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# Vertical differential grout pump experimental studies methods validation

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The article is devoted to creation and substantiation of experimental research method of vertical differential grout pump with flowing piston mark PH 2-4, developed by researchers at Poltava National Technical Yuri Kondratyuk University. Experiments type has been substantiated, variation intervals of the studied parameters values have been determined, the preparation of the experimental sample of the grout pump for research has been described, an experimental installation for research has been designed, the measuring means have been selected, the conditions for performing the experiments have been determined. This technique enables to find the rational values for the following parameters of the solution pump when working with plaster solutions of different displacement: working body frequency movement, diameter, mass and height of lifting over the valve, the hole diameter in the valve sockets.

**Keywords:** plastering works, plaster works complex mechanization, plaster works mechanization equipment, mortar transportation by pipelines, mortar pump, test facility, test procedure, experiment, experimental accuracy.

# Обґрунтування методики експериментальних досліджень вертикального диференціального розчинонасоса

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Статтю присвячено створенню та обґрунтуванню методики експериментальних досліджень вертикального диференціального розчинонасоса з проточним поршнем марки РН 2-4, розробленого науковцями Полтавського національного технічного університету імені Юрія Кондратюка. Метою експериментальних досліджень є: перевірка висунутих під час аналітичних досліджень гіпотез, обґрунтування вибору найбільш раціональних значень основних конструктивних параметрів розроблюваного розчинонасоса, обґрунтування сфери застосування методів регулювання подачі шляхом зміни довжини та швидкості руху робочого органа, а також отримання експлуатаційних регулювальних характеристик досліджуваного насоса. Обґрунтовано тип експериментів, визначено проміжки варіювання значень досліджуваних параметрів, описано підготовку експериментального зразка розчинонасоса для досліджень, спроектовано експериментальну установку для досліджень, вибрано засоби вимірювань, визначено умови виконання дослідів. Як критерій ефективності прийнятих конструктивних рішень прийнято об’ємний коефіцієнт корисної дії розчинонасоса. Виготовлена дослідницька установка дозволяє приготувати будівельний розчин необхідної рухомості та складу і визначити час наповнення мірної місткості при різних комбінаціях величин досліджуваних конструктивних параметрів розчинонасоса. Значну увагу приділено визначенню похибок проведення експериментів. Запропонована методика дозволяє гарантувати з імовірністю 90%, що абсолютна похибка у визначенні об’ємного коефіцієнта корисної дії на основі середньоарифметичного значення п’яти замірів при кожній комбінації досліджуваних параметрів, зумовлена систематичною і випадковою складовою, не перевищить 1,9%. Така методика дозволить знайти раціональні значення наступних параметрів розчинонасоса при роботі зі штукатурними розчинами різної рухомості: частота руху робочого органа, діаметр, маса і висота підйому над гніздом кульок клапанів, діаметр отвору в гніздах клапанів.

**Ключові слова:** штукатурні роботи, комплексна механізація штукатурних робіт, засоби механізації штукатурних робіт, транспортування будівельних розчинів трубопроводами, розчинонасос, випробувальний стенд, методика випробувань, експеримент, похибка експерименту.

**Introduction**

During the construction of multi-dwelling houses, a significant amount of construction work is made by plastering walls wet processes. They are labor-intensive and difficult to mechanize. Recently, transporting building plaster solutions to the workplace plaster on pipelines technology is widely used for the purpose of their mechanized application on the surface to be treated with the help of a special nozzle. During the transport of plaster mixes by pipelines, there are problems [1, 2, 3], which were tried to solve by a number of scientists.

**Review of research sources and publications**

The researches of the Department of Building Machines and Equipment [4, 5] Poltava National Technical Yuri Kondratyuk University have made significant progress in solving these problems [6 – 14], proposing the design of new machines and substantiating their effectiveness. Technological process main machine for plastering works is a grout pump. A group of scientists and the author of the article as well, developed a vertical differential grout pump of a new design, which was called PH 2-4 [15 – 21].

**Definition of unsolved aspects of the problem**

The results of analytical studies and the design of the experimental sample displayed the advantages of the developed grout pump before the existing ones. However, they enabled only the qualitative dependence on influence of the design parameters on the efficiency of its work. Therefore, the purpose of experimental studies is to check the hypotheses proposed in the process of analytical research, to substantiate the choice of the most rational values of the basic design parameters of the grout being developed, to validate the scope of the application supply control methods by changing the length and frequency of the working body stroke, as well as obtaining the operational control characteristics of the pump under test.

To achieve the above objective, the following tasks need to be solved:

– to determine the type of experiments;

– to determine the range of variation of the values of the parameters under study;

– to prepare an experimental sample of a mortar pump for research;

– to create an experimental plant for research;

– to select measurement tools;

– to determine the conditions for the experimentation.

**Problem statement**

The purpose of this article is to create and substantiate the methodology of experimental research of a vertical differential solenoid pump with flowing piston of the mark PH 2-4.

**Basic material and results**

Considering the task set for the study of the dissolved pump design parameters influence developed on its volume efficiency, laboratory experiments were selected, since they are less labor-intensive and, due to the high reproducibility of the conditions for the production of experiments, enable to obtain fairly accurate results.

In order to achieve the set goal, it is provided in the process of staging experiments to be varied by the following parameters of the grout pump: height of lift, diameter and ball of the suction valve, as well as the mass of this ball at constant diameter, length and frequency working body movement.

In connection with it, steel balls with a diameter of 40, 50 and 60 mm in weight, respectively, of 0.26, 0.51 and 0.89 kg were purchased for the suction valve (Figure 1, 3). Two Silverstone balls are cast in diameter 60 mm (Figure 1, 3). Due to the presence of internal weighing cores, their masses are 0.28 and 0.55 kg, which is close to the masses of steel beads with diameters, respectively, 40 and 50 mm. Instead of a standard ball valve lifting limiter, adjustable balls (Figure 1, 4 and Figure 2, 3) are made for each ball size, which allow a height change of 0…25 mm to be changed. They are supplied with replaceable valve sockets (Figure 1, 2 and Figure 2, 4). The diameters of these nests are arranged so that for each size of the ball, the value of $K$ is provided in the range of 0.3…0.9 in increments of 0.1 and is 12, 15, 16, 18, 20, 24, 25, 28, 30, 32, 35, 36, 40, 42, 45, 48 and 54 mm.

The stroke length of the operating body of the grout pump is changed by the normal supply regulator within 0…72 mm.

A pair of step pulleys (Fig. 1) is made to change the operating frequency of the working member. The steps of the diameters are calculated in such a way that, in the presence of a standard motor, considering its slipping, the operating frequencies of the operating unit of the grout pump are 126.0, 151.5 and 177.0 rpm (gradation is 25.5 rpm). These frequencies correspond approximately to the theoretical performance of the pump 4, 5 and 6 m$^3$/h. The type of section and tension of the belt are chosen from those considerations, in order to avoid slipping in the range of loads under investigation (up to 0.6 MPa). The results of search experiments displayed that there is practically no increase in the slippage of an electric motor with increasing load in this range.

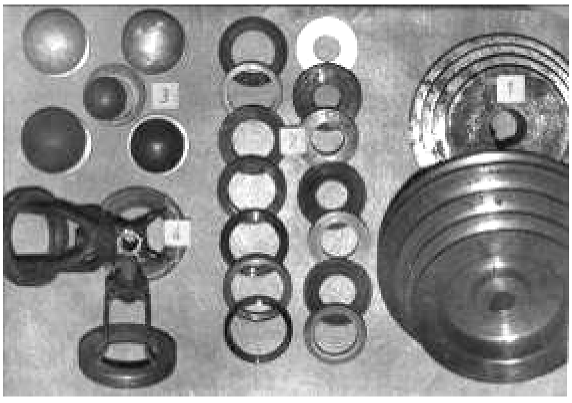


**Figure 1 – Grout pump replaceable elements for varying studied design parameters value**

An experimental installation (Figure 2) has been designed and manufactured for research of the considered grout pump, which includes the mixer for solution 1, the investigated pump 2, the load device 7 and the measuring capacity 5. The discharge pressure is monitored using a standard pressure gauge 6.

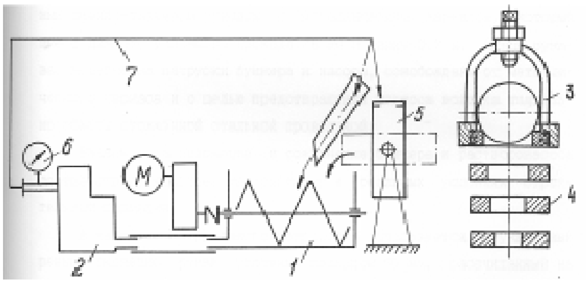


**Figure 2 – Experimental installation schematic diagram for the study of grout pumps**

The capacity of the mixer for the solution is determined by the required volume of the prepared batch, which is determined from the following considerations: 20 liters of solution are required for filling the loading arm, measuring capacity 60 liters, 10 liters of the suction arm and cavities of the grout pump. In order for the grout pump not to «swallow» the air during the suction cycle, at least 80 liters of solution must remain in the mixer. Since the mixing efficiency is significantly reduced when the mixer's working body is fully buried, we reserve a reserve volume of 110 liters. The mixer capacity in this case is 300 liters.

It is equipped with a reversible belt unit with a rotational speed of 18 rpm, which consists of two equal parts with opposite winding. In this case, when the shaft rotates in one direction, the solution flows to the middle of the bunker, and when it rotates to the other, to its ends. Reversible rotation of the mixer provides faster and better mixing of the solution. In the middle lower part of the mixer there is a pipe for connecting a grout pump.

For ease of maintenance, the studied pump, together with the mixer, is raised above the floor to a height of 0.3 m. The suction inlet of the mortar pump is connected to the hopper by a vacuum sewage rubber hose with a metal frame 75 mm in diameter and 0.7 m long and the pump, freed from the metal frame and in order to prevent air leaks, are carefully crimped with annealed steel wire.

Mutual arrangement and connection of the mixer and mortar pump correspond to the most used in real conditions of the construction site.

A plaster rubber-fabric sleeve with a conditional passage of 50 mm, designed for a pressure of 4.0 MPa, 20 m long, rolled into a coil with a diameter of at least 2 m is used as a load device. It is connected to the pump using a standard quick-release coupling.

The measuring tank with a volume of 60 liters is made in the shape of a cylinder with a diameter of 300 mm with the bottom. The design of the stand enables it to tip over for emptying into the mixer.

The experimental set also includes: a special scraper for cleaning the remaining solution from the measuring container and a device that prevents the solution from passing into the suction hose from the mixer while the suction nozzle is disconnected from the mortar pump for the next setting of variable parameters of the suction valve.

Removal of the spent solution and flushing of the system is carried out using the mortar pump under study. The water supply is provided from the water supply both for flushing and cooling the seal of the rotor pump rod, and for flushing the mixer and measuring container after removing the spent solution from the system.

The appearance of the installation is shown in Figure 3.

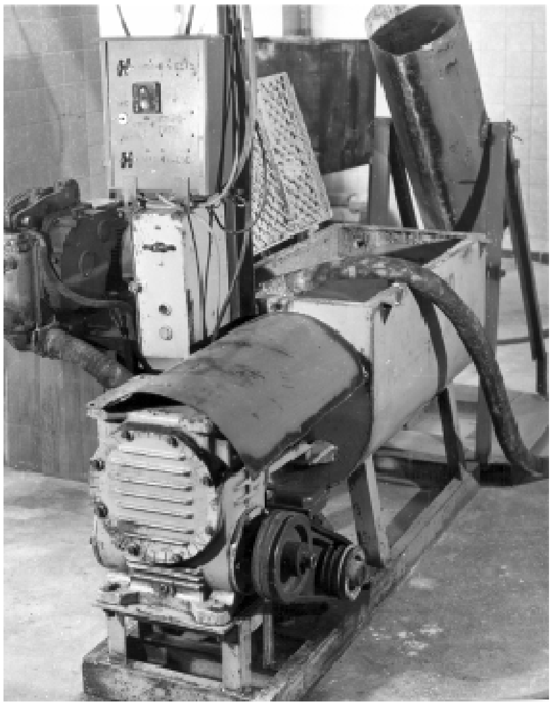

**Figure 3 – Experimental installation for grout pumps study**

For research, we use the most frequently pumped mortar-pumped lime-sand grout of a 1:3 composition with aggregate fractions up to 5 mm. Its mobility is determined using the standard cone according to the method described in [22].

Exploratory experiments have shown that with stirring in a mixer and when pumping a solution by a pump over a closed ring, its intense heating occurs, which in turn leads to a change in its consistency. A specially conducted series of measurements showed that an increase in the mobility of a solution by 1 cm occurs when its temperature increases by 3…4 ºC.

Following measurement procedure was adopted. Set the required values of the studied design parameters. The solution is prepared somewhat lower mobility than is necessary for the formulation of experience. When the solution in the bunker becomes homogeneous, the mortar pump is turned on and the mobility of the pumped medium is periodically measured. As soon as its value reaches the required value, the pressure is transferred from the mixer to the measuring tank with simultaneous activation of the stopwatch. The time of its filling is noted and the mobility of the solution is measured again. If the mobility during the filling of the tank has not changed, the result of the experiment is considered valid. Otherwise, if the solution is fresh, let it cool and repeat the experiment, and if it is outdated, replace it.

Thus, the experimental setup enables to prepare a grout of the required mobility and composition and determine the time for filling the measuring capacity with various combinations of the values of the studied design parameters of the grout pump.

**Measuring instruments and experimental techniques.** The chosen volumetric efficiency of a grout pump as a criterion for the effectiveness of design solutions. $\eta_0$, %, cannot be measured directly. It is determined by indirect methods – by direct measurement of its functionally determining quantities.

It is advisable to use the following dependency

$$\eta_0 = \frac{Q}{Q_T}100 = \frac{24 \cdot 10^9 \cdot V}{\pi \cdot D^2 \cdot n \cdot L \cdot t}\ , \quad (1)$$

where $Q$ – experimentally measured pump flow;
$Q_T$ – theoretical supply;
$V$ – measured capacity volume, $V$ = 60 L;
$D$ – grout pump piston diameter, $D$ = 100 mm;
$L$ – pump body stroke length, mm;
$n$ – working body movement frequency, rpm;
$t$ – time of filling with a solution the measuring tank.

Calibration of the measuring tank was made by weighing method by weighing it in an empty and filled with water condition. Water was poured until the mass of the tank with water exceeded by 60 kg the mass of the empty tank. For this purpose, we used platform scales mobile scale РП-200Ш13 with a scale of 50 g. It is considered the piston diameter to be an exact value equal to 100 mm, since the inaccuracy is enabled by us in this case is negligible compared to the measurement accuracy of other quantities included in the above formula. It is determined the length of the stroke working body using the square with the price of 1 mm division. The time of filling the measuring vessel with a solution and the frequency of working body movement are determined using the stopwatch СДСпр-1-2-800 with a dividing price of 0.1 s. As a result of exploratory experiments, it was established that the inaccuracy of the established number of strokes of the working body within 1 minute is no more than ± 0.5 double strokes. Over this limit, the values did not go out either with an increase in load or with variation of the power network parameters.

The measurement inaccuracy is determined by the recommendations set out in [23, 24]. To do it, in the center of the response surface (in the area of the expected extremum), select the "point" and, using the proposed method, find the volume efficiency here. The following values of the studied design parameters were chosen as such a «point»: $D_{III}$ = 60 mm (steel ball), $OK$ = 10 cm, $n$ = 126 rpm, $H$ = 15 mm, $K$ = 0.7, $L$ = 72 mm. The filling time of the measuring tank was 68.7 s. Then, the volumetric efficiency is

$$\eta_0 = \frac{24 \cdot 10^9 \cdot 60}{\pi \cdot 10^4 \cdot 126 \cdot 72 \cdot 68.7} = 73.5\ . \quad (2)$$

The relative inaccuracy $\delta$, %, in the definition of the values included in the formula are:

$$\delta_V = \frac{\sqrt{2} \cdot 0.05}{60}100 = 0.12\ ;$$
$$\delta_n = \frac{0.05}{126}100 = 0.4\ ;$$
$$\delta_L = \frac{\sqrt{2} \cdot 1}{72}100 = 1.96\ ; \quad (3)$$
$$\delta_t = \frac{0.1}{68.7}100 = 0.15\ ,$$

where is the multiplier $\sqrt{2}$ means that the inaccuracy is calculated as the value of the lower and upper measurements inaccuracy. All of these inaccuracies are components of the non-excluded residuals of systematic inaccuracy.

Boundaries $\Theta_j$, %, for inaccuracy in determining the volumetric efficiency introduced $j$ onsisting non-excluded residuals of systematic inaccuracy distinguished by formula

$$\Theta_j = \frac{\eta_0}{100} \cdot \delta_j\ , \quad (4)$$

Then

$$\Theta_V = \frac{\eta_0}{100} \cdot \delta_V = \frac{73.5}{100} \cdot 0.12 = 0.09\ ;$$
$$\Theta_n = \frac{\eta_0}{100} \cdot \delta_n = \frac{73.5}{100} \cdot 0.4 = 0.29\ ;$$
$$\Theta_L = \frac{\eta_0}{100} \cdot \delta_L = \frac{73.5}{100} \cdot 1.96 = 1.44\ ; \quad (5)$$
$$\Theta_t = \frac{\eta_0}{100} \cdot \delta_t = \frac{73.5}{100} \cdot 0.15 = 0.11\ .$$

Non-excluded residuals of systematic inaccuracy boundaries $\Theta(P)$, %, at the figure of compounds $N \geq 4$ is counted [24] by formula

$$\Theta(P) = \pm k \cdot \sqrt{\sum_{j=1}^{j=4} \Theta_j^2}\ , \quad (6)$$

where $k$ – coefficient determined by the selected confidence level $P$ and figure $N$ compound [23]

$$\Theta(0.9) = \pm 0.95 \times \times \sqrt{0.09^2 + 0.29^2 + 1.44^2 + 0.11^2} = \pm 1.4\ , \quad (7)$$

An additional inaccuracy introduces inaccuracy of the solution composition dosage and the change in its properties over time. To reduce its influence, all measurements made at each «point» are distributed in time, performing them in different batches and in different sequences with measurements at other «points».

To obtain empirical dependencies, statistical methods were used, such as experiment planning and the least squares method, which enabled not only to reduce the amount of experimental work, but also to obtain a fairly reliable and accurate mathematical interpretation of existing patterns. The most effective, and most importantly, correct use of these methods requires preliminary processing of measurement results, which consists in evaluating the experimental error with the required reliability, determining the required number of experience repetitions, eliminating gross measurement errors, verifying the compliance of the distribution of measurement results with the law of normal distribution and, if necessary, in converting this distribution to normal. Preliminary processing of measurement results is made in accordance with the requirements. [23 – 29].

As a result of measurement at each «point», the arithmetic average of several measurements made here has been used. The number of these measurements depends on the accepted values of the confidence interval and the confidence probability that the true value of the measured value does not go beyond this interval. In other words, the number of experience repetitions is determined by the magnitude of the maximum error, with which the arithmetic mean of the measurements to correspond to the true value of the measured quantity, and the probability that the current error does not exceed the specified maximum value. Increasing the number of measurements at each «point» even with their accuracy unchanged, the reliability of confidence estimates can be increased or the confidence interval for the true value of the measured value can be narrowed. However, it leads to an increase in the complexity of the experiment. Therefore, the number of experience replication in research in the field of technology is not recommended [26] to take $N > 8$, and the use of statistical data processing methods loses meaning [23], if $N < 4$.

The choice of the number of measurements from the specified range is made by calculation [25, 26, 29], for which purpose in the center of the assumed extreme area at the selected point, four measurements of the filling time of the measuring capacity are taken and the corresponding values of the volumetric efficiency are calculated. As a result of the experiment, four values of volumetric efficiency $\eta_{0cp}$ are got: 73.5, 74.5, 76.0, 74.0 %.

Calculate the arithmetic mean value $\eta_{0cp}$, %, received sample

$$\eta_{0cp} = (73{,}5+74{,}5+76{,}0+74{,}0) / 4 = 74{,}5 \tag{8}$$

Corrected variance $S_{uc}^2$ this empirical distribution is determined [26] by formula

$$S_{uc}^2 = \frac{\sum_{i=1}^{N=4}\left(\eta_{0_i} - \eta_{0_{cp}}\right)^2}{N-1} = \frac{1}{4-1}\cdot\left[\begin{array}{l}(73.5-74.5)^2+(74.5-74.5)^2+\\+(76-74.5)^2+(74-74.5)^2\end{array}\right] = 1.17, \tag{9}$$

where $\eta_{0i}$ – the current value of the volumetric efficiency of the resulting series.

Selective standard deviation $S_{uc}$ is [26]

$$S_{uc} = \sqrt{S_{uc}^2} = \sqrt{1.17} = 1.1\,. \tag{10}$$

The value obtained is an unbiased estimate for the standard deviation $\sigma$ theoretical distribution

Evaluation $S_{uc}\left(\eta_{0_{cp}}\right)$, %, the standard deviation of the random component of the calculated average value error $\eta_{0_{cp}}$ is calculated by formula

$$S_{uc}\left(\eta_{0_{cp}}\right) = \frac{S_{uc}}{\sqrt{N}} = \frac{1.1}{\sqrt{4}} = 0.55\,. \tag{11}$$

In normal studies in the technique for finding the dependencies of the influence of various factors, the confidence probability of 0.9 is sufficient [29]. Based on its value, according to [29], the compromise between the value of the permissible absolute error of the experiment is chosen, which is given in the table in fractions of the standard deviation of the theoretical distribution $\sigma$, and the number of replications of experience. The permissible error equal to $1.0\cdot\sigma$, achieved when performing 5 measurements ( $N=5$ ) is appropriate.

In this case, the confidence limits $\varepsilon(P)$, random inaccuracy of the measurement result at a confidence level $P=0.9$ и $N=5$ specify [23] according to the formula

$$\varepsilon(P) = t(P,N)\cdot S_{uc}\left(\eta_{0_{cp}}\right), \tag{12}$$

where $t(P,N)$ – Student's coefficient [14].

$$\varepsilon(P=0.9) = 2.132\cdot 0.55 = 1.17\,. \tag{13}$$

For distinguishing the sum $\Delta(P)$, %, systematic and random components of the measurement result inaccuracy, it can be estimated the ratio

$$\frac{\Theta(P)}{S_{uc}\left(\eta_{0_{cp}}\right)} = \frac{1.4}{0.55} = 2.54\,. \tag{14}$$

As $0.8 < 2.54 < 8$, inaccuracy confidence limit result is determined [14] by formula

$$\Delta(P) = K(\gamma)\cdot\left[\Theta(P)+\varepsilon(P)\right], \tag{15}$$

where

$$\gamma = \frac{\Theta(P)}{\sqrt{3}\cdot k\cdot S_{uc}\left(\eta_{0_{cp}}\right)} = \frac{1.4}{\sqrt{3}\cdot 0.95\cdot 0.55} = 1.5\,, \tag{16}$$

$$K(\gamma) = \frac{\sqrt{1+\gamma^2}}{1+\gamma} = \frac{\sqrt{1+1.5^2}}{1+1.5} = 0.72\,. \tag{17}$$

Then

$$\Delta(P=0.9) = 0.72\cdot(1.4+1.17) = 1.9\,. \tag{18}$$

Thus, performing five measurements of the time of filling the measuring capacity with a solution on each of the «points» under study, guarantees with 90 % probability that the absolute error in determining the volumetric efficiency based on the arithmetic average of these measurements will not exceed 1.9 %.

If, when performing measurements at the «point», a measurement result is obtained that differs sharply from all others, a suspicion arises that a gross error has been made. In this case, it is immediately verified that the basic measurement conditions are not violated. If such a check was not done on time or it was unsuccessful, then the question of one «pop-up» value rejection expediency is solved by comparing it with the rest of the measurement results.

For the number of the experiment repetitions from 3 to 5, the following method for screening gross errors is recommended [26]. The arithmetic average and corrected variance of the obtained data has been calculated and the maximum relative deviation $\tau$ suspicious metering has been determined

$$\tau = \frac{\left|\eta_{0_i} - \eta_{0_{cp}}\right|}{S_{uc}} \le \tau_{1-p}\,, \tag{19}$$

where $\eta_{0_i}$ – «pop-up» value of volumetric efficiency.

Gained value $\tau$ compare with the tabular quintile distribution for the maximum relative deviation $\tau_{1-p}$, taken from the table in [26] with a confidence level of 95 % (which corresponds to the level of significance $p = 0.05$). In this case, with five measurements $\tau_{1-p} = 1.87$ if the value obtained does not exceed the table value, then this measurement is not screened out. In case of the measurement exclusion, the characteristics of the empirical distribution should be recalculated according to the data of the reduced sample, after which the screening procedure is repeated for the next maximum absolute deviation of the measurement in absolute value. If, as a result of screening, the sample remains less than four values, it must be supplemented with additional measurements (in our case up to five values) and repeat the procedure.

To test the hypothesis of the normal distribution values the volumetric efficiency obtained at the «point», it is recommended [26] to calculate the mean absolute deviation using the formula

$$CAO = \frac{\sum\left|\eta_{0_i} - \eta_{0_{cp}}\right|}{N}\,. \tag{20}$$

If the series of values obtained has an approximately normal distribution law, the expression should be true:

$$\left|\frac{CAO}{S_{uc}} - 0.7979\right| < \frac{0.4}{\sqrt{N}}\,. \tag{21}$$

The issue of eliminating gross inaccuracy and testing the hypothesis of the normal distribution results obtained was solved on a PC using the MathCAD software product. There were no deviations from the normal distribution.

**Conclusions**

The method of experimental research of a vertical differential solenoid pump with flowing piston of mark PH 2-4, developed at Poltava National Technical Yuri Kondratyuk University, is proposed. The compliance of this method with the purpose of increasing the efficiency research grout pump is substantiated. The equipment necessary for conducting experimental research is selected. It is verified inaccuracy in conducting research. This technique enables to find the rational values of the following parameters of the solution pump when working with plaster solutions of different displacement: working body frequency movement, diameter, mass and height of lifting over the valve, the diameter of the hole in the valve sockets.

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