Theoretical and Experimental Investigations of the Pumping Medium Interaction Processes with Compensating Volume of Air in the Single-Piston Mortar Pump Compensator

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Abstract The article considers the theoretical and experimental investigations of the pumping medium interaction processes with compensating volume of air in the single-piston mortar pump compensator as well as factors that affect the air removal kinetics from the compensator of single-piston mortar pumps. The problem of air removal from the cylindrical chamber analysis of the combined mortar pump compensator is carried out. Indicators characterizing the rate of compressed air removal from the compensator during the operation of the mortar pump are set. It is established and proved that air is removed from the cylindrical chamber depending on: pressure, productivity of mortar pump, solution temperature and intensity of exchange between pumped solution and compressed air. The allowable compressed air contact area of the compensator's cylindrical chamber is established by installing a float at the air-solution interface.

Keywords Mortar pump with increased volume combined compensator · Cylindrical chamber · Degree of pressure pulsations · Volumetric efficiency · Solution mobility

1 Introduction

Analysis of modern mortar pumps indicates the search for ways to simplify and improve the schematic diagram of single-piston mortar pumps while minimizing ripples in the pipeline during the transportation of mortars.

In order to reduce the ripple in modern single-piston mortar pumps, pressure ripple compensators are used mainly in the form of air caps of different volumes.

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But the caps, along with the advantages of simplicity of design, have significant disadvantages: the compressed air in contact with the pumped solution is quickly removed from the cap during operation of the mortar pump. Especially the removal of air is observed with increasing supply pressure to 1,2…1,5 MP. At the same time pressure pulsations increase, and efficiency of work of the compensator essentially decreases. But in the compensator, the process of kinetic interaction of air with the solution is currently insufficiently studied.

Therefore, there is a need to develop new designs of compensators and improve single-piston mortar pumps of increased reliability, which will provide moderate levels of pulsations of the solution, ease of operation and maintenance, increased technical parameters and efficiency.

2 The Analysis of the Latest Sources of Research

An important negative phenomenon in the pumping of mortars is the removal of compressed air from the compensators, which negatively affects the level of the degree of pulsation and the quality of finishing work.

Studies on the relationship between the state of contact of the liquid with air in the compensators are diverse. But the processes of both interaction and removal of air from the compensator are not sufficiently confirmed by experimental studies.

From the literature [1] we can note the statement, which considers that at a volume of the compensator in 350 l and supply of the pump of 50 l/s, at high pressures, the air which is placed in the compensator, dissolves in liquid, owing to continuous passing of the last through the compensator and gradually decreases. It is also stated that after 13.3 min the air is completely removed from the compensator. Conclusions based on experiments to determine the solubility of air in petroleum products. But these conclusions cannot be compared with the operation of compensators in mortar pumps, as there is a significant difference in the solubility of air in petroleum products and in mortars.

Known experimental data [1], which were carried out when pumping water and clay solutions with specific gravity 1,22; 1,28; i 1,6 г/см^3, with a duration of pumping, which ranged from 1 h 45 min to 4 h 45 min at a pump supply of 260 l /min and a pressure of 5 MPa. When pumping the clay solution, it was found that the volume of compressed air in the compensator, reduced to atmospheric pressure, has not changed.

Highlight parts of a common problem that have not been solved before. To solve the problem of removing air from the cap, it is necessary to analyze how the air dissolves in the mortar at the interface "solution—air" when the pressure increases, as well as how the solution is compressed. It is known that the compression of a fluid depends on its properties, temperature and pressure.

With increasing pressure, the air in the solution in the free state, partially becomes soluble in the interaction with water, and the rest of the insoluble solution is compressed according to the Boyle-Marriott law.

According to research [2], the value of absolute compression is the difference between the volume of free air at atmospheric pressure V_0^{noB} and the volume of air in the free state $V_{B.c}^{noB}$, remaining after partial dissolution at the appropriate pressure p_1

$$\Delta V_p = V_0^{noB} - V_{B.c}^{noB} = V_0^{noB} - \left(V_0^{noB} - k \cdot V_p \cdot \left(\frac{p_1}{p_0} - 1\right)\right) \cdot \frac{p_1}{p_0} \quad (1)$$

The equation shows that all the free air that is in solution in the form of bubbles at some pressure $p_{p.n}$ will go into a soluble state and further compression of the solution will stop, ie the change in the volume of the solution will be carried out only by compressing its liquid and solid phases. But according to the data [3, 4], water at room temperature at a pressure of 70 MPa is compressed only by 2,9%. It can be assumed that water is practically not compressed to the pressure of the solution (not higher than 4 MPa).

The magnitude of the pressure $p_{p.n}$, in which there is a complete dissolution of the air mixed in the solution, assuming that $\Delta V_p^{\max} = V_0^{noB}$, is equal to [2]

$$p_p \cdot n = p0 \cdot \left(\frac{V_0^{noB}}{k \cdot V_p} + 1\right) \quad (2)$$

This dependence indicates that as the volume of free air that is in the solution in the form of bubbles under normal conditions increases, the pressure of the maximum volumetric compression of the solution increases.

An important value that characterizes the air content in the solution is the relative volumetric compression of the mortar

$$\varepsilon_p \left[\frac{V_0^{noB}}{V_{\mathrm{p}}} - \frac{p_0}{p_1 \cdot V_p} \cdot \left(V_0^{noB} - k \cdot V_{\mathrm{p}} \cdot \left(\frac{p_0}{p_1} - 1\right)\right)\right] \cdot 100\% \quad (3)$$

Formula analysis makes it possible to state that for sedentary solutions that have less water and more air, the maximum compression of the solution is carried out at a higher pressure than for solutions with greater mobility. Theoretical analysis of the compression of the solution is confirmed by experimental data [2], shown in Fig. 1.

The considered theoretical and experimental researches do not fully reveal processes of dissolution and removal of air in air compensators.

As notes in [5] the capacity of the compensator of the mortar pump should be not less than 50 l that at its diameter of 150 mm will have height about 2800 mm. Such overall dimensions of a cap are very big and inadmissible from the operational point of view. There is a statement of Charny [1], that the compensator of the big sizes, almost in complete absence of air in it, nevertheless is capable to reduce to some extent pressure pulsations due to elasticity of the pumped liquid, walls of the compensator and discharge pipes.

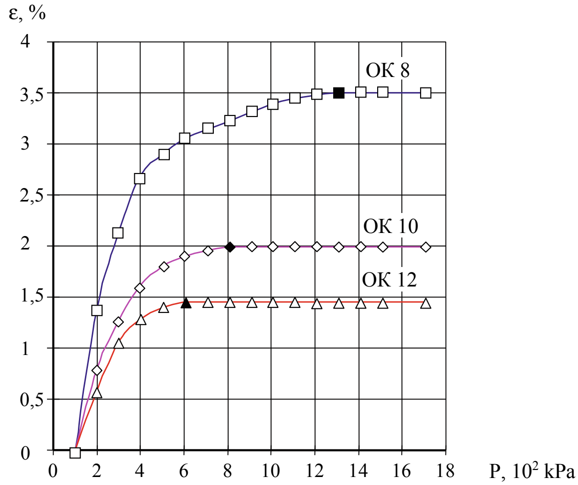


Fig. 1 Graph of the dependence of volumetric compression of solutions of different mobility on pressure

Experimental data [5] indicate that the level of pressure fluctuations of the pumped solution does not exceed 25–30%, if the compensator has a volume of 4–5 L, and the supply pressure is not more than 1.5 MPa. The same level of pressure pulsation in compensators with a volume of 10–15 l gives the chance to raise pressure to 2,5–3,0 MPa [5–14].

Increasing the working pressure of the solution above the level of 2.5 MPa makes the air compensator inefficient. It is also necessary to take into account that, as industrial practice shows, after operation of the mortar pump at a pressure of 4–5 MPa in the compensator at all there is no air presence [5].

Sometimes, to increase the efficiency of the air compensator, compressed air is pumped into it through the non-return valve during pump operation. Of course, such pumping will have a positive effect on the level of pressure ripples. But it is technically difficult to pump air when the pump is running at high pressure, because reciprocating compressors usually allow air compression of up to 0.7 MPa.

Setting a task. To solve this problem, experiments were performed with a solution pump C-263 by pumping various solutions with compensators with a capacity of 2.2; 4.4; 6,6 and 8,8 l both without introduction, and with introduction in the compensator of compressed air [5]. Experiments have shown that when operating without compressed air, the volume of the compensator increases, as expected, and the pressure ripple decreases. At a pressure of up to 0.6–0.8 MPa and the introduction of compressed air sufficient uniformity of the solution in the main was observed already at the compensator with a capacity of 6.6 l. It is proved that to ensure a sufficiently uniform pulsation of the pressure of the solution it is necessary to install compensators with a capacity of 8–10 l.

The analysis of operation of operating compensators has shown that for stabilization of pulsations of pressure actual use of the combined compensators of the closed type is actual.

The purpose and objectives of the study. The purpose of the presented work is to increase the efficiency of a single-piston mortar pump by reducing the ripple of the supply through the pipeline and increase its volumetric efficiency through the use of a combined compensator of increased volume in rational modes of technological processes.

It is necessary to perform the following tasks: to establish the mechanism of dissolution intensity and removal of the proportion of the compensating volume of air in the cylindrical chamber of the combined compensator depending on the factors influencing this process; theoretically investigate on the basis of the laws of hydraulics and thermodynamics the process of dissolving and removing air from the cylindrical chamber of the compensator and experimentally confirm the results.

Research methods. The object of the study is a single-piston mortar pump with combined compensators of pressure pulsation and increased volume.

The subject of research is the working processes of transporting mortars through the pipeline when they are fed by a single-piston mortar pump with combined compensators of pressure pulsation and increased volume.

Research methods—thermodynamic analysis of processes in the cylindrical chamber of combined compensators of the mortar pump on the basis of methods and provisions of thermodynamics, hydraulics, mathematical physics, physical and mathematical modeling by methods of applied mechanics, processing of experimental data. The basis of mathematical modeling is the equation of classical machine-building hydraulics and thermodynamics.

The studies were performed using a full-scale sample of the mortar pump, as well as test benches.

The main material. Combined pressure compensators of the investigated mortar pumps (Fig. 3a) have two chambers, one of which is filled with atmospheric air before the start of the mortar pump. When the pump begins to pump mortar, the air in the cylindrical chamber is compressed at the top of the chamber, in constant contact with the pumped mortar.

Since the air pressure in the compensator chamber during operation of the mortar pump is higher than atmospheric, part of the compressed air, according to Henry's law, is additionally dissolved in the aqueous component of the solution and removed from the cylindrical compensator chamber together with the pumped solution. At the same time the total reduced volume of air in the combined compensator of pressure considerably decreases that causes deterioration of efficiency of work of the compensator therefore, pulsations of pressure of solution increase.

A similar phenomenon is observed during the operation of all mortar pumps equipped with pressure compensators in the form of an air cap filled with free air. But the consequences of air removal in this case will be more negative—because together with the pumped solution can be removed most of the available air compensator and it will cease to perform a compensatory function. Therefore, the study of factors that contribute to the accelerated removal of air from the caps by the pumped solution is of practical importance.

It is necessary to mathematically analyze the influence on the intensity of air removal from the cylindrical chamber of the compensator, such factors as solution supply pressure, air solubility coefficient in the solution of this mobility, solution temperature, solution pump supply and the degree of solution renewal in the upper part of the chamber.

The structural component of mortars is water, in which air dissolves with increasing pressure. Therefore, the current concentration of dissolved air in the solution can be represented by the ratio of the volume of air dissolved in its aqueous component to the volume of the aqueous component in the solution.

$$C = \frac{V_{noB \cdot p}}{V_{Bo\partial}}$$

The solubility of gases in liquids, according to Henry's law, is directly proportional to the external pressure [2, 15]

$$V_{noB.p} = k \cdot V_{Bo\partial} \frac{p}{p_0} \tag{4}$$

where $V_{no\text{в}.\,p}$—the volume of air that is removed from the cylindrical chamber by dissolving the air in the aqueous component of the mortar under the action of pressure; $V_{\text{в}o\partial}$—the volume of the aqueous component in the solution; k—the coefficient of solubility of air in the aqueous component of the solution at a given temperature; p_0—pressure at the beginning of the solution supply; p—pressure at the end of the solution supply.

According to Henry's law, you can determine the current concentration of air saturation in the soluble component

$$c_{Hac} = k \cdot \frac{p_{cp}}{p_0} \tag{5}$$

where k—the coefficient of solubility of air in the aqueous component of the solution at a given temperature; p_0—the initial supply pressure of the solution; p_{cp}—the final supply pressure of the solution.

Coefficient k solubility of air in the aqueous component of the mortar at base temperature $t = 20$ °C, by data [2], can be determined by dependence

$$k = \frac{V_{0noB}}{V_{Bo\partial} \cdot \left(\frac{p_{\text{г}p}}{p_{amM}} - 1 \right)} \tag{6}$$

where $V_{0\,no\text{в}}$—the content of air in a solution of a certain mobility at atmospheric pressure; $V_{\text{в}o\partial}$—the volume of the aqueous component in the solution; $p_{\text{г}p}$—the ultimate pressure at which all the free air in the solution in the form of small bubbles dissolves in the aqueous component of the solution; $p_{am\text{м}}$—atmospheric pressure.

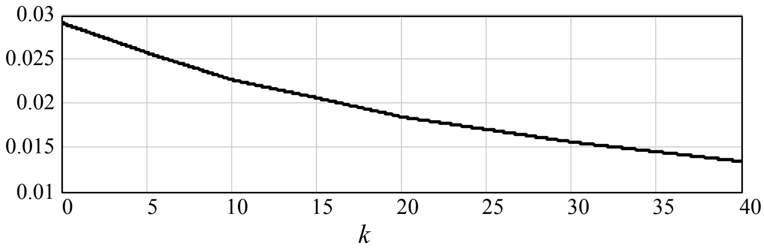


Fig. 2 Dependence of the coefficient k solubility of gases in the aqueous component depending on the temperature

Quantitative values of the coefficient k for mobility solutions П 8, 10 i 12 cm given in the work [2].

The coefficient of solubility of air in the aqueous component, respectively, and in solution, according to [15], largely depends on the water temperature (Fig. 2) (Table 1).

Taking into account the temperature of the solution, which varies depending on the ambient temperature and affects the dissolution of the air in the cylindrical chamber, as well as taking into account the pressure change, the solubility coefficient of air in the mortar, taking into account the dependences, [16–19]. will look like

$$0 \le \varphi \le \pi \quad k = \frac{p_{amM} \cdot V_{0noB}}{VBo\partial \cdot \left(\frac{V_{koMn}}{V_0 - F_n \cdot \left\{ R \cdot (1 - \cos\varphi) - \left[l - \sqrt{l^2 - (R \cdot \sin\varphi - e)^2} \right] - \frac{h_n}{2\pi} \cdot \varphi \right\}} \cdot \frac{T_0}{T} - p_0 \right)}$$

$$0 \le \varphi \le 2\pi \quad k = \frac{p_{amM} \cdot V_{0noB}}{VBo\partial \cdot \left(\frac{V_{koMn}}{V_0 - F_n \cdot \left[\left(x_\pi - \frac{h_n}{2} \right) - \frac{h_n}{2\pi} \cdot (\varphi - \pi) \right]} \cdot \frac{T_0}{T} - 1 \right)} \tag{7}$$

Therefore, taking into account the known dependence of the dissolution of air in the aqueous component depending on the temperature, which are shown in Fig. 2 and the value of the dissolution coefficients in the gases listed in Table 2, determine the dissolution coefficient of air k in the aqueous component of the cylindrical chamber of the expansion pump compensator.

The processes occurring in the cylindrical chamber of the compensator can be described by the Mendeleev-Clapeyron law, which are true when $p \le 1$ MPa and at $T \ge 20$ °C.

$$p \cdot V = \nu \cdot R \cdot T \tag{8}$$

For real gas with increasing temperature, as well as high pressure, the van der Waals equation holds

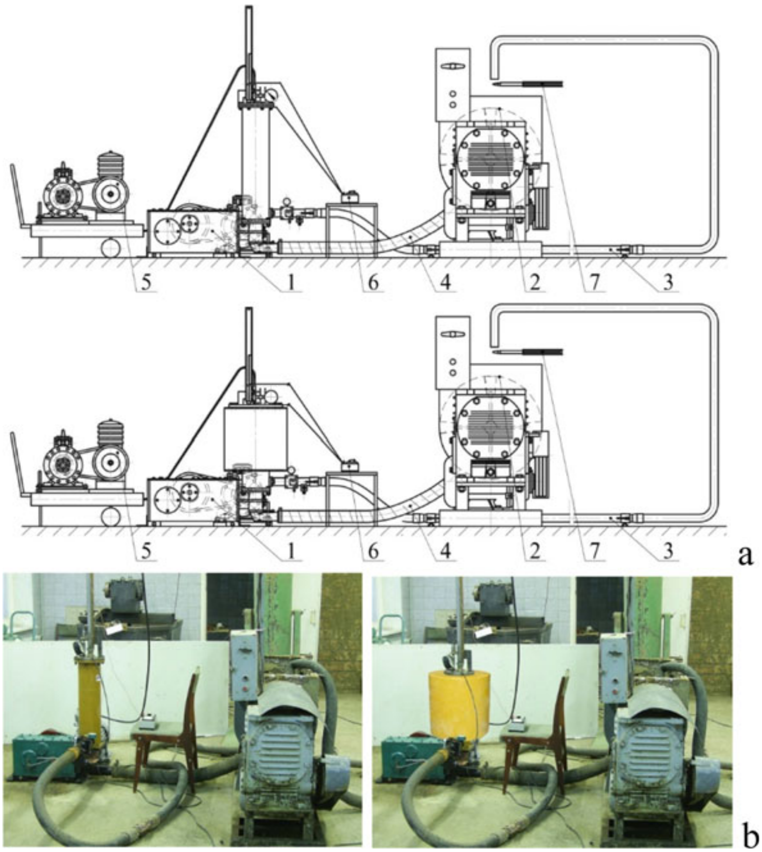


Fig. 3 Experimental stand for determining the intensity of air removal from the cylindrical chamber of the mortar pump when pumping solutions by mobility П 8, 10, 12 cm and at medium supply pressures $p = 0, 9$ MPa, $p = 1, 2$ MPa, $p = 1, 7$ MPa: a—schematic image; b—photo of experimental stands. 1—single-piston mortar pump with combined pressure ripple compensator; 2—mortar mixer; 3—pressure line; 5—suction pipe; 6—mobile compressor; 7—milliammeter; 8—alcohol thermometer

$$\left(p - \frac{\nu^2 a}{V^2}\right) \cdot (V - b \cdot \nu) = \nu \cdot R \cdot T \quad (9)$$

where p—pressure in the cap; V—volume of gas (air); a i b—gas constants (air (80% N_2, 20% O_2) $a = 135, 8$ KPa·dm6/moll2, $b = 0, 0364$ dm^3/moll); R—gas constant; ν—amount of gas.

As the temperature of the solution increases, the density of the solution changes, and the process of expanding the solution by increasing the volume of air bubbles in the solution. In this case, the gas bubble will pop up if its lifting force is sufficient to overcome the shear forces of the layers in the solution. The limiting diameter of a bubble that does not pop up can be determined by the equation [7]

Table 1 Coefficients of solubility of gases in the aqueous component (volume of gas that is reduced to normal conditions in the volume of water)

	Temperature									
Degrees Celsius	0	5	10	15	20	30	40	50	60	80
Degrees of Kelvin	273	278	283	288	293	303	313	323	333	353
Gases	Water solubility coefficients in water									
N_2	0,0236	0,0209	0,0185	0,0168	0,0151	0,0130	0,0111	0,0095	0,0084	0,0053
O_2	0,0486	0,0429	0,0376	0,0342	0,0304	0,0251	0,0216	0,0186	0,0158	0,0097
78%N_2 + 22%O_2	0,0291	0,0257	0,0227	0,0206	0,0185	0,0156	0,0134	0,0115	0,0100	0,0062

$$d_0 = \frac{6 \cdot \tau_0}{\lambda \cdot g \cdot \left(\rho_p - \rho_n\right)} \tag{10}$$

where τ_0—dynamic shear stress of the solution; ρ_p—the density of the solution; ρ_n—air density; g—free fall acceleration; λ—experimental coefficient ($\lambda = 1 \ldots 1, 25$).

If you use the speed of the ball to fall into the viscous-plastic liquid u, then it is possible to take advantage of the dependency

$$u = \frac{d \cdot \tau_0}{2 \cdot \mu} \cdot \left[\sqrt{\frac{g \cdot d \cdot (\rho_p - \rho_n)}{6 \cdot \lambda \cdot \tau_0}} - 1\right] \tag{11}$$

where d—the diameter of the air bubble; μ—structural viscosity.

When flowing, the bubble increases in volume, then according to the Boyle-Marriott law we have the expression.

$$Z \cdot \frac{\pi \cdot d_H^3}{6} \cdot \rho_{noy} = Z_H \cdot \frac{\pi \cdot d^3}{6} \cdot \rho \tag{12}$$

where, $d_н$, d—diameters of bubbles at $\rho_{noч}$, ρ; $Z_{noч}$, Z—compression ratios at the initial and current density of the solution $\rho_{noч}$, ρ.

Solving this equation with respect to and substituting in the equation, we will receive

$$u = \frac{d_H \cdot \tau_0}{2 \cdot \mu} \cdot \sqrt[3]{Z_{om} \cdot \frac{\rho_{noy}}{\rho}} \cdot \left[\sqrt{\left(\frac{d_H \cdot g \cdot \left(\rho_p - \rho_n\right)}{6 \cdot \lambda \cdot \tau_0} \cdot \sqrt{Z_{om} \cdot \frac{\rho_{noy}}{\rho}}\right)} - 1\right] \tag{13}$$

Under such conditions, the dissolution of air decreases, and, accordingly, the dissolution of air in the aqueous component of the solution decreases. Bubbles with a diameter of about 0.12 cm begin to float in a straight line, larger—in a spiral [6].

Coalescence and dispersion of air bubbles are also observed during the movement of a viscous medium. In the flow of solution, air bubbles are more dispersed. Under certain conditions, shear stresses and dispersion levels, the motion of bubbles in the solution stops.

The rate of dissolution of air in the aqueous component depends on the lack of gas to equilibrium, and the frequency of collisions of gas molecules with the interface.

Then we can assume that one of the important factors in removing air from the compensator at the distribution of soluble and air phases is the rate of dissolution

$$W = \alpha \cdot \left(\frac{c_{Hac} - c}{c}\right)^{A} \cdot \left(\frac{p_{cp}}{p_0}\right)^{B} \tag{14}$$

where c—the current concentration of dissolved air in the aqueous component of the solution; $c_{нac}$—equilibrium concentration of dissolved air, which changes over time; p_{cp}—the average pressure at which all the free air that is in the solution in the form of small bubbles, dissolves in the aqueous component of the solution; p_0—atmospheric pressure; A, B—indicators of degree (are experimentally depending on temperature); α—the intensity factor of saturation-dissolution of air in the aqueous component of the solution.

Expression $\frac{c_{Hac}-c}{c}$—characterizes the lack of gas (air) to equilibrium, and expression $\frac{p_{cp}}{p_0}$—characterizes the frequency of collisions of gas molecules with the interface; c, $c_{нac}$, p_{cp}—functions from time, which are determined as a result of processing for each of the experiments.

The intensity of dissolution, removal of air from the cylindrical chamber at the separation of the solution and the air phases per unit time will be

$$W = -\frac{dV_{noB}}{d\tau} \quad \text{or} \quad -dV_{noB} = Wd\tau. \tag{15}$$

From where the amount of dissolved air in the aqueous component of the solution over time will look like

$$-dV_{noB} = \int_0^{\tau} Wd\tau = \int_0^{\tau} \alpha \cdot \left(\frac{c_H - c}{c}\right)^{A} \cdot \left(\frac{p_{cp}}{p_0}\right)^{B} d\tau \tag{16}$$

In expression (3) unknown value is the coefficient of intensity of dissolution-saturation of air—the aqueous component of the solution, which after solution can be determined by

$$\alpha = \frac{\Delta V_{noB}}{\int_0^{\tau} \left(\frac{c_H - c}{c}\right)^{A} \cdot \left(\frac{p_{cp}}{p_{amM}}\right)^{B}} = \frac{\Delta V_{noB} \cdot \left[\frac{T_1(\tau)+K}{293}\right]^{-1}}{\int_0^{\tau} \sqrt{\left(\frac{k \cdot V_{Bo\partial \cdot p03}}{V_{p \cdot noB}}\right) \cdot \left(\frac{p_{cp}}{p_{amM}}\right)} d\tau} \tag{17}$$

where $\Delta V_{noв}$—the amount of dissolved saturated air over time.

Depending on (4) the amount of air removed by the pumped solution from the compensator, namely from the cylindrical chamber during the operation of the mortar pump, is directly proportional to the magnitude of the solution pressure increase from atmospheric level and the exchange rate between the pumped solution and compressed air in the chamber α, and the solubility coefficient of air in the aqueous component of the solution k at a given temperature T_1.

However, the solution is heated during pumping, and the rate of air removal should decrease, because the solubility coefficient of air in the aqueous component, with increasing temperature, decreases by the inversely exponential law. That is, the process of dissolving gases in the aqueous component of the solution is accompanied by the release of heat according to the exothermic law [6, 7]. It follows that in summer, when the pumped solution has a higher temperature, the rate of removal of compressed air from the cylindrical chamber will be much lower than in the cold season. The effect of increasing the temperature of the solution on the rate of air removal due to its pumping in production conditions will be insignificant, because the mortar passes through the hydraulic part of the mortar pump and pipelines once.

From the analysis of all factors influencing the rate of air removal from the cylindrical chamber, it is necessary to reduce the area of contact of the volume of compressed air with the pumped solution. This reduction can be achieved by using in the middle of the cylindrical chamber a float made of a material whose density is much less than the solution (Fig. 4), and which insulates most of the surface of the solution from contact with compressed air. But the best design solution will be complete isolation of the surface of the solution from compressed air, although this solution requires special diaphragms or containers made of flexible elastic materials.

Confirm the results of theoretical research on the intensity of air removal from the cylindrical chamber of the combined compensator single-piston mortar pump when pumping mortars of different mobility, created a test bench (Fig. 3), which is designed in accordance with the requirements for technological kits in different conditions playgrounds. The studies were performed on a single-piston mortar pump with two structurally different compensators.

The stand consists of a single-piston mortar pump 1, mortar mixer 2, pressure line made of steel pipelines 3, pressure rubber hoses 4, suction pipe 5 made of reinforced rubber fabric sleeve, compressor 6, milliammeter 7 and alcohol thermometer 8.

As part of a single-piston mortar pump installed a measuring device, which was used to measure the parameters of the intensity of air removal from the cylindrical chamber of the compensator. The measuring device consists of a solution pump of single action [3, 19] (Fig. 4), which is equipped with a cylindrical chamber 1, in the cover 2 of which there are three holes. Through the first hole hermetically passed rod 3, designed to determine the volume of air in the cylindrical chamber, which passes through the hole in the nut 4 and the rubber gasket 5, which prevents the etching of air from the cylindrical chamber.

The dependences of the reduced volume of compressed air in the cylindrical chamber of the mortar pump and the degree of pulsations of the solution supply on the time of pumping the solution are established.

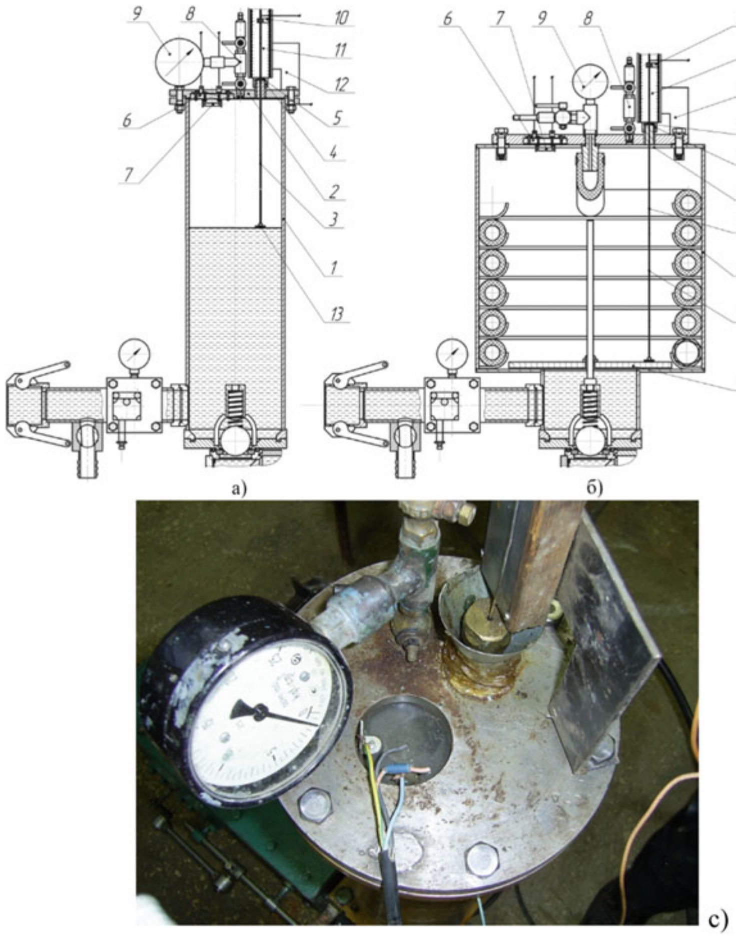


Fig. 4 Measuring device as part of a single-piston mortar pump to determine the intensity of air removal from the cap when pumping solutions by mobility П 8, 10, 12 cm and at supply pressures $p = 0,9$ MPa, $p = 1,2$ MPa, $p = 1,7$ MPa: **a** the scheme of the cylindrical chamber of the combined pressure ripple compensator; **b** scheme of the combined compensator of the increased volume with a float; **c** image of the measuring device. 1—cylindrical air cap; 2—cover; 3—rod; 4—nut; 5—rubber gasket; 6—organic glass; 7—light bulb; 8—air valve; 9—manometer; 10—check box; 11—metal ruler; 12—tripod; 13—rubber gasket; 14—float

The reduced air volume in the cylindrical chamber of the combined pressure pulsation compensator is presented as a function of the main parameters of the working process (19), over time, depending on the current temperature of the solution was determined by the formula (18).

In the second hole is fixed organic glass 6 and an electric light bulb of the cap 7. This hole is needed to control the contact surface of the solution in the cylindrical chamber with the lower end of the rod 3. Also, to check the contact moment of the solution meniscus with the end of the rod Ц 4354-М1 ТУ 25–04-3303–95.

For more precise contact of the rod with the solution, the contact meniscus is separated by a rubber gasket 13. The air valve 8 with the manometer 9 is screwed into the third hole, through which air is pumped from the compressor. Fixing the height of the air column in the cylindrical chamber is carried out using a flag 10, which is fixed on the rod 3 and equipped with a ruler 11 (0–1000 DSTU GOST 427–2001), which is mounted on a tripod 12.

To confirm the theoretical research, a number of experimental studies were conducted on the stand discussed above in Figs. 3 and 4 to determine the intensity (speed) of air removal from the compensators of different design solutions for single-piston mortar pump when pumping lime-sand solutions of different mobility.

The given volume is determined by the formula

$$V_{koMn} = \pi \cdot \frac{D_{y.k.}^2}{4} \cdot H_{noB} \cdot \frac{p_{cp}}{p_{amM}} \cdot \frac{T_0}{T} \tag{18}$$

where $D_{ц.к.}$—the diameter of the cylindrical chamber; $H_{пов}$—the height of the air column in the cylindrical chamber of the compensator, dm; T—the current temperature of the solution, К.

Dependencies in Fig. 3 are presented as a function

$$V_{koMn} = f\left(\tau, T, p, V_{p03}, \rho\right) \tag{19}$$

where τ—the time of pumping the solution pump, dm; T—the current temperature of the pumped solution, К; p—solution supply pressure, MPa; $V_{роз}$—volume of solution in a cylindrical chamber; ρ—the density of the solution, kg/dm^3.

The results of measurements and calculations are presented in Table 2 and in Fig. 5. The test results (Fig. 5) indicate that during the operation of the mortar pump compressed air is relatively quickly removed from the cylindrical chamber of the compensator by the pumped solution. In this case, the rate of air removal is significantly affected by the supply pressure. The higher the supply pressure, the higher the rate of compressed air removal. If at a pressure of 0.9 MPa for 180 min of pumping solutions with a mobility of P 8, 10 and 12 cm (Fig. 5) on the differences of the current fixed volumes were removed, respectively, 2.57; 2.45 and 2.04 dm^3 of the reduced volume of air, and already at a pressure of 1.7 MPa—already 6.56; 5.31 and 4.18 dm^3.

This result is partly explained by Henry's law, which is based on the dissolution of air in solution. Observations of the process in the cylindrical chamber through the glass window showed that the removal of compressed air is affected by the pulsation of the solution, or rather the amplitude of oscillations of the solution, due to which more intensive mixing of the solution with the contact air. In addition, with pressure drops from $p_{\max}$ till $p_{\min}$ there is a condensation of vapors which were saturated with air and at increase of pressure settle down on a solution surface.

Table 2 Parameters of intensity of removal of air from the cylindrical chamber of the combined compensator of pulsation of pressure of the single-piston mortar pump

Mobility of the solution, cm	The height of the air column H_{noe}, dm	Time of change of an air column τ, s	p_{max}/p_{min}, MPa	Average supply pressure p_{cp}, MPa	Changing the degree of pulsation	The temperature of the solution T, °C	Time of change of temperature of solution τ, c
П8	2,4329	0	0,98/0,82	0,9	17,8	22	0
	2,3848	35	0,99/0,81		20,0	22	30
	2,3366	80	1,00/0,80		22,2	24	60
	2,2884	173	1,01/0,79		24,4	26	90
	2,2872	180	1,01/0,79		24,4	27,5	120
						28,5	150
						29,2	180
	1,8247	0	1,35/1,05	1,2	25,0	22	0
	1,7647	40	1,37/1,03		28,3	23,2	30
	1,7107	106	1,38/1,02		30,0	25,5	6
	1,6703	159	1,39/1,01		31,7	27	90
	1,6610	180	1,39/1,01		31,7	28,5	120
						29	150
						30	180
	1,2880	0	1,94/1,46	1,7	28,2	22	0
	1,2571	12	1,96/1,44		30,6	22,5	30
	1,1919	62	1,98/1,42		32,9	26	60
	1,1439	107	1,99/1,41		34,1	28	90
	1,0959	176	2,00/1,40		35,3	29,5	120
	1,0911	180	2,00/1,40		35,3	31	150
						32	180
П10	2,4329	0	0,96/0,84	0,9	13,3	22	0
	2,3841	35	0,97/0,83		15,6	22	30
	2,3444	80	0,98/0,82		17,8	24	60
	2,2985	160	0,99/0,81		20,0	25,9	90
	2,2940	180	0,99/0,81		20,0	27,5	120
						28,3	150
						29	180
	1,8247	0	1,31/1,09	1,2	18,3	22	0
	1,7677	40	1,32/1,08		20,0	23	30
	1,7180	94	1,33/1,07		21,7	25,2	60
	1,6822	148	1,34/1,06		23,3	26,8	90
	1,6759	180	1,34/1,06		23,3	28,4	120
						28,9	150
						29,9	180

(continued)

Table 2 (continued)

Mobility of the solution, cm	The height of the air column $H_{пов}$, dm	Time of change of an air column τ, s	p_{max}/p_{min}, MPa	Average supply pressure p_{cp}, MPa	Changing the degree of pulsation	The temperature of the solution T, °C	Time of change of temperature of solution τ, c
	1,2880 1,2610 1,2460 1,1994 1,1292 1,1286	0 18 58 107 172 180	1,87/1,53 1,89/1,51 1,90/1,50 1,91/1,49 1,92/1,48 1,92/1,48	1,7	20,0 22,4 23,5 24,7 25,9 25,9	22 22,5 25,8 28 29,4 30,9 31,7	0 30 60 90 120 150 180
П12	2,4329 2,3848 2,3365 2,3172	0 35 104 180	0,95/0,85 0,96/0,84 0,97/0, 83 0,975/0,825	0,9	11,1 13,3 15,6 16,7	22 22,5 24,2 26 27,3 28,5 29	0 30 60 90 120 150 180
	1,8247 1,7767 1,7286 1,7095	0 33 105 180	1,29/1,11 1,30/1,10 1,31/1,09 1,315/1,085	1,2	15,0 16,7 18,3 20,0	22 23,3 25 28 29 30 30,5	0 30 60 90 120 150 180
	1,2880 1,2400 1,1919 1,1632 1,1652	0 38 109 177 180	1,84/1,56 1,85/1,55 1,87/1,53 1,88/1,52 1,88/1,52	1,7	16,5 17,6 20,0 21,2 21,2	22 23 26 29 30 31 31,5	0 30 60 90 120 150 180

In addition to the pressure, the intensity of compressed air removal is affected by the mobility of the pumped solutions. The results of research show (Fig. 5) that the lower the mobility of the solution, the higher the intensity of air removal. Thus, with a decrease in mobility from P 12 to 10 and 8 cm at a pressure of 1.7 MPa, the reduced volume of removed air increases to 4.18; 5.31 and 6.56 dm^3.

The rate of air removal slows down over time, as evidenced by the decrease in the angles of inclination of the dependencies (Fig. 5) $V = f(\tau)$. There are two reasons for this (Table 3).

First, over time, the volume of compressed air in the cylindrical chamber decreases, and the height of the volume of the solution in it, on the contrary, increases. Therefore, there is a decrease in the plane of interaction of compressed air with the

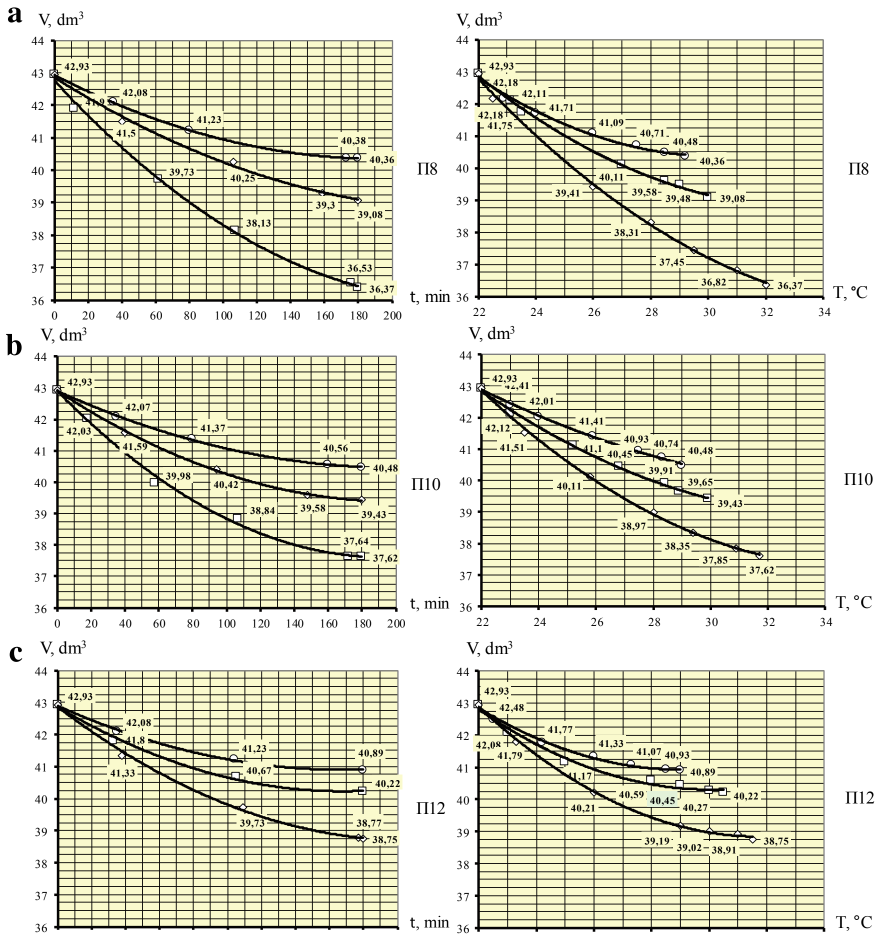


Fig. 5 Dependences of the reduced volume of compressed air in the cylindrical chamber of the combined compensator of pulsation of pressure of solution pump and temperature of solutions on time of pumping of solutions by mobility П 8 cm (**a**), П 10 cm (**b**) i П 12 cm (**c**) at medium pressure $p_{cp} = 0, 9$ (O); 1,2 (Δ); 1,7 (□) MPa

solution and the intensity of mixing of the solution. Secondly, the results of research (Fig. 5) indicate that the gradual decrease in the intensity of air removal from the cylindrical chamber is due to an increase in the temperature of the pumped solution. In addition, increasing the temperature of the solution in the summer to 40 °C and above leads not only to the suspension of air removal from the cylindrical chamber, but also an increase in air volume in the cylindrical chamber, which is accompanied by the emergence of air bubbles from the solution.

The results of research (Fig. 5) show that the intensity of air removal from the cylindrical chamber of the compensator is affected by the volume of solution in the

Table 3 Parameters of intensity of removal of air from the cylindrical chamber of the combined compensator of the increased volume of the single-piston mortar pump with the float established in it

Mobility of the solution, cm	The height of the air column $H_{пов}$, dm	Time of change of an air column τ, c	p_{max}/p_{min}, MPa	Average supply pressure p_{cp}, MPa	Changing the degree of pulsation, %	The temperature of the solution T, ^oC	Time of change of temperature of solution τ, s
П8	2,4329 2,4273 2,4221 2,4165	0 43 104 180	0,98/0,82 0,99/0,81 1,00/0,80 1,00/0,80	0,9	17,8 20,0 22,2 22,2	22 23 25,5 27,0 29,0 29,5 31,5	0 30 60 90 120 150 180
	1,8247 1,8111 1,8055 1,8038	0 34 113 180	1,35/1,05 1,36/1,04 1,365/1,035 1,365/1,035	1,2	25.0 26,7 27,5 27,5	22 22,5 25,0 26,5 28,7 29,5 30,0	0 30 60 90 120 150 180
	1,2880 1,2703 1,2610 1,2595	0 37 109 180	1,94/1,46 2,01/1,39 2,02/1,38 2,02/1,38	1,7	28,2 29,4 30,6 30,6	22 22,5 26 28 29,5 31 32	0 30 60 90 120 150 180
П10	2,4329 2,4272 2,4244 2,4233	0 47 102 180	0,96/0,84 0,97/0,83 0,975/0,825 0,975/0,825	0,9	13,3 15,6 16,7 16,7	22 22,6 23,2 24,0 25,5 27,5 28,3	0 30 60 90 120 150 180
	1,8247 1,8145 1,8073 1,8064	0 33 116 180	1,31/1,09 1,32/1,08 1,33/1,07 1,33/1,07	1,2	18,3 20,0 21,7 21,7	22 23,5 24,5 25,4 27,6 28,5 29,0	0 30 60 90 120 150 180

(continued)

Table 3 (continued)

Mobility of the solution, cm	The height of the air column $H_{пов}$, dm	Time of change of an air column τ, c	p_{max}/p_{min}, MPa	Average supply pressure p_{cp}, MPa	Changing the degree of pulsation, %	The temperature of the solution T, ^oC	Time of change of temperature of solution τ, s
	1,2880 1,2742 1,2670 1,2655	0 36 111 180	1,87/1,53 1,88/1,52 1,89/1,51 1,895/1,505	1,7	20,0 21,2 22,4 22,9	22 23,6 24,8 26,5 28,4 29,5 30,5	0 30 60 90 120 150 180
П12	2,4329 2,4289 2,4272 2,4250	0 51 100 180	0,95/0,85 0,95/0,85 0,955/0,845 0,955/0,845	0,9	11,1 11,1 12,2 12,2	22 22,3 23,0 24,0 25,7 27,4 28,2	0 30 60 90 120 150 180
	1,8247 1,8153 1,8094 1,8081	0 38 120 180	1,29/1,11 1,29/1,11 1,30/1,10 1,33/1,07	1,2	15,0 15,0 16,7 16,7	22 22,7 23,8 25,5 27,3 28,4 29,0	0 30 60 90 120 150 180
	1,2880 1,2754 1,2685 1,2670	0 32 114 180	1,87/1,53 1,89/1,51 1,89/1,51 1,90/1,50	1,7	16,5 16,5 17,6 17,6	22 23,3 24,6 26,4 28,1 29,2 30,2	0 30 60 90 120 150 180

cylindrical chamber, and the larger this volume, the lower the intensity of air removal from the compensator.

This is due to the decrease in the rate of mixing of the solution on the surface of contact with air.

To reduce the intensity of air removal from the cylindrical chamber of the combined compensator of increased volume in its middle is installed a float with a diameter of 14 Ø 270 mm and height 8 mm (Fig. 4, б). Due to the float, the contact area of the solution with air in the cylindrical chamber decreased from 1.96 dm ^{2} till 0,15 dm^2 (for the experimental-industrial sample of the solution pump).

Research results (Fig. 6) show that due to the introduction into the cylindrical chamber of the combined compensator of the increased volume of the float, the intensity of air removal from the cylindrical chamber is significantly reduced.

So, with reduced mobility П 12 till 10 and 8 cm at pressure 1,7 MPa the reduced volume of air in the cylindrical chamber of the combined pressure ripple compensator

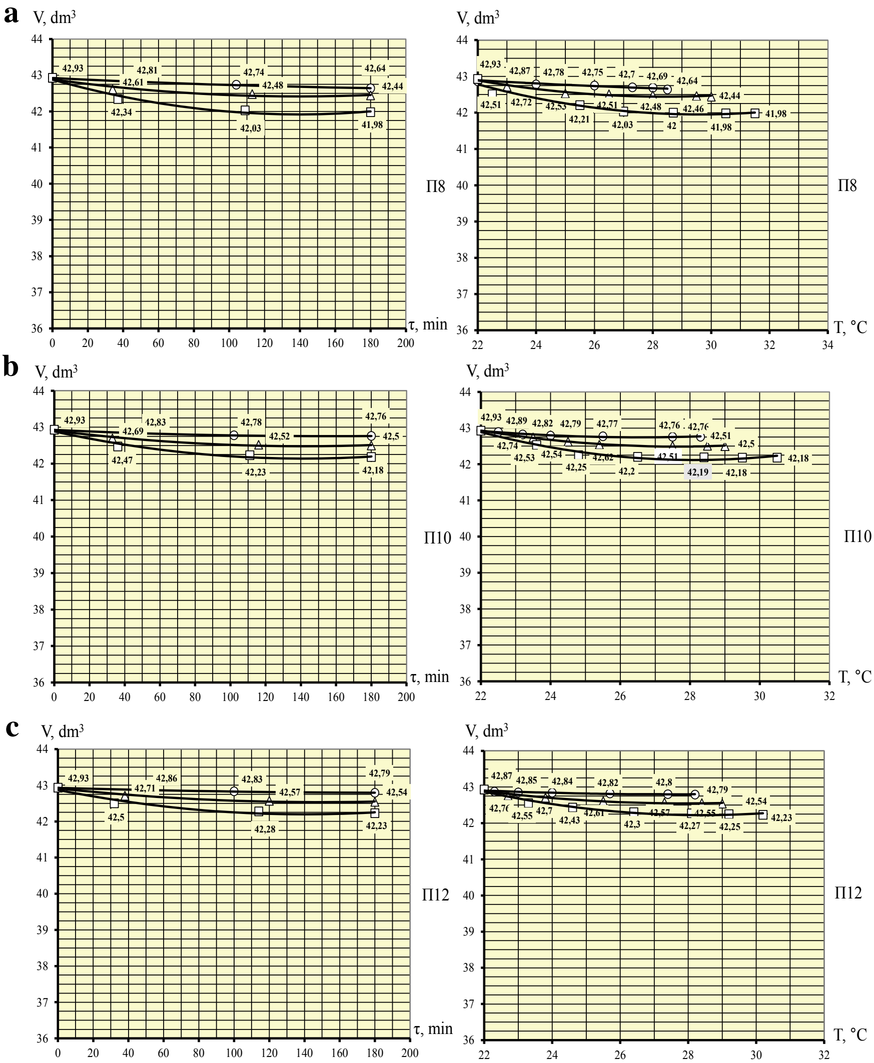


Fig. 6 Dependences of the reduced volume of compressed air in the cylindrical chamber of the combined compensator of the increased volume of the solution pump with a float and temperature of solutions on time of pumping of solutions by mobility П 8 cm (**a**), П 10 cm (**b**) i П 12 cm (**c**) at medium pressure $p_{cp} = 0,9$ (O); 1,2 (Δ); 1,7 (□) MPa

in relation to the volume of the cylindrical chamber of the combined compensator of the increased volume with a float has changed from 4,18 to 0,7 dm^3; from 5,31 to 0,75 dm^3 and from 6,56 to 0,95 dm^3 accordingly.

Dependencies (Fig. 7) indicate that during the pumping of the solution over time there is an increase in the degree of pressure pulsations. This is due to two factors: a decrease in the volume of air in the cylindrical chambers of the combined volume compensators and the combined pressure ripple compensator, and an increase in the average supply pressure of the solution. There is also a proportional increase in the degree of pressure pulsations in relation to the decrease in the compensation volume in the cylindrical chambers of the compensators, as well as with increasing supply pressure.

Therefore, the expediency of installing a float in the middle of the cylindrical chamber of the compensator of increased volume at the separation of the air and liquid phases is justified in relation to reducing the degree of pulsation of the supply pressure.

Experimental studies of air removal from a cylindrical chamber with different mobility of solutions are consistent with the previously considered hypotheses and are a practical confirmation of the results of theoretical studies of changes in the volume of compressed air in a cylindrical chamber by changing the current air concentration per minute with increasing pressure by 0.1 MPa.

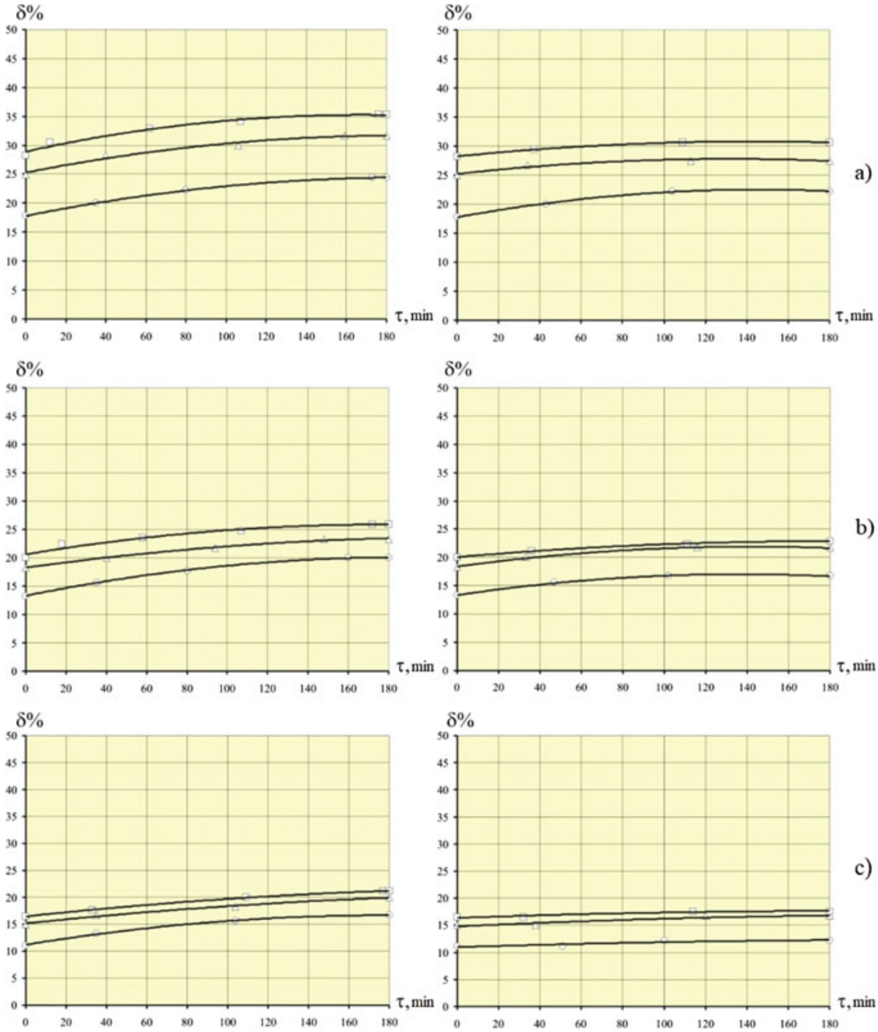
The coefficient of intensity of air removal from the cylindrical chamber, which is determined on the basis of dependence (4) and are given in Tables 4 and 5.

Dependencies (Fig. 8) indicate that the concentration of air in the solution decreases with decreasing air volume in the cylindrical chamber during the pumping of the solution of reduced mobility. Also, the introduction into the cylindrical chamber of the combined compensator of the increased volume of the float provides a decrease in the coefficient of intensity of air removal from the cylindrical chamber in proportion to the area of contact of the solution with air. The research results confirm the need to isolate the air volume in the cylindrical chamber of the combined compensators by means of a float with chipboard 10 mm thick with a guide rod, which will reduce air removal and increase the degree of pulsations of the solution.

According to research, it can be argued that in sedentary solutions, which have a lower water content and, accordingly, more air, the maximum compression of the solution occurs with increasing pressure than for solutions with greater mobility. Also, when the pressure rises to the limit, depending on the mobility, there is a complete dissolution of air in the water of the solution.

According to Henry's law, Mendeleev-Clapeyron's law, the van der Waals equation, processes occur, both dissolution and the emergence of air bubbles on the separation of air and liquid phases depending on pressure and temperature.

Coalescence and dispersion of air bubbles are also observed during the movement of viscous media. In the flow of the solution, due to the viscosity of the medium, air bubbles are more dispersed. Under certain conditions of shear stresses during the supply or stop of the solution and the level of dispersion, the movement of bubbles in the solution stops.



cylindrical chamber of the compensator pressure ripple

cylindrical chamber of the compensator increased volume

Fig. 7 Dependences of the degree of solution pressure pulsations in cylindrical chambers of combined pressure pulsation compensators at free contact of air with the solution and the increased volume with the float on the time of pumping solutions by mobility Π 8 cm (**a**), Π 10 cm (**b**) i Π 12 cm (**c**) at medium pressure $p_{cp} = 0,9$ (O); 1,2 (Δ); 1,7 (□) MPa

Table 4 The coefficient of intensity of air removal from the cylindrical chamber of the combined compensator of pulsation of pressure of a solution pump at the parameters characterizing this process

Parameters			8 cm	10 cm	12 cm
№ experiment	The height of the air column H, dm	Medium pressure filing p_{cp}, MPa	The coefficient of intensity of air removal from the cylindrical chamber,α		
1	2,4329	0,9	0,00,383	0,00,379	0,00,373
2	1,8247	1,2	0,00,368	0,0035	0,00,314
3	1,2880	1,7	0,00,343	0,0029	0,00,241

Table 5 The coefficient of intensity of air removal from the cylindrical chamber of the combined compensator of the increased volume of the mortar pump at the parameters characterizing this process

Movability		8 cm		10 cm		12 cm	
№ експерименту	Average supply pressure P_{cp}, MPa	The height of the air column H, dm	The coefficient of intensity of air removal from the cylindrical chamber,α	The height of the air column H, dm	The coefficient of intensity of removal of air from a cylindrical chamber, α	The height of the air column H, dm	The coefficient of intensity of removal of air from a cylindrical chamber, α
1	0,9	2,47	0,00,089	2,46	0,00,085	2,445	0,00,071
2	1,2	1,82	0,00,081	1,78	0,00,072	1,735	0,00,065
3	1,7	1,26	0,00,069	1,25	0,00,063	1,29	0,00,062

The rate of dissolution of air in the aqueous component depends on the lack of gas to equilibrium, and the frequency of collisions of gas molecules with the interface.

On the basis of theoretical and experimental researches quantitative indicators of coefficient of intensity of removal of air from a cylindrical chamber are established α, which characterizes quantitatively the current concentration of air removed by dissolving in the solution, as well as due to the saturation of the solution with air (in the process of changing the surface of the solution in the area of contact with air during pumping). It is experimentally proved that the air from the cylindrical chambers of the combined compensators of the solution pump is removed under the influence of such factors as: solution supply pressure, mobility of pumped solutions, temperature of solution or air and saturation of solution with air.

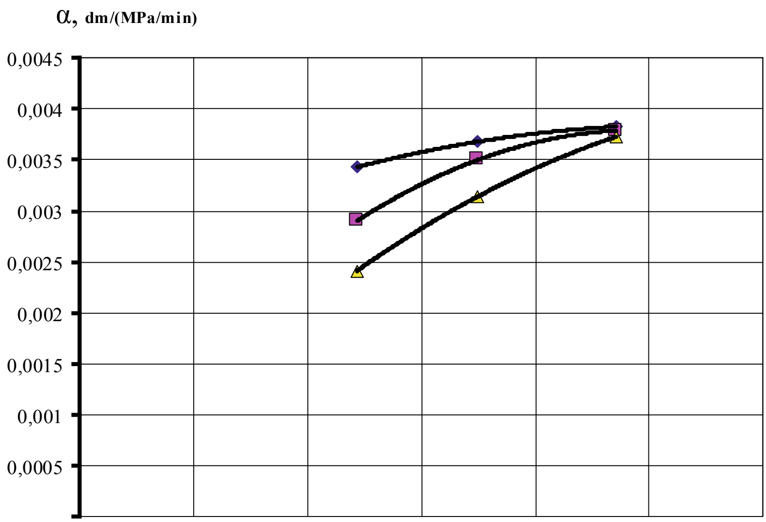


Fig. 8 Dependences of the coefficient of intensity of air removal from the cylindrical chambers of the mortar pump on the height of the column of compressed air *H* when pumping solutions at medium pressure: 0,9; 1,2; 1,7 MPa: ◆—П8; ■—П10; ▲—П12—for a cylindrical chamber of the combined pressure pulsation compensator; × – П8; □—П10; ●—П12—for the cylindrical chamber of the combined compensator of the increased volume

3 Conclusions

1. The relative amount of air that can dissolve in the soluble mixture to its saturation is directly proportional to the pressure at the phase distribution surface.
2. Compressed air is saturated on the distribution surface when changing the surface layer of the solution is partially joined and together with the flow of solution is removed.

   The rate of air removal slows down over time, as evidenced by the angles of inclination of the tangents to the horizontal. This is established for two reasons. First, during pumping, the volume of compressed air in the cylindrical chamber decreases intensively over time, and the height of the column of the volume of the solution in it, on the contrary, increases. As a result, there is a decrease in the plane of interaction of compressed air with the solution and the intensity of mixing of the solution. Secondly, as the temperature of the pumped solution increases, the intensity of air removal from the cylindrical chamber gradually decreases. The rate of removal of air from the cylindrical chamber of the compensator is also affected by the volume of solution in the cylindrical chamber, and the larger this volume, the lower the intensity of removal of air from the compensator. This is explained by the fact that at a relatively minimum height of the solution column in the cylindrical chamber there is a faster change of the solution layer at the interface due to the flow of solution from the valve space, which in turn is much faster saturation-mixing of air into the solution.

3. The research results show that the quantitative indicator is the coefficient of intensity of air removal from the cylindrical chamber during pumping by the compensator of the increased volume in relation to pumping by the compensator pressure pulsations decreased by 5 times due to installation of a float in the cylindrical chamber. This significantly reduced the pressure ripple of the solution 10%.

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