The volume of oil supplied to the separation unit	Q_f	3.71	m^3/hour
Atmospheric pressure	P_a	762	mm. Hg.
Mass fraction of water	w	0.036	–
Productivity of the oil plant	G_{ol}	100	tons/day
Productivity of the gas plant	Q_{gn}	10^5	nm^3/day

The relative gas density by air is calculated by the formula [8] $\Lambda=\rho_{cv}/1.205$, where ρ_{cv} is the density of natural gas under standard conditions.

The real root of the Benedict-Webba-Rabin equation determines the value of the gas compressibility factor.

The calculation of the parameters of the mathematical model of the separation system, given by the equations (3)–(6), was carried out according to a program written in the algorithmic language of the MatLab environment. The results of the calculations are summarized in Table 4.

The productivity of the separation unit for oil is $G_{ol}=100$ tons/day, for gas $Q_{gn}=10^5$ nm^3/day (Table 3), which we shall express in units of mass per unit of time according to the following formula

$$G_g=Q_{gn}\rho_{cv}/k,$$

where k is the conversion factor, which makes it possible to express G_g in kg/sec (k=86.400).

Then we will determine the mass fraction of gas in the oil and gas mixture as follows

$$x=G_g/G_{ol}k_1+G_g, \tag{10}$$

where $k_1=10^3/k$.

Table 4

Results of calculations of the parameters of the mathematical model (3)—(6)

Parameter name	Designation	Value	Unit of measurement
Gas compressibility factor	z	0.9979	–
Degree of filling of the separator B-1	$\nu_p(h)$	0.504	–
Degree of filling of the separator B-2	$\nu_{p1}(h_1)$	0.487	–
Density of the oil and gas mixture	ρ_f	70.47	kg/m^3
–	θ_g	830.25	kg/MPa
The intensity of filling of the separator B-1	$q_p(h)$	0.424	m^{-1}
The intensity of filling of the separator B-2	$q_{p1}(h_1)$	0.423	m^{-1}
Mass fraction of gas in oil and gas mixture	x	0.45	–
Natural gas solubility factor	α_1	0.3593	MPa^{-1}
Productivity of the separator B-1 (of gas)	G_{g1}	0.6453	kg/sec
Productivity of the separator B-2 (of gas)	G_{g2}	0.3037	kg/sec
Gas density under normal conditions	ρ_n	0.8801	kg/m^3
Productivity of the separator B-1 (of gas)	Q_{g1}	$6.3356 \cdot 10^4$	nm^3/day
Productivity of the separator B-2 (of gas)	Q_{g2}	$2.9818 \cdot 10^4$	nm^3/day
–	$\alpha_g(U_1)$	0.4761	kg/sec (K/MPa)$^{1/2}$
Gas separation factor	ε_g	0.3064	–
Productivity of the separator B-1 on the liquid	G_{f1}	1.4433	kg/sec
Separation factor of the separator B-1	ε_{f1}	0.6852	–
Productivity of the separator B-2 for oil	G_{o2}	1.1574	kg/sec
Mass fraction of gas (separator B-2)	x_1	0.1981	–
–	$\alpha_o(U_2)$	0.1881	kg/sec (K/MPa)$^{1/2}$
The liquid density in the separator B-1	ρ_{f1}	60.30	kg/m^3
Mass of liquid at $h=D$ where D is the diameter of the separator B-1	M_0	$6.0301 \cdot 10^3$	kg
–	ξ_f	1.9672	kg/sec (K/MPa)$^{1/2}$
Gas separation factor (second stage)	ε_{g1}	0.2079	–
–	θ_{g1}	829.05	kg/MPa
Mass of liquid at $h_1=D_1$, where D_f is the diameter of the separator B-2	M_{01}	84300	kg
–	$\alpha_{o1}(U_{s2})$	0.0703	kg/sec·(m^3/kg·MPa)$^{1/2}$
–	$\alpha_{g1}(U_{s1})$	10.1204	kg/sec (K/MPa)$^{1/2}$

We will determine the density of the oil and gas mixture ρ_f as far as we know the proportion of gas in the oil and gas mixture x. The results of the calculations by the formula (10) are recorded in Table 4.

Since gas is supplied to the first stage of separation in the amount of G_g, and $G_f=G_{ol}k_1+G_g$, then by comparing with the formula (10), we arrive at the conclusion that $G_0=x$.

The efficiency of the first stage of gas separation $Q_g^{(1)}$ can be calculated using the following formula

$$Q_{g1} = Q_f(1-w)\cdot(G'_0-\alpha_1 P_1), \tag{11}$$

where α_1 is the solubility factor of natural gas in oil.

Formula (11) can be represented as follows:

$$Q_{g1}\rho_g = Q_f\rho_f(\rho_g/\rho_f)\cdot(1-w)\cdot(G'_0-\alpha_1 P_1), \tag{12}$$

where ρ_f is the density of the gas is reduced to the conditions of separation of the first degree.

Since $G_{g1}=Q_{g1}\rho_g$ and $G_f=Q_f\rho_f$, and taking into account that $G_0'=G_0\cdot\rho_f/\rho_g$, the equation (12) will take the form:

$$G_{g1}=G_f(1-w)\cdot(\mathrm{G}_0-\rho_g/\rho_f\cdot(\alpha_1 P_1)). \tag{13}$$

The density of the gas for the conditions of separation in B-1 is calculated by a formula that is similar to the formula:

$$P_g=(P_1/zT_1)\cdot\gamma_{cv}, \tag{14}$$

where $\gamma_{cv}=(\rho_{cv}\cdot T_{cv})/P_{cv}$.

The gas compressibility factor z is calculated from the Benedict-Webb-Rabin equation at a pressure P_1 and temperature T_1, while $T_1=T_0$. The solubility factor of natural gas α_1 was determined from the graphical dependence, which is given in [2] (Table 4).

The productivity of the B-2 separator for gas G_{g2} will be determined as the difference between the overall performance of the separation unit and the performance of the separator B-1

$$G_{g2}=G_g-G_{g1}. \tag{15}$$

The calculated values G_{g1} and G_{g2} are recorded in Table. 4.

Table 4 contains the data on the performance (volumetric) of Q_{g1} and Q_{g2} of B-1 and B-2 separators, which are brought to normal conditions under the following formulas

$$Q_{g,i}=k(G_{g,i}/\rho_n),\ i=1, 2, \tag{16}$$

where Q_{gi} has a dimension of nm^3/day.

Recalculation of gas density ρ_{cv} to normal conditions (P_{cv}=0.1013 MPa, T_{cv}=273 K) was carried out according to the following formula:

$$\rho_{cv}=\rho_{cv}(P_{cv}T_{cv}/P_{cv}T_{cv}). \tag{17}$$

Taking into account that the established mode of the separation system is considered, we find that:

$$\xi_f = G_f\Big/\sqrt{\rho_f(P_0-P_1)}. \tag{18}$$

Oil and gas mixture is supplied to the second stage of separation, which we calculate as the difference between the mass amount of oil and gas mixture G_f, supplied to the separation system and the amount of gas G_{g1} that has been isolated at the first stage of separation,

$$G_{f1}=G_f-G_{g1}. \qquad (19)$$

Then we determine the performance of the separator B-2 for oil by the formula, which is similar to the formula (19):

$$G_{o2}=G_{f1}-G_{g2}. \qquad (20)$$

The mass fraction of gas in the oil and gas mixture entering the second stage of separation will be as follows:

$$x_1=G_{g2}/G_{f1}. \qquad (21)$$

Since the established mode of the separation system is considered, we obtain the following system of algebraic equations from the equations (3)–(6), which describe the dynamics of the separation system:

$$\alpha_g(U_1)\frac{1}{\theta_g}\sqrt{\frac{\left(P_1^2-P_{g2}^2\right)}{\tilde{z}T_1}}+$$
$$+\alpha_o(U_2)\frac{P_1}{M_0}\sqrt{\rho_{f1}\left(P_1+\rho_{f1}gh\cdot 10^{-6}-P_2\right)}=$$
$$=\left(\frac{\varepsilon_g}{\theta_g}+\frac{P_1}{M_0}\varepsilon_{f1}\right)\xi_f\sqrt{\rho_f\left(P_0-P_1\right)}, \qquad (22)$$

$$\alpha_o(U_2)\sqrt{\rho_{f1}\left(P_1+\rho_{f1}gh\cdot 10^{-6}-P_2\right)}=$$
$$=\varepsilon_{f1}\xi_f\sqrt{\rho_f\left(P_0-P_1\right)}, \qquad (23)$$

$$\alpha_o(U_2)\left(\frac{\varepsilon_{g1}}{\theta_{g1}}+\frac{P_2}{M_{01}}\right)\sqrt{\rho_{f1}\left(P_1+\rho_{f1}gh\cdot 10^{-6}-P_2\right)}-$$
$$-\alpha_{g1}(U_{s1})\frac{1}{\theta_{g1}}\sqrt{\frac{P_2^2-P_{g3}^2}{T_2}}-$$
$$-\alpha_{o1}(U_{s2})\frac{P_2}{M_{01}}\sqrt{\rho_o\left(P_2+\rho_o gh_1\cdot 10^{-6}-P_3\right)}=0, \qquad (24)$$

$$\alpha_o(U_2)\sqrt{\rho_{f1}\left(P_1+\rho_{f1}gh\cdot 10^{-6}-P_2\right)}-$$
$$-\alpha_{o1}(U_{s2})\sqrt{\rho_o\left(P_2+\rho_o gh_1\cdot 10^{-6}-P_3\right)}=0. \qquad (25)$$

The system of equations (22)–(25) is linear according to the unknown values $\alpha_g(U_1)$, $\alpha_o(U_2)$, $\alpha_{g1}(U_{s1})$, and $\alpha_{o1}(U_{s2})$.

We introduce the following designations:

$$\alpha_{11}=\frac{1}{\theta_g}\sqrt{\frac{\left(P_1^2-P_{g2}^2\right)}{\tilde{z}T_1}},$$

$$\alpha_{12}=\frac{P_1}{M_0}\sqrt{\rho_{f1}\left(P_1+\rho_{f1}gh-P_2\right)},$$

$$\alpha_{22}=\sqrt{\rho_{f1}\left(P_1+\rho_{f1}gh-P_2\right)},$$

$$\alpha_{13}=0,\ \alpha_{14}=0,$$

$$\alpha_{21}=0,\ \alpha_{23}=0,\ \alpha_{24}=0,$$

$$\alpha_{31}=0,\ \alpha_{41}=0,\ \alpha_{43}=0,$$

$$\alpha_{32}=\left(\frac{\varepsilon_{g1}}{\theta_{g1}}+\frac{P_2}{M_{01}}\right)\sqrt{\rho_{f1}\left(P_1+\rho_{f1}gh-P_2\right)},$$

$$\alpha_{34}=-\frac{P_2}{M_{01}}\sqrt{\rho_o\left(P_2+\rho_o gh_1-P_3\right)},$$

$$\alpha_{33}=-\frac{1}{\theta_{g1}}\sqrt{\frac{P_2^2-P_{g3}^2}{T_2}},$$

$$\alpha_{42}=\sqrt{\rho_{f1}\left(P_1+\rho_{f1}gh-P_2\right)},$$

$$\alpha_{44}=-\sqrt{\rho_o\left(P_2+\rho_o gh_1-P_3\right)},$$

$$b_1=\left(\frac{\varepsilon_g}{\theta_g}+\frac{P_1}{M_0}\varepsilon_{f1}\right)\xi_f\sqrt{\rho_f\left(P_0-P_1\right)},$$

$$b_2=\varepsilon_{f1}\xi_f\sqrt{\rho_f\left(P_0-P_1\right)},\ b_3=0,\ b_4=0,$$

$$x_1=\alpha_g(U_1),\ x_2=\alpha_o(U_2),$$

$$x_3=\alpha_{g1}(U_{s1}),\ x_4=\alpha_{o1}(U_{s2}).$$

$$\alpha_{11}x_1+\alpha_{12}x_2+\alpha_{13}x_3+\alpha_{14}x_4=b_1,$$
$$\alpha_{21}x_1+\alpha_{22}x_2+\alpha_{23}x_3+\alpha_{24}x_4=b_2,$$
$$\alpha_{31}x_1+\alpha_{32}x_2+\alpha_{33}x_3+\alpha_{34}x_4=b_3,$$
$$\alpha_{41}x_1+\alpha_{42}x_2+\alpha_{43}x_3+\alpha_{44}x_4=b_4. \qquad (26)$$

The system of equations (25) was solved by the Gauss's reverse method with the choice of the maximal element [13].

When recording equations (22)–(25), it was taken into account that the pressures P_1, P_2, P_3, P_{g2} i P_{g3} are measured in MPa, and the hydrostatic pressure $P=\rho gh$ is measured in Pa.

When calculating the values of θ_g i θ_{g1} (Table 4), we assume that the temperatures in the separators B-1 and B-2 are the same. The gas constant R_g for natural gas, which is included in the expressions θ_g i θ_{g1} (Table 4), is calculated by the following formula [8]:

$$R_g=(288.15/\Lambda)\cdot 10^{-6}, \qquad (27)$$

where R_g is measured in MJ/kg·K.

7. Results of studies of a two-stage separation unit

The mathematical model (3)–(6) of the separation system will be solved with the following assumptions:

– pressures P_0, P_{g2} and P_{g3} are accepted as stable;

– the temperature of the gas stream entering the separation system and the temperature of the products in the separators B-1 and B-2 are the same and unchanged in time for the period of the transition time ($T_0=T_2=T_1$);

– we neglect the influence of temperature on the density of oil;

– the gas compressibility factor is computed at pressure

$$\tilde{P}_g = \frac{P_1 + P_{g2}}{2}$$

and temperature T_1;

– gas in the separator B-2 is considered ideal;

– we consider mass particles of gas x and x_1 in the separators B-1 and B-2 unchanged.

The input values that cause the change in the output values P_1 and P_3 and levels h_1 and h_2 in the separators B-1 and B-2 will be considered as changes in the values of α_g (U_1), α_o (U_2), α_{g1} (U_{s1}) and α_{o1} (U_{s2}).

We use the Runne-Kutta method [13] to solve the system of differential equations that describe the dynamics of the separation unit, which in the vector form implements the following iterative procedure:

$$\bar{f}_1^{(k)} = \bar{f}\left(\bar{y}_k\right),\ \bar{f}_2^{(k)} = \bar{f}\left(\bar{y}_k + \frac{h_t}{2}\bar{f}_1^{(k)}\right),$$

$$\bar{f}_3^{(k)} = \bar{f}\left(\bar{y}_k + \frac{h_t}{2}\bar{f}_2^{(k)}\right),\ \bar{f}_4^{(k)} = \bar{f}\left(\bar{y}_k + h_t\bar{f}_3^{(k)}\right),$$

$$\bar{y}_{k+1} = \bar{y}_k + \frac{h_t}{6}\left(\bar{f}_1^{(k)} + 2\bar{f}_2^{(k)} + 2\bar{f}_3^{(k)} + \bar{f}_4^{(k)}\right), \qquad (28)$$

where

$$\bar{y} = \begin{bmatrix} P_1 \\ h \\ P_2 \\ h_1 \end{bmatrix}$$

is the vector of output quantities;

$$\bar{f}(\bar{y}) = \begin{bmatrix} \frac{1}{1-\nu_p(h)}\left(\left(\frac{\varepsilon_g}{\theta_g} + \frac{P_1}{M_0}\varepsilon_{f1}\right)\xi_f\sqrt{\rho_f\left(P_0 - P_1\right)} - \right. \\ -\frac{\alpha_g(U_1)}{\theta_g}\sqrt{\frac{\left(P_1^2 - P_{g2}^2\right)}{\tilde{z}T_1}} - \\ \left. -\frac{P_1}{M_0}\alpha_o(U_2)\sqrt{\rho_{f1}\left(P_1 + \rho_{f1}gh\cdot 10^{-6} - P_2\right)}\right) \\ \frac{1}{q_p(h)M_0}\begin{pmatrix} \varepsilon_{f1}\xi_f\sqrt{\rho_f\left(P_0 - P_1\right)} - \\ -\alpha_o(U_2)\sqrt{\rho_{f1}\left(P_1 + \rho_{f1}gh\cdot 10^{-6} - P_2\right)} \end{pmatrix} \\ \frac{1}{1-\nu_{p1}(h_1)}\left(\left(\frac{\varepsilon_{g1}}{\theta_{g1}} + \frac{P_2}{M_{01}}\right)\alpha_o(U_2)\times\right. \\ \times\sqrt{\rho_{f1}\left(P_1 + \rho_{f1}gh\cdot 10^{-6} - P_2\right)} - \\ -\frac{P_2}{M_{01}}\alpha_{o1}(U_{s2})\sqrt{\rho_o\left(P_2 + \rho_o gh_1\cdot 10^{-6} - P_3\right)} - \\ \left. -\frac{1}{\theta_{g1}}\alpha_{g1}(U_{s1})\sqrt{\frac{P_2^2 - P_{g3}^2}{T_2}}\right) \\ \frac{1}{q_{p1}(h_1)M_{01}}\left(\alpha_o(U_2)\sqrt{\rho_{f1}\left(P_1 + \rho_{f1}gh\cdot 10^{-6} - P_2\right)} - \right. \\ \left. -\alpha_{o1}(U_{s2})\sqrt{\rho_o\left(P_2 + \rho_o gh_1\cdot 10^{-6} - P_3\right)}\right) \end{bmatrix},$$

is a vector-function, the components of which are right parts of the system of differential equations (3)–(6).

The step of discreteness h_t is calculated by the formula $h_t=(t_f-t_0)/n$, where t_0, t_f is the start and end time; n is the number of iterations in the computational process.

The program for solving the system of differential equations (3)–(6) is written in the algorithmic language of the MatLab package.

As an example of solving the system of differential equations (3)–(6), consider the change in the output values P_1, h, P_2 and h_1 in time, depending on the change in the input value α_o (U_2), which is defined as follows:

$$\alpha_o(U_2)=\alpha_o(U_2^{(0)})+\Delta\alpha_o(U_2). \qquad (29)$$

The increment of the value $\Delta\alpha_o$ (U_2) will be calculated as $\Delta\alpha_o$ $(U_2)=\chi\alpha_o$ $(U_2^{(0)})$.

Taking into account the value $\Delta\alpha_o$ (U_2), the formula (30) will take the form of:

$$\alpha_o(U_2)=\alpha_o(U_2^{(0)})(1+\chi). \qquad (30)$$

The values of α_g (U_1), α_o (U_2), α_{g1} (U_{s1}) and α_{o1} (U_{s2}), in essence, are the throughput characteristics of the regulatory bodies of the corresponding actuators (Fig. 1).

Table 5 establishes the correspondence between the parameters of the mathematical model (3)–(6) of the separation system and machine variables. In the same table, the numerical values of the values included in the model (3)–(6) are given.

In the process of solving the mathematical model (3)–(6), the following values of variables selected by the user were selected:

– the number of iterations n=500;

– the duration of the transition process t_f=800 sec;

– the change value of α_o ($U_2^{(0)}$) – χ=1.0.

The result of a numerical solution of a mathematical model is shown in Fig. 2–4.

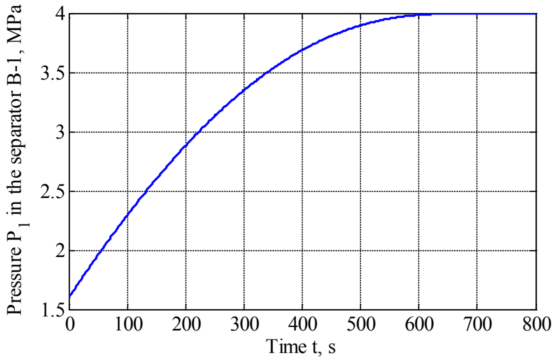

Fig. 2. The change of pressure $P_1(t)$ in the separator B-1 as a function of time t

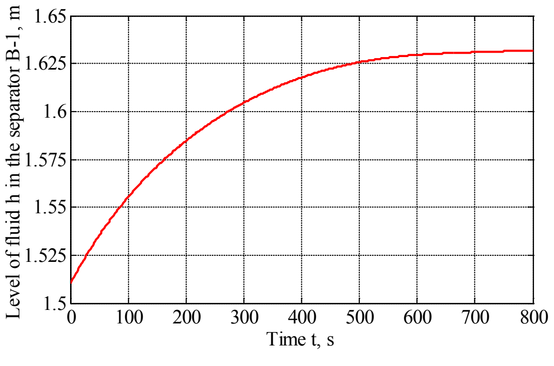

Fig. 3. The change of the fluid level $h(t)$ in the separator B-1

Table 5

Correspondence between the parameters of the mathematical model and the machine variables

Parameter name	Designation	Machine variable	Value
The degree of filling of the separator B-1	$v_p(h)$	Vp	0.5042
The degree of filling of the separator B-2	$v_{p1}(h_1)$	Vp1	0.4823
Density of oil and gas mixture	ρ_f	ro_f	70.47
–	θ_g	teta_g	830.2487
The intensity of change in the degree of filling of the separator B-1	$q_p(h)$	Q	0.4241
The intensity of change in the degree of filling of the separator B-2	$q_{p1}(h_1)$	q1	0.4243
Gas solubility factor	α_1	alpha1	0.44
Productivity of the separator B-1 by gas (mass)	G_{g1}	Gg1	0.6453
Productivity of the separator B-2 by gas (mass)	G_{g2}	Gg2	0.3037
–	$\alpha_g(U_1)$	alphag_U1	0.4761
Gas separation factor	ε_g	eps_g	0.3064
Productivity of the separator B-1 by liquid	G_{f1}	Gf1	1.4611
Separation factor of the separator B-1	ε_{f1}	eps_f1	0.6936
Productivity of the separator B-2 by oil	G_{o2}	Go2	1.1574
Density of liquid in the separator B-1	ρ_{f1}	ro_f1	60.30
Mass of liquid at $h=D$, where D is the diameter of the separator B-1	M_0	M0	$6.0301\cdot10^3$
–	$\alpha_o(U_2)$	alphaN_U2	0.1881
–	ξ_f	ksi_f	6.9298
Gas separation factor (second separation segment)	ε_{g1}	eps_g1	0.2079
–	θ_{g1}	teta_g1	829.05
Mass of liquid at $h1=D1$, where $D1$ is the diameter of the separator B-2	M_{01}	M01	84.300
–	$\alpha_{o1}(U_{s2})$	alphaN1_US2	0.0703
–	$\alpha_{g1}(U_{s1})$	alphaG1_US1	10.1204
Oil density	ρ_o	ro_ol	843

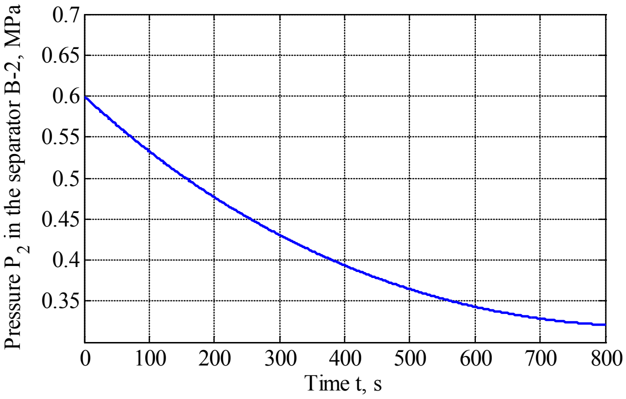

Fig. 4. The change of pressure P_2 in the separator B-2

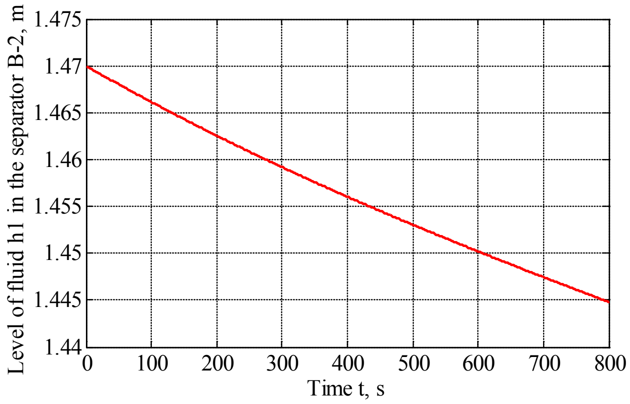

Fig. 5. The change of the fluid level h_1 (t) in the separator B-2

The above graphs (Fig. 2–5) for the steady-state operation of the two-stage separation system are the result of a program that is written in the Matlab algorithmic language.

8. Discussion of the results of the study of the simulation model of the process of two-stage oil separation

The mathematical model of the process of two-stage separation is obtained, which, in contrast to the known models [10, 13], takes into account the interaction of the first and second stages of separation. The simulation model of the two-stage separation system is investigated by a numerical method in the MatLab's mathematical laboratory to change the key parameters of the level and pressure in each separator. The results obtained in the form of graphs (Fig. 2–5) describe the dynamics of transients for each separator individually, which collectively reflects the work of the system in general.

Due to the combination of two horizontally placed B-1 and B-2 separators and an oil storage tank, functional dependencies were obtained that allow establishing the interconnection of the technological parameters, in other words, the change in the value of the parameters at the second stage of separation will depend on the first one and vice versa. The advantage of such use of technological equipment is the possibility of improving the one-stage technological process of oil separation, in particular, increasing the overall oil separation factor. The study was conducted with the following assumptions:

– pressures P_0, P_{g2} and P_{g3} are accepted as stable;

– the temperature of the gas stream entering the separation system and the temperature of the products in the separators B-1 and B-2 are the same and unchanged in time for the period of the transition time (T_0=T_2=T_1);

– the gas compressibility factor is computed at pressure and temperature T1;

– we considered gas in the separator B-2 ideal;

– we considered mass particles of gas x and x_1 in the separators B-1 and B-2 unchanged. The disadvantage is the neglect of the influence of temperature on the density of oil.

This simulation model is investigated by a numerical method in MatLab and can be used to synthesize effective control systems for the process of two-stage separation and to create mathematical models in terms of “input-output”. Difficulties in further research may be low informing about the processes associated with oil production and not taking into account new perturbations that can influence the system in general.

9. Conclusions

1. A mathematical model of the material balance of the two-stage separation for the first B-1 and the second B-2 horizontally placed separators is created, which takes into account the interaction and mutual influence of the first and second stages of separation. Automated control systems that operate on the principle of negative feedback were used to stabilize the main technological parameters of oil separation. Since the deviations of the regulated quantities from their prescribed values are small, this allowed linearizing the nonlinear model of the two-stage process of oil separation.

2. The parameters of the mathematical system of two-stage separation for simulation modeling are identified. All values of physical quantities are obtained for the steady mode of operation of the two-stage separation system. During the identification of the parameters, it was assumed that the pressures P_1, P_2, P_3, P_{g2} and P_{g3} are measured in MPa, and the hydrostatic pressure $P=\rho g h$ is measured in Pa, and it is assumed that the temperatures in the separators B-1 and B-2 are the same when calculating the values of θ_g and θ_{g1}.

3. As a result of the research of the newly created simulation model in the MatLab program, it was determined that the increase in pressure P_1 is the increase in the fluid level h in the separator B-1 from 1.51 m to 1.6319 m. It was also established that an increase in the hydraulic resistance due to the closure of the regulatory body of the executive mechanism of the ED_h, which is mounted on the initial line of the separator B-1, causes an increase in pressure P_1 from 1.6 MPa to 3.9970 MPa. On the basis of changes of the technological parameters P_1 and h in the separator B-2, it is obvious that the liquid level h_1 is from 1.47 m to 1.4448 m due to the decrease in the flow of liquid from the separator B-1. Such a decrease in the liquid level in the separator B-2 entails a reduction in the pressure P_2 from 0.6 MPa to 0.3210 MPa. This means that the received scientific result in the form of functional dependencies allows us to establish the relationship of technological parameters, in other words, the change of the value of the parameters at the second stage of separation will depend on the first one and vice versa. Thus, the applied aspect of using the obtained scientific result is the possibility of improving the typical technological process of oil separation.

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