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MATHEMATICAL MODEL OF GAS-LIQUID-SAND MIXTURE SEPARATION IN THE FOUR-PHASE SEPARATOR OF INERTIAL TYPE FOR SUBSEA APPLICATION

1. INTRODUCTION

Analyzing the mechanism of separation and its performance, the stream that comes from the inlet pipe to the separator is observed, which has a nature a four-phase gas--liquid-sand mixture. Drops of liquid phase (condensated water) are formed in the flow from the source of admission (reservoir) and to the entrance of the separator. The sand particles are directed to dranage tube and are mixed with water to be evacuated from separator. Oil passes through the outlet oil pipe as lighter fluid. Then oil and gas is pumped by multiphase twin screw pump to the floater. In order to evaluate the efficiency of the separator is necessary to know the volumetric content of the liquid phase ω, the average drop radius R_c and the distribution of them in size $n(R)$. During the development of subsea deposits [1–3] and movement of mixture from the reservoir to the separator the pressure and temperature are continuously changing. As a result the thermodynamic equilibrium of the whole four-phase multi-component system is disturbed and the process of mass transfer (condensation and evaporation) between phases is realized. We are analizing in article the separation of two main components of mixture – gas and water.

2. MATHEMATICAL MODEL

Condensation leads to the formation of small droplets whose size varies due to condensation growth in supersaturation conditions and coagulation as well as grinding in

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the gas stream. As a result, in the inlet pipe before the separator some equilibrium distribution of droplets in size is created, which is characterized by the parameters ω, R_c and σ_1, where σ_1^2 – variance distribution.

If before the separator there is not any the device of prior condensation, the gas flow with established distribution $n(R)$ enters the separator, in which the phase separation is realized. In this case, the basic mechanisms of the droplets formation in a turbulent gas stream is pounding and coagulation processes. Both processes occur simultaneously. As a result, a size distribution is established, which according to experimental data, has the form of lognormal distribution:

$$n(R) = \frac{n_* \cdot R_1}{\sigma_1 \cdot R} \exp\left\{-\frac{\ln^2(R/R_1)}{2\sigma_1^2}\right\} \tag{1}$$

where:

R – radius of the droplet,

$n_* = 3\omega \exp\left(-2.5\sigma_1^2\right) / 4\pi\sqrt{2\pi} R_c^4$,

$R_1 = R_c \exp\left\{-0.5\sigma_1^2\right\}$.

Estimation of the variance distribution showed that over a wide speed range, characteristic for separators, $\sigma_1 = 0.4–0.5$ [4].

To determine the average radius R_c of drops it's necessary to consider the mechanism of coagulation and crushing. It is known that the drops in the gas stream are crushed when their radius exceeds a certain critical value.

Probability of drops crushing with a radius smaller than the critical, very small and therefore they can only coagulate until their size reaches a critical value again. Therefore, as a medium radius it's necessary to take a critical radius, which has been determined experimentally in a turbulent gas stream. Treatment of experimental results led to a following empirical formula:

$$R_{кр} = 0,12d \cdot \mathrm{We}^{-3/7} \cdot (\rho/\rho_1)^{4/7} \tag{2}$$

where:

ρ – density of the gas phase,

ρ_1 – density of the liquid phase,

$\mathrm{We} = \frac{\rho \Delta u^2 d}{\sigma}$ – number of Weber,

Δu – difference of gas velocity in the pipe at the inlet and outlet,

d – diameter of the pipe,

σ – surface tension of the liquid phase.

The main parameter that characterizes the degree of separation of liquid from the gas separator is the efficiency factor equal to the ratio of volume of the liquid phase Q_{dep}, which is deposited in the separator, to the volume of the liquid phase Q_{lp} contained in the gas stream at the inlet of the separator:

$$\eta = \frac{Q_{dep}}{Q_{lp}}$$

So, determined efficiency factor η depends on the design of the separator, thermobaric conditions, flowsheet parameters, composition and physico-chemical properties of gas-liquid flow.

Since the inertial separators, construction of which we consider, the separation of gas and liquid phase mixture is very fast, the change in the separator thermobaric conditions, in our opinion, does not have time significantly affect the initial distribution of droplets, which is the input stream gas-liquid mixture. Based on this assumption separator efficiency ratio should be calculated according to the formula:

$$\eta = 1 - \frac{\omega_1}{\omega_0} \tag{3}$$

where ω_1 – volumetric liquid content in the flow inlet separator, equal to:

$$\omega_0 = \int_0^{\infty} V \cdot n_0(R)\,dR \tag{4}$$

where ω_0 – volumetric liquid content in the stream at the outlet of the separator, equal to:

$$\omega_1 = \int_0^{R_m} V \cdot n_0(R)\,dR \tag{5}$$

where:

$V = \frac{4}{3}\pi R^3$ – the volume of drop,

$n_0(R)$ – initial distribution of droplets at the inlet,

R_m – minimum radius of droplets that settle in the separator.

Substituting (4) and (5) into (3), we obtain:

$$\eta = 1 - \frac{4\pi}{3\omega_0}\int_0^{R_m} R^3 \cdot n_0(R)\,dR \tag{6}$$

If we take as initial distribution lognormal distribution, given by (1), then we have the final expression for determining the efficiency of the separator:

$$\eta = 1 - \frac{\exp\left(-3\sigma_1^2\right)}{\sqrt{2\pi}\cdot\sigma_1}\int_0^{Z_m} z^2 \exp\left\{-\frac{\ln^2\left(z/z_1\right)}{2\cdot\sigma_1^2}\right\}dz \tag{7}$$

where:

$Z_m = R_m / R_c$,

$z_1 = R_1 / R_c = \exp\left(-0.5\sigma_1^2\right)$.

From the expression (7) for the coefficient of performance is known that the efficiency of the separator is determined by the upper limit of the integral Z_m, and thus by the limit of minimum radius of drops R_m – that are deposited in the separator. It is therefore necessary to explore the process of separation of droplets in the separator, the design of which is shown in Figure 1. The separator consists of two coaxial cylinders of equal height, outer radius r_2, and inner radius r_1, and has holes jalousie type. To the inner surface of the outer cylinder is adjacent pipe through which a mixture by the inlet pipe of diameter d is fed into the space between the cylinders.

The main factors that determine the efficiency of the separator is the centrifugal force T directed from the axis to the periphery and opposite her in direction the resistance force R. Considering the traffic of drops the vertical forces acting on it are neglected to simplify the calculation model, and it is assumed that it moves in a plane perpendicular to the axis of the separator. This assumption somewhat simplifies the true picture of drops traffic, but given the fact that the centrifugal force plays a major role, it is quite justified.

In other similar conditions (diameter of droplet, its density, viscosity and density of the medium) the resistance force of medium depends on the radial velocity component υ_r, and centrifugal force T – from centrifugal acceleration a, which, in turn, is directly proportional to the square of the tangential velocity υ_t $\left(a = \frac{V_t^2}{2}\right)$.

Centrifugal force to drop, which is located in the gas stream can be found by the formula:

$$T = \frac{4\pi\cdot R^3\left(\rho_1 - \rho\right)\upsilon_t^2}{3r} \tag{8}$$

where:

- r – radius of the trajectory drop,
- υ_t – tangential velocity at radius, r,
- R – radius of the drop,
- ρ_1 – density of the liquid phase,
- ρ – density of the medium.

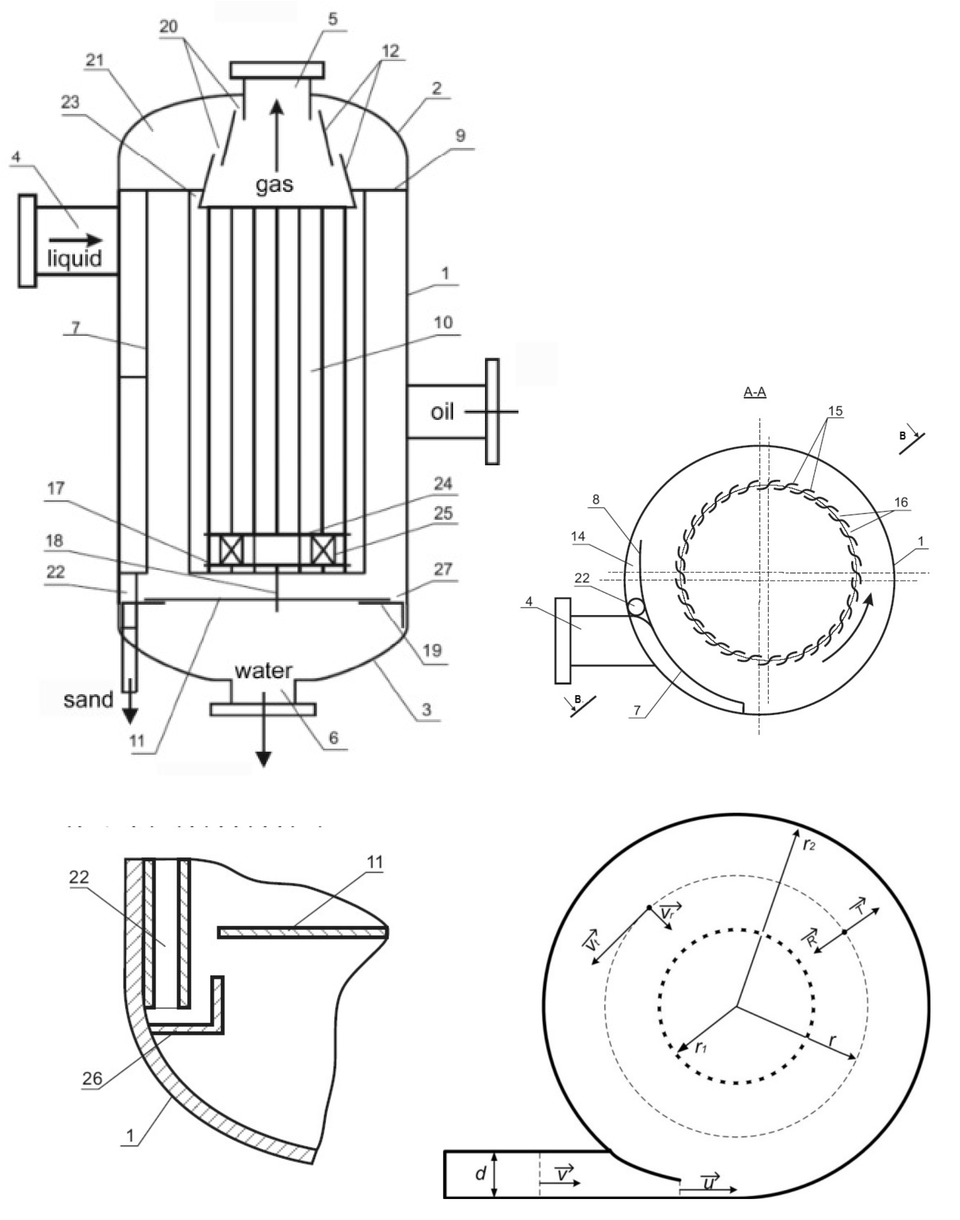

Fig. 1. Scheme of inertial vortex type 4-phase separator

1 – cylindrical housing, 2 – cover, 3 – bottom, 4 – inlet, 5 – gas outlet, 6 – water outlet, 7 – deflector, 8 – plate of attack, 9 – horizontal divertor, 10 – separation set, 11 – conditional bottom, 12 – conical directional confusor, 13 – outlet orifice, 14 – catch pocket, 15 – separation plates, 16 – split channels, 17 – disk, 18 – pin, 19 – L-form plates, 20 – clearances ring, 21 – chamber of accumulation, 22 – drainage pipe, 23 – catching space, 24 – axial disk, 25 – radial plates, 26 – space for a sand drainage pipe, 27 – circular clearance

Resistance of environment consists of a dynamic resistance P and viscosity resistance S. Dynamic resistance, according to Newton's law, is expressed by the formula:

$$P = \frac{\pi}{3} R^2 \rho \upsilon_r^2 \tag{9}$$

Frictional resistance is given by the formula Stokes:

$$S = 6\pi\mu R \upsilon_r \tag{10}$$

where:

μ – dynamic viscosity of the medium,

υ_r – radial velocity.

Although both resistances act simultaneously, their values are different and depending on the speed of the medium and the size of the drop. If for some dimention of drop will be carried condition $T = P + S$, then they will be in equilibrium and can be a long time (except for the coagulation process drops) circulate in the separator. Droplets larger are discarded by centrifugal force to the outer wall of the separator; droplets smaller than the limit R_m, would be subjected to the internal wall of the separator and are going through the holes in it fall into the inner vortex flow upward.

The equilibrium of drop can be expressed by the equation:

$$\frac{4}{3}\pi R_m^3 (\rho_1 - \rho)\frac{\upsilon_t^2}{r} = \frac{\pi}{3} R_m^2 \rho \upsilon_r + 6\pi \upsilon_r \mu R_m$$

or

$$\frac{4}{3}(\rho_1 - \rho)\frac{\upsilon_t^2}{r} R_m^2 - \frac{1}{3}\rho \upsilon_r^2 R_m - 6\mu \upsilon_r = 0 \tag{11}$$

Solving quadratic equation (11) with respect to R_m, we obtain:

$$R_m = \frac{\frac{1}{3}\rho \upsilon_r^2 r + \sqrt{\frac{1}{9}\rho^2 \upsilon_r^4 r^2 + 32(\rho_1 - \rho)\mu \cdot \upsilon_t^2 \cdot \upsilon_r \cdot r}}{\frac{8}{3}(\rho_1 - \rho)\upsilon_t^2} \tag{12}$$

In order to be able to find R_m from formula (12), it is necessary to know the dependence υ_t and υ_r from the radius of rotation trajectory r. Find the radial velocity of the conditions of continuity of flow that passes through the coaxial cylinders inside the separator:

$$\upsilon_r = \frac{Q}{2\pi h r} \tag{13}$$

where:

- Q – separator performance,
- r – radius of the coaxial section,
- h – height of coaxial cylinder, which can be considered equal to the height of the separator.

Based on the analysis of theoretical and experimental studies we can assume that the relationship between υ_t and r to move the mixture in the separator is characterized by the equation:

$$\upsilon_t \cdot r^n = \text{const} \tag{14}$$

where the exponent n is determined by the turbulence of flow mixture. At low turbulence it is close to 1, while high – up to 0.3–0.5.

For practical calculations a first approximation the exponent n can be taken as 0.5.

The constant in (14) can be determined using the boundary condition, which is that the tangential flow velocity at radius r_2 is equal to speed in the underwater section of the pipe, ie $\upsilon_t = u$ at $r = r_2$. Then the tangential velocity of the mixture at a radius r from the axis of the separator is equal to:

$$\upsilon_t = \left(\frac{r_2}{r}\right)^n \cdot u \tag{15}$$

Velosity u of mixture fed to the separator through the inlet pipe can be found from the formula:

$$u = \varphi \cdot \sqrt{\frac{2\Delta p}{\rho} + \left(\frac{4Q}{\pi d^2}\right)^2} \tag{16}$$

where: φ – speed ratio that takes into account the speed reduction of flee due to losses and uneven distribution of velocities in the hole due to changes in the shape and size of the cross-sectional feeding pipe. If the change is smooth, in the first approximation the loss rate is negligible and assumed by $\varphi \approx 1$.

However, it should be noted that due to the expansion of mixture jet and friction against the wall of separator speed υ_t on radius r_2 is slightly smaller than the velocity u. More precisely, this speed can be determined if you know the pressure distribution along the radius of the separator using the formula:

$$\frac{\upsilon_t^2}{r} = \frac{1}{\rho} \cdot \frac{dp}{dr} \tag{17}$$

You can get a simpler formula than (12) to calculate R_m, considering the two limiting cases. If the force that occurs under the influence of radial flow of gas within the law of Stokes, which happens at low Reynolds numbers, the critical resistance of the viscosity is crucial and value *P* can be neglected. At high Reynolds numbers dynamic resistance plays a key role, and the value of *S* can be neglected.

Reynolds number Re for the separator can be found from the following expression:

$$\mathrm{Re} = \frac{\Delta \upsilon_r D \rho}{\mu} \tag{18}$$

where:

$D = 2R$ – average diameter of the droplets,

υ_r – radial velocity,

μ – dynamic viscosity of the medium.

Thus, for large values of Re are:

$$R_m = \frac{\rho \Delta \upsilon_r^2 \cdot r}{4(\rho_1 - \rho)\upsilon_t^2} = \frac{\rho d^4 \cdot r^{2n-1}}{256(\rho_1 - \rho)h^2 r_2^{2n}} \tag{19}$$

and for small values of Re are:

$$R_m = \sqrt{\frac{9\mu r \upsilon_r}{2(\rho_1 - \rho)\upsilon_t^2}} = \frac{3}{8}\left(\frac{r}{r_2}\right)^n d^2 \cdot \sqrt{\frac{\pi\mu}{hQ(\rho_1 - \rho)}} \tag{20}$$

The above formulae (19) and (20) to determine the radial u_t and tangential u_r rates do not include the compressibility of gas-liquid mixture. They can be used in the case of poor performance separator at velocities $u \le 0.2\, a$ (where a – speed of sound in the mixture). For natural gas speed limit below which you can not ignore the compressibility of gas is equal to 90 m/s.

In the case of large values of performance (flow rates) of separator, hence of large potential differential pressure on inlet tube of separator, it's necessary to consider the compressibility of gas-liquid mixture.

In the first approximation we neglect losses caused by internal friction and a change in shape and size inlet ($\varphi \approx 1$), and process of flee the mixture in the separator is considered adiabatic, then flee rate can be determined by the St Venant formula:

$$u = \sqrt{\frac{2k}{k-1}\frac{p}{\rho}\left[1 - \left(\frac{p_1}{p}\right)^{\frac{k-1}{k}}\right] + \upsilon^2} \tag{21}$$

where:

$\upsilon = \dfrac{Q_m}{\rho F}$ – the speed of the mixture in the inlet tube,

$Q_m = \rho_0 Q$ – mass flow rate of mixture,

ρ_0 – density of the mixture under normal conditions, ρ – density of the mixture in the inlet pipe, which can be expressed in terms of the pressure p in it, using the real gas equation of state $\frac{p}{\rho} = zRT$ (z – coefficient of compressibility, which for each gas is a function of reduced pressure and temperature, determined experimentally),

p_1 – pressure in separator, near its outer wall on the radius r_2,

k – adiabatic index (for natural gas $k \approx 1.3$ and for air $k \approx 1.4$),

$F = \frac{\pi d^2}{4}$ – cross sectional area of inlet pipe,

T – temperature of the mixture in the inlet pipe,

$R = 8.31\ \frac{\text{J}}{\text{mole}\cdot\text{K}}$ – universal gas constant.

Since the high speed mixture density can not be sustained, it is necessary to know how depend the pressure and density of the mixture in the separator on the radius of rotation. We assume that the temperature of the mixture in all places is the same and equal to temperature at the site of flee in the separator, which is defined by the formula:

$$T_1 = T - \frac{k-1}{2k}\frac{M}{R}\left(u^2 - \upsilon^2\right) \tag{22}$$

where:

T – temperature,

υ – velocity of the mixture in inlet pipe,

u – flee velocity of mixture in the separator,

M – molecular weight of the mixture.

We find the dependence of the pressure in the separator on the distance r to its axis. For this we use the formula (17) by substituting into it the expression of density through the pressure from the equation of state of real gas:

$$dp = \frac{pM}{zRT}\frac{\upsilon_t^2}{r}dr \tag{23}$$

Dividing the variables, this equation can be integrated over:

$$\ln p = \frac{M}{zRT}\int \frac{\upsilon_t^2}{r}dr + \ln C \tag{24}$$

Substituting in the formula (24) the expression (15) for the tangential velocity υ_t and determining the constant C from the initial conditions $p(r = r_2) = p_1$, we obtain:

$$p(r) = p_1 \exp\left\{\frac{Mu^2}{2nzRT_1}\left[1 - \left(\frac{r_2}{r}\right)^{2n}\right]\right\} \tag{25}$$

Then the density of the mixture is determined by the formula:

$$\rho(r) = \frac{p(r)M}{zRT_1} \tag{26}$$

and radial velocity by the formula:

$$\upsilon_r = \frac{Q_m}{2\pi r h \rho(r)} \tag{27}$$

The above formulas allow us to study the dependence of the efficiency of the separator on various parameters. From the expression (7) one can find that the efficiency ratio is defined by dispersion distribution of droplets σ_1 along the radius and parameter Z_m, which is the upper limit of the integral in this expression. This parameter is equal to the ratio of the limit minimum radius of drops R_m, which are deposited in the separator, the average radius R_c of drops that are formed in the inlet pipe. Therefore, its value and, consequently, the coefficient of efficiency of the separator depends on the physico--chemical properties of gas-liquid mixture (molar mass M, density ρ, dynamic viscosity coefficient μ and compressibility z of the gas phase, liquid phase volume content ω, it density ρ_1 and the surface tension coefficient σ), geometric parameters (diameter of inlet pipeline d, working height h, r radius of outer r_2 and inner r_1 of separator cylindrical walls) and the performance of separator (volumetric flow of gas Q). Numerical study of the dependence of the coefficient of efficiency on the above parameters shows that the separator efficiency ratio is close to unity in a wide range of reasonable changes that could indicate high efficiency of this method of separation.

To investigate the influence of physical and technological parameters on the operation of the separator performance, we have taken the air-water mixture, but the conclusions derived from these functional dependencies do not lose their generality and can be applied to any two-phaze gas-liquid mixture, such as wet gas that must be drained before use.

The Figure 2 illustrates the diagrams dependence of the efficiency η on the parameter Z_m for different values of dispersion distribution along the radius of liquid drops $\sigma_1$that are formed in inlet pipeline. As seen from this figure, when $Z_m = 0.5$ the efficiency ratio is equal to 1 for any value of the variance, while whis the further its growth it decreases as sharper, as the smaller is the variance of the distribution.

Figure 3 shows the dependence of the efficiency η on the pressure p in the feeding tube for different values of gas flow Q. The figure shows that the efficiency ratio with increasing of pressure initially increases gradually and reaches its maximum value and then gradually decreases. The maximum coefficient of performance achieved in the area at p = 5–8 MPa. Increasing the gas flow leads to a significant reduction in the efficiency and narrowing of the horizontal section of the chart, where its value is close to the maximum.

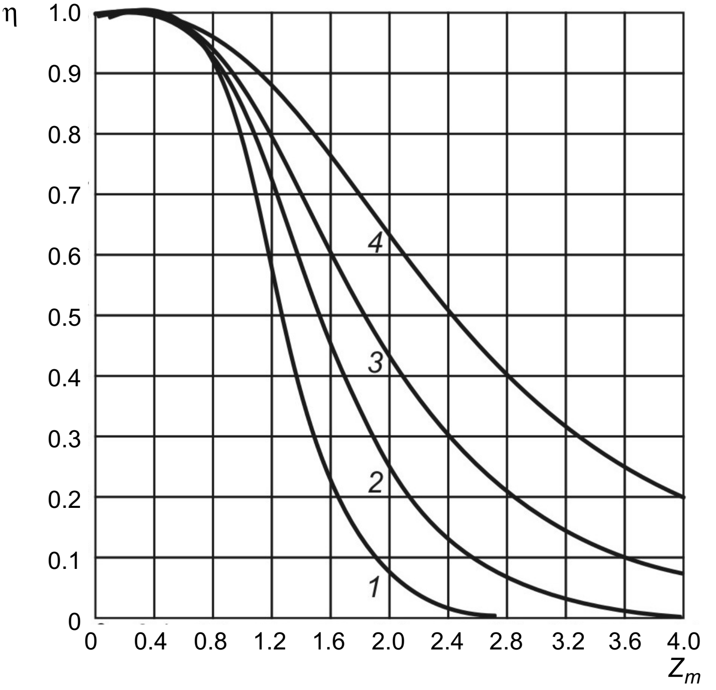

Fig. 2. Dependence of the efficiency η on the parameter Z_m for different distribution of variance values σ_1: 1) 0.3, 2) 0.4, 3) 0.5, 4) 0.6

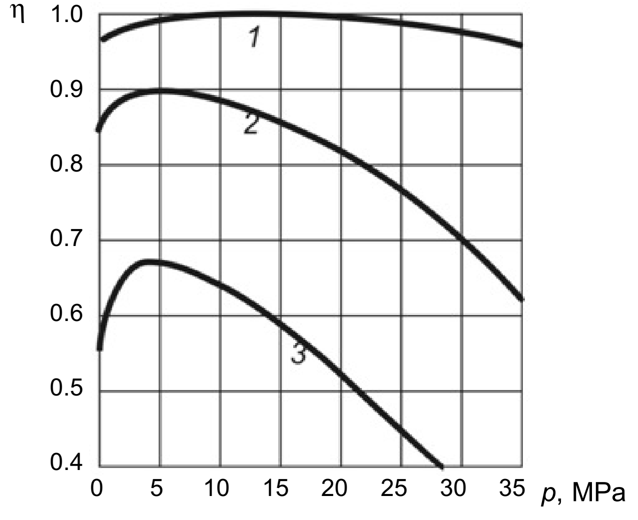

Fig. 3. Dependence of the efficiency η on the pressure p for different values of gas flow rate Q, m^3/s ($d = 0.15$ m, $M = 29 \cdot 10^{-3}$ kg/mole, $T = 300$ K, $p = 10$ MPa, $k = 1.4$, $\rho_1 = 10^3$ kg/m^3, $\mu = 10^{-5}$ Pa · s, $z = 1$, $\sigma = 0.03$ N/m, $h = 0.25$ m, $r_1 = 0{,}1$ m, $r_2 = 0.2$ m, $r = 0{,}17$ m, $n = 0.5$): 1) 20, 2) 40, 3) 60

The Figure 4 presents the diagrams dependence of the efficiency η on the gas flow Q for two different inlet pipes of diameters d. From these, it follows that with increasing of gas flow the efficiency ratio decreases, and the stronger with the larger diameter of the inlet pipe. The decrease of the coefficient of efficiency with increasing of pressure, gas flow and diameter of inlet pipe can be qualitatively explained as follows. Increasing pressure leads to an increase in gas density and decrease of its speed in inlet tube, which causes an increase of average radius of the droplets R_c, which are formed in it. Decrease of speed in the input stream in the separator, and increase of gas density leads to a decrease in the centrifugal force acting on the droplet, and therefore the limit radius of drops R_m, which precipitate on the inner surface of the outer wall of the separator will grow faster than their average radius. As a result, the parameter Z_m will increase and the efficiency ratio will decrease. It should also be noted that the pressure effects on the surface tension of the liquid. Coefficient of surface tension with increasing of pressure initially decreases sharply and then changed slightly. Therefore, increasing of the pressure in other similar conditions, initially reduces the average size of drops, and then leaves it practically unchanged, which does not qualitatively change the above-mentioned dependence of the efficiency on the pressure.

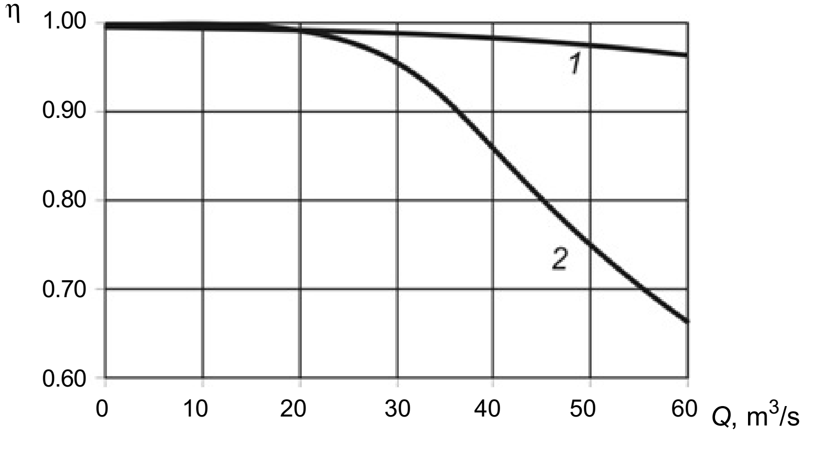

Fig. 4. Dependence of the efficiency η on the flow of gas Q for two different values of d, ($M = 29 \cdot 10^{-3}$ kg/mole, $T = 300$ K, $p = 10$ MPa, $k = 1.4$, $\rho_1 = 10^3$ kg/m^3, $\mu = 10^{-5}$ Pa · s, $z = 1$, $\sigma_1 = 0.4$, $\sigma = 0.03$ N/m, $h = 0.25$ m, $\rho_1 = 0.1$ m, $r_2 = 0.2$ m, $r = 0.17$ m, $n = 0.5$): 1) 0.1, 2) 0.15

Increasing the flow of gas at constant pressure increases the velosity of the input stream gas in separator, and hence the tangential component of velocity and centrifugal force acting on the drop, but on the other hand, increases the radial component of the gas velocity υ_r, through which the drops are forced by resistance and friction forces directed against the centrifugal force. Moreover, the significant flow and pressure will significantly increase the resistance force of pressure, the magnitude of which is proportional to the gas density and the square of radial velocity. Therefore, the increase of gas flow resistance force will grow faster than the centrifugal force, and the efficiency ratio will decline.

Obviously, the input flow rate at a given pressure and gas flow will be the smaller, the larger the diameter of the inlet pipe. Therefore, the centrifugal force will be smaller at a constant force of resistance, which is determined by the radial component of velocity, which depends on the flow of gas. Thus, the efficiency ratio decreases sharply with increasing of the inlet pipe diameter.

Figure 5 shows the dependence of the efficiency η on the height of the working area of separator h for different values of gas flow Q. As shown in Figure 5, the increase of the height of the working area greatly increases the efficiency ratio of separator.

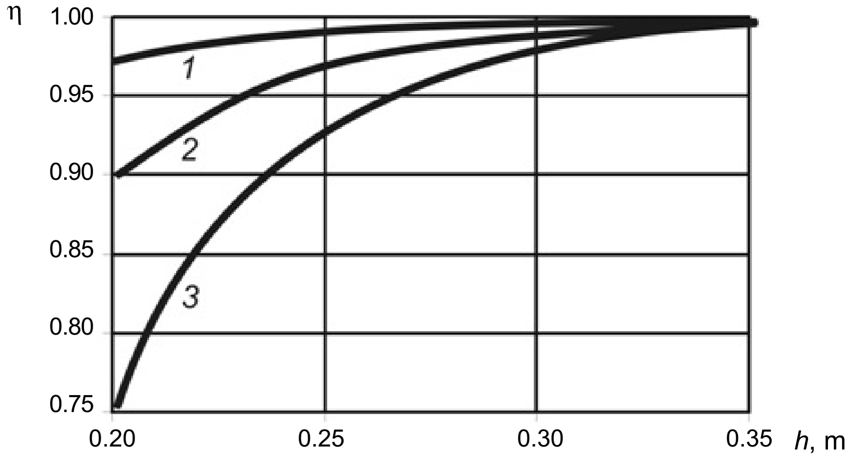

Fig. 5. Dependence of the efficiency η on the height of the working area of separator h, m for different values of the gas flow rate Q, m^3/s ($d = 0.13$ m, $M = 29 \cdot 10^{-3}$ kg/mole, $T = 300$ K, $p = 10$ MPa, $k = 1.4$, $\rho_1 = 10^3$ kg/m^3, $\mu = 10^{-5}$ Pa · s, $\sigma = 0.03$ N/m, $h = 0.25$, $r_1 = 0.1$ m, $r_2 = 0.2$ m, $r = 0.17$ m, $\upsilon = 0.15$, $z = 1$, $n = 0.5$, $\sigma_1 = 0.4$): 1) 20, 2) 30, 3) 40

This is because at a constant speed of input stream, which means that at a constant centrifugal force, the resistance decreases sharply as the radial velocity decreases, the value of which is inversely proportional to the height of the working area of separator.

In this regard, the result should produce the inlet pipe so that at a constant cross-sectional area its shape smoothly passed from cylindrical to rectangular with a hole in the form of a narrow slit adjacent to the outer wall of the separator. The greater is the length of the slit so the larger is height of working area of separator and the greater its efficiency factor.

Efficiency ratio significantly depends on the differencial pressure at the inlet of the separator. In Figure 6 shows the dependence of the efficiency η expressed as a percentage of the relative pressure drop at the inlet of the separator for different values of gas flow Q. From these relationships, we can conclude that with the increase of pressure drop coefficient of efficiency increases dramatically and even a slight pressure drop (about 0.3% of the working pressure) provides efficiency factor close to 1 for sufficiently large flow.

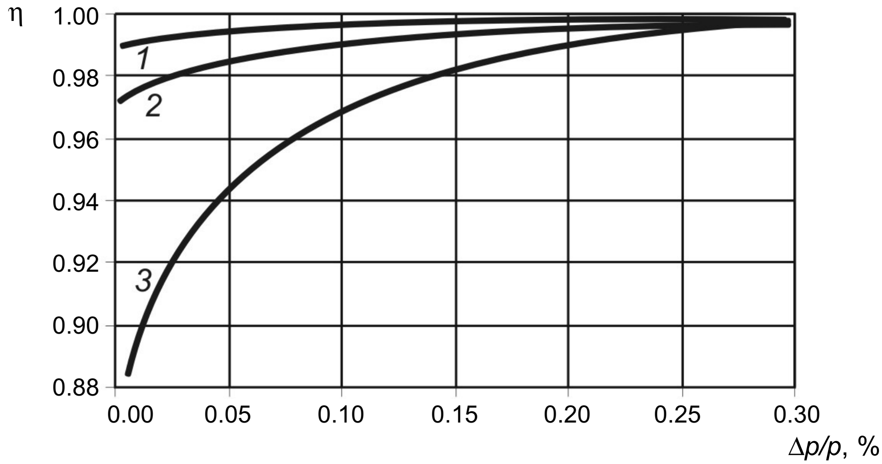

Fig. 6. Dependence of the efficiency η on the relative difference pressure $\Delta p/p$, % at the inlet in separator for different values of gas flow rate Q, m^3/s ($d = 0.13$ m, $M = 29 \cdot 10^{-3}$ kg/mole, $T = 300$ K, $p = 10$ MPa, $k = 1.4$, $\rho_1 = 10^3$ kg/m^3, $\mu = 10^{-5}$ Pa · s, $\sigma = 0.03$ N/m, $\sigma_1 = 0.4$, $h = 0.25$, $r_1 = 0.1$ m, $r_2 = 0.2$ m, $r = 0.17$ m, $z = 1$, $n = 0.5$): 1) 20, 2) 30, 3) 40

This result is quite clear and is explained by the fact that whis the increase of pressure drop input gas flow rate increases sharply, which increases the centrifugal force at a constant force of resistance (gas flow rate remains constant).

We believe it is important to investigate the pressure distribution of gas-liquid mixture which rotates in the separator depending on the distance r to the axis.

Figure 7 shows the theoretical dependence of the pressure in the separator on the distance to its axis, obtained by formula (25) for different values of the exponent n in the equation for the tangential velocity (15). Since the value of this parameter depends on the mode of motion, the comparison of the experimental curves obtained in a particular installation with theoretical allow to find the degree of turbulent motion of the mixture in the separator points that are located at different distances from its axis.

In order to clarify important issues in our opinion the effect of volume content of the liquid phase in the mixture on the efficiency ratio separator, we have suggested that the increase of the liquid in the mixture increases its viscosity. We obtained the following reasons. First, with increasing content of liquid phase properties of gas-liquid mixture should approach to the properties of the liquid.

Second, with increasing liquid content greatly increases the number of small droplets that are moving with the gas flow towards the large droplets, washing them exert some resistance to their movement. Thus we can somewhat formally assume that the coefficient of dynamic viscosity of the gas phase with increasing liquid content increases. Although this question, in our opinion, requires more detailed experimental and theoretical study. In view of the above, we believe appropriate result in Figure 8 dependence of the efficiency η of the dynamic viscosity coefficient μ for different values of gas flow Q.

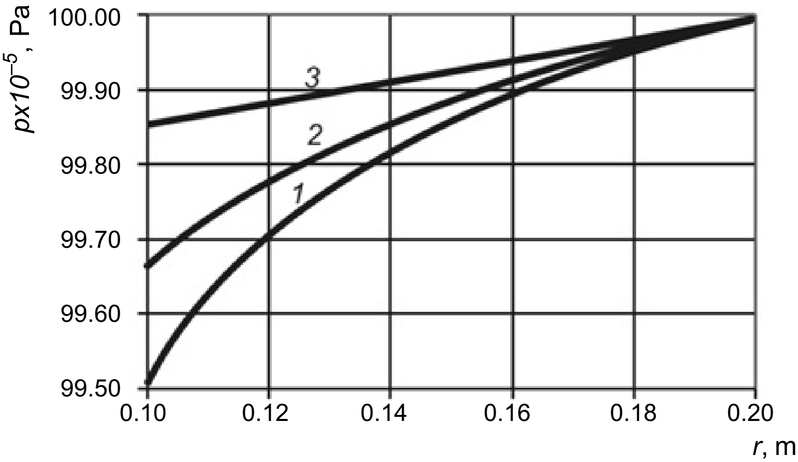

Fig. 7. The dependence of the pressure p inside the separator on the distance r to the axis of rotation of mixture at a pressure near the outer wall of the separator $p_1 = 10$ MPa and gas flow $Q = 30$ m^3/s for three different values of the exponent n in equation (15). (All other settings are the same as for Fig. 3.): 1) $n = 1$, 2) $n = 0$, 3) $n = -1$

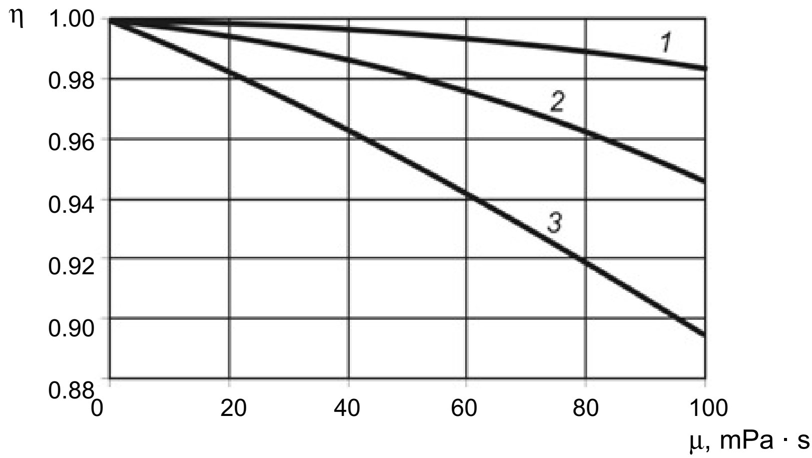

Fig. 8. Dependence of the efficiency η on the dynamic viscosity coefficient μ for different values of gas flow rate Q, m^3/s ($\sigma_1 = 0.4$, $d = 0.13$ m, $M = 29 \cdot 10^{-3}$ kg/mole, $T = 300$ K, $p = 10$ MPa, $k = 1.4$, $\rho_1 = 10^3$ kg/m^3, $\mu = 10^{-5}$ Pa · s, $\sigma = 0.03$ N/m, $h = 0.25$ m, $r_1 = 0.1$ m, $r_2 = 0.2$ m, $r = 0.15$ m, $z = 1$, $n = 0.5$): 1) 20, 2) 30, 3) 40

These dependences show that the efficiency ratio decreases the stronger with the increase of the coefficient of dynamic viscosity the greater is flow rate of gas. This enables us to come to the qualitative conclusion that the increase in content of liquid phase will reduce the efficiency ratio of separator.

It should be noted that our proposed mathematical model describing the mechanism of inertial gas-liquid mixture separation is not absolutely perfect and without flaws. Its main drawback is that it is somewhat simplified and does not take into account some processes (condensation, coagulation and fragmentation of drops) that can be realized inside the separator and would have nonequilibrium nature. While at high velocities of gas-liquid mixture, because of the small time it stays in the separator they, in our opinion, would not be decisive and do not change the basic nature of the relationships derived from the proposed model.

Another disadvantage is that in this study we not examined the process of sedimentation of liquid drops when gas-liquid mixture is passing through the cracks of domestic cylinder and vortex character of its motion in the inner cylinder. However, we believe that this process is minor compared to the process of sedimentation of drops on the inner surface of the outer cylinder by centrifugal force, which we consider crucial. Consideration and correcting of these deficiencies will be the subject of further theoretical and experimental studies. In conclusion, we note that the obtained dependences can determine the effectiveness of the separation of gas-liquid mixture in the separator of similar designs for different modes of operation, and specify design parameters, which allow to achieve the desired performance.

3. CONCLUSIONS

1. The choice of structural elements of the separator from the conditions of its division into parts is done. The impact of each of internal element of separator on the value of the coefficient of its effectiveness has been illustrated. It is shown that the main part of droplet of moisture and solids is separated in the deflector on the inner surface of the separator shell and in separation package.
2. The mathematical model for proposed construction of separator is elaborated. We consider equilibrium of droplet which is located in flow gas-liquid mixture, and the analytical expression to determine its limit radius.
3. The dependence of the thermodynamic parameters (pressure and density) of separated gas-liquid mixture on the radius of rotation of the layers has been theoretically investigated. The analytical dependence of the efficiency of the separator on gas flow, pressure in the separator, the separator geometric parameters and others characteristics have been determined.

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